CONSTRUCTION PRODUCTS THAT CONTRIBUTE TO INCREASED FLEXIBILITY IN WOOD-FRAME LOW-RISE HOUSING

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ABSTRACT

With the greatly increased rate of social and economic change in North America since World War II, the flexible/adaptable house has become an alternative to the conventional single-family, detached housing that both exceeds the needs and means of many non-traditional households. Theories and experience worldwide have shown that housing flexibility that is based on user participation allows decision-makers to adapt housing projects to meet the changing general needs. However, technological bottlenecks in the invention of new materials and techniques can restrict flexibility. This study examines construction products that contribute to increased flexibility in wood-frame low-rise housing.

Prefabrication has been the construction industry's approach to achieving housing flexibility. The strategy has been to incorporate flexibility into each subsystem or component through the use of new materials and techniques, in order to create overall building flexibility. The research presented in this thesis shows that different products offer different levels of flexibility, and that combining them does not necessarily produce greater overall flexibility. By examining the positive and negative aspects of these products, the author is able to suggest new directions for the development of future innovations in housing flexibility.

RÉSUMÉ

Lorsque l'on considère la vitesse à laquelle se produisent les changements économiques et sociaux, la maison adaptable et flexible devient une nécessité. Les théories et les expériences démontrent que la flexibilité de la maison, basée sur la participation de l'utilisateur, permettrait une adaptation plus facile et plus satisfaisante à des besoins changeants. Des restrictions techniques peuvent réduire les degrés de flexibilité en ce qui concerne une réponse satisfaisante de la maison aux besoins de l'occupant. Cette étude examine les produits utilisés en construction qui pourront augmenter la flexibilité de la maison résidentielle à structure de bois.

Pour atteindre la flexibilité, la préfabrication a été la tendance principale de l'industrie de la construction. En vue d'obtenir la flexibilité ou l'adaptabilité generale de l'édifice, la stratégie est de rechercher cette flexibilité à travers chacun des sous-systèmes ou composants par l'utilisation de techniques et de matériaux nouveaux. La recherche montre que des produits différents ont des niveaux différents de flexibilité et que tous ne peuvent être combiné pour atteindre une plus grande flexibilité. Les aspects positifs et négatifs des produits peuvent aussi nous indiquer de nouvelles directions pour le développement des innovations futures.

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CHAPTER ONE

INTRODUCTION

This chapter is intended to provide readers with the necessary background and approach for the subject studied. In the rationale for the study, the author begins by reviewing housing problems and solutions. Later, the research question is stated and key terms are defined to identify the general direction of the subject. The content and target audience of this research as well as its scope and limitations, are outlined in the objectives section. Finally, the procedures for writing the report are summarized in the section on methodology.

1.1 RATIONALE FOR THE STUDY

The main difficulty facing some Canadians is that they cannot afford adequate and suitable housing. Housing affordability problems include increasing household expenditure, increasing housing prices, a disproportionate shelter cost/income ratio, and a decline in the accessibility of home ownership (Carter 1990). In fact, this phenomenon is due to higher interest rates, higher cost of serviced land, higher infrastructure costs, and increased real estate speculation (Rybczynski et al. 1990). In addition, the state and the structure of the economy also have had a negative impact on job security, wage levels, and employee benefits making homebuyers financially unstable. This statement is especially true for young, first-time buyers. Many low-income earners will have difficulty finding affordable and appropriate housing. The outcome of this situation is similar to what Medek (1994) has described: "Potential buyers are becoming prudent shoppers and they are often forced to make a trade-off: the need to balance desired amenities and budgetary constraints frequently result in lowered expectations."

Special buyer groups have particular spatial needs. These are shaped by socio-demographic changes such as the growing number of elderly people and of people living alone; as well as by the emergence of non-traditional families, which would include single parent families, couples without children, and individuals living with others (Figure 1.1). In fact, a CMHC report (Lewis 1997) shows that the size of households has decreased from 4 people in 1961 to 2.7 in 1991, and the average household size will range from 2.5 to 2.6 in 2016. Fifty six percent of the households have only 1 or 2 persons (Statistics Canada 1996). This decrease in household size is due to the increase of single parent families, empty nesters and couples who are waiting longer to have their first child. How do we house these people?

The income level of a household also determines the choice of housing. Statistical data (CMHC 1991) indicates that single parent families and unattached individuals have the lowest average incomes, particularly female single parent families with no earning members. They have an average income of $11,776, and 95% of them are living in poverty. In consequence, more low-cost housing is required in order to house these people with diverse family structures and income levels.

The traditional housing types may not satisfy the needs of many non-traditional families, and are often less affordable. The amount of space required for each household depends on its type and economic characteristic. As mentioned above, demographic changes have caused a decrease in household size. The tendency to have smaller families has a direct influence on the size of the dwelling unit (Fung 1993). Homebuyers anticipate future needs when buying a home. Their demands for changes in interior space may relate to changes in future family size, in personal preference, or to the need for independent rooms for special purposes. Therefore, it is important not only to identify the real housing needs of users, but also to translate them into a design strategy that corresponds to their socio-economic characteristics within an affordable housing context.

A builder's response to the affordability problem is to increase supply while cutting down on housing costs. Although housing prices are affected by socio-economic conditions, they are directly controlled by the cost of home building. According to a study of The Homeownership Task Force of the United States League of Saving Institutions in 1983, house prices have been affected by changes specifically related to home size, construction and land costs, labor costs and regulatory costs (U.S. League of Saving Institutions 1983). Given these cost factors, the builder understands that affordable homes can be made possible by constructing smaller buildings and constructing buildings more quickly.

The objective of reducing costs is to develop a mass housing type that accommodates the different needs of a homebuyer, while retaining a price range that is within the buyer's financial reach. Rybczynski et al. (1990) suggest that "The reduction of costs requires a careful consideration of three factors: area, complexity, and quality." If buyers have control over these three factors, they will have control over their final house costs. The concept of housing flexibility enables the builder to design interior layouts that suit the buyer's specifications. Homebuyers are reducing costs by buying only what they need. This idea is discussed in the Evaluation of Affordable Housing Projects Based on the Grow Home Concept (Friedman and Cammalleri 1992):

> Accounting for about one third of the total construction costs, the finishing operations in housing units are among the most labor intensive. By allowing for a flexible interior space, the timing and magnitude of these costs can be manipulated. By leaving the second floor unpartitioned at the time of purchase, as an open loft space for instance, a savings of about $5,000 can be achieved. The space may then be finished by the owner at his or her own discretion.

The traditional approach to provide mass housing is to design a general model that a majority of people will adapt. This is only a temporary solution since it does not anticipate the future needs of the user. It also lacks flexibility in terms of affordability and quality because buyers have little or no choice about the price and the interior finishes.

New approaches in affordable housing introduce the notion of building flexibility. Although cutting down on costs by mass production and by applying minimum standards have been an alternative, the outcomes were often the sameness in styles and sometimes led to further restriction. As society changes towards the non-traditional family, more and more people lack the resources that were once available to two income family units. The house itself should be an active response to the user's needs. A new housing approach is then required to better control costs. This is possible by separating the "shell" infrastructure and the "occupancy" components. The combination of user participation and building flexibility helps to create more variety, and gives users the satisfaction of making a contribution which is in accordance with their own individual budget, creativity and knowledge. The increase in user participation will have an impact on the housing industry. For example, the role of existing professionals will change. Builders may be more concerned with the base building, while architects may assist users in design. Manufacturers will come up with packages for pre-design construction or post-design modification (Warshaw 1974).

The combination of user participation and building flexibility helps to create many more varieties. The degree to which each user participates will differ according socio-demographic characteristics, budgets, and knowledge. The housing flexibility approach accommodates the freedom of layout and future changes, therefore, it is less subject to rejection.

Given the demographic diversity and different needs of present-day homebuyers, traditional housing is becoming less suitable for the housing market. Housing flexibility allows a home to be built according to the occupant's specifications, and to their satisfaction. Although a builder (the most influential party in the home delivery process), has the capacity to offer flexibility, technically, it depends on a house's design and physical structure. Over the past two decades, there have been many technical inventions in low-rise wood frame housing that have changed the way we build to allow greater flexibility. New products of housing flexibility are being developed to increase user input into the design process in order to accommodate the needs of various users. However, these innovations have rarely been put together for the purpose of finding the overall building flexibility. Therefore, the whole area of flexible building systems, such as Support and Infill components, is in need of further research.[1]

1.2 LITERATURE REVIEW

In 1965, Habraken's SAR (Stichting Architecten Research) methodology demonstrated how the concept of flexibility that is used in commercial and retail sectors can be successfully applied in the residential sector. It is based on a system of "Zones and Margins" which are used to define possibilities for the layout of detachable units within Support structures[2] (Figure 1.2 & 1.3). Habraken has also created a system that allows user participation. The "Infill System" is an approach that offers users the opportunity to select their own floor plan, and the freedom to choose the quality level of the equipment to be installed (Habraken 1992). Habraken noticed that users tend to be more satisfied when they are given the opportunity to select their interior accommodations.

The separation of Infill and Support can be advantageous to a homebuilder. Traditionally, a homebuyer's choices are often limited to selecting bathroom or kitchen equipment as well as the colors of tiles and other surface finishing. Builders would prefer not to offer many choices because they are not sure if the costs of interior customization

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[1] The Support generally includes the load bearing structure, all common circulation spaces, portion of the mechanical systems, and sometimes the building's envelope. The Infill includes the non-load bearing walls, building systems in the distribution level such as fixtures, equipment and, all plumbing, wiring and duct work (Kendall 1995). The detail is described in 2.1.2 THE SAR METHODOLOGY.

[2] According to Habraken's, the "Support" comprises not only the shell of the building, including façade and roof, but also all load bearing parts as well as the major conduits that feed the individual dwelling units: those for gas, electricity, water and sewage. These conduits run to a specific point in each unit from where further deployment is done by means of the Infill system. (Habraken 1992)

can be passed on to the buyer. Therefore, the builder objects to any change that will disrupt his planning, cost more money and take more time (Habraken 1992). Since the fit-out work is separated from the Support, by giving the rest of the fit-out work to a subcontractor, the builder can be involved up to the point where the support is complete. This gives the builder the option of taking less financial risk by decreasing his/her involvement in the construction (Kendall 1995).

User participation is the natural outcome of housing flexibility. The question is what level of user participation is the builder willing to accept? There are two levels of participation: decision-making and building. Everyone has a different capacity in these areas. These capacities relate to imagination, creativity, judgment, information, and they require aptitude, skill and experience. They correspond to the individual talents of each householder, which, of course, are never the same (Warshaw 1974). Therefore, different levels of flexibility and choice should be offered to different householders. For example, not everyone is willing to accept the maximum flexibility of an empty house. Or, vice versa, a pre-designed house may have little flexibility to some householders. Too much flexibility may not be good for everyone.

Furthermore, a householder may intervene as far as his resources and competence permit. This can be done either by getting the work done by a professional, according to his specifications; or choosing ideas, components and packages, planned and installed by others; or doing it themselves by planning and installing the necessary components in his/her living space. All these reflect a certain range of flexibility (Warshaw 1974).

People have different needs, standards and constraints with respect to housing. The budget further limits the number of choices available to a householder. Therefore, the range of flexibility is reduced. Moreover, a pre-designed house may not cost more than a do-it-yourself flexible house that is similarly equipped. Developers and builders also have their ranges of profit, which should be incorporated to determine a new range of flexibility.

An experiment was done in France to explore the positive and negative aspects of flexibility in home building, and to determine whether the concept of housing flexibility has lived up to its expectations.

Builders experimented in the Montereau project to find out how occupants wanted their space: room shapes, areas and internal circulation. For the user participation part, the space was built according to occupants' wishes and needs. For the technical part, the use of the Support and Infill concept and the adoption of the modular systems allowed a large number of combinations. At first, the theory and its technological breakthroughs sounded convincing, however, it was not totally practical. The integration of modular systems restricted the number of possible layouts. The 90cm grid was too large to be flexible. There were other problems as well; the rents that were asked for these apartments were not very affordable. Nevertheless, the project showed clear success in user participation. For example, the inhabitants of the experimental building used the freedom provided by the movable partitions to make large living space. The plans they designed were not only adapted to their needs but also to their personalities and lifestyles. The authors of the article have also analyzed the number of possible combinations versus the number of people per household: less people, more possibilities (because of increased flexibility), and vice versa (Figure 1.4).

The evaluation generated a number of questions: Who are the occupants? Does the flexibility provided at Montereau correspond to the needs of every tenant? Should occupants be allowed to arrange their homes in a way that could contravene building regulations, safety or health codes, etc.? What is a "habitable" home? Nevertheless, the tenants were satisfied that they planned out their own accommodations (Martel and Ignazi, 1974).

1.3 RESEARCH QUESTION

The objective is to document products that can increase the range of housing flexibility in the construction industry. The research can be summarized in the following questions:

> **What building products and techniques are presently available that can provide options to increase interior flexibility in North American low rise wood frame housing?**

What does the author mean by "range of housing flexibility"?

The degree of finishing done to a house that is sold to homebuyer can vary greatly depending on needs. A higher degree of flexibility means the interior can be more freely outfitted to meet specific demands before, during, and after construction. In general, flexibility refers to the freedom of controlling the arrangement of a building. This research will focus on the maximum degree of flexibility presently permitted by indigenous North American housing flexibility technology.

By "products and techniques" the author refers to new technologies or the combination of existing technologies in new ways that appear in the form of new products. Housing flexibility innovations and new technologies have three basic goals:

1) To improve interior flexibility by converting non-flexible building components into flexible ones (this may include the creation of new tools, equipment and installation).

2) To improve interior flexibility by resolving or reducing obstacles which cause inflexibility (this may include the modification of existing tools, equipment and installation).

3) Combination of the two functions described above.

1.4 OBJECTIVES

1. To research theories about housing flexibility and user participation.

2. To review past projects that were designed to allow user participation in the preoccupancy stage.

3. To examine and analyze the current housing flexibility technologies that allow innovations in low rise wood frame houses in North America.

4. To propose additional means of flexibility for future house construction.

1.5 SCOPE AND LIMITATION

This research will be restricted to products and techniques of housing flexibility. The items are selected from two stages of house construction: 1) framing, 2) plumbing, heating and electrical rough-in. Furthermore, attention will be given to those that are applicable for low-rise house using the traditional light wood frame construction. The thesis addresses the North American home building industry, builders/developers, architects, designers, engineers, dwelling occupants, and manufacturers because they are the creators, implementers and users of housing flexibility. It does not aim to promote products that are studied here, but to make the industry aware of ideas that have been realized using present technologies. The cost of products and their installation are not the main aspects of this report, nor are innovative housing flexibility design concepts.

1.6 METHODOLOGY

This thesis can serve as a summary report of the innovative North American housing flexibility products that are presently available. The author consulted the accurate and up-to-date sources for this research, as well as relevant literature to obtain sufficient background on the subject. Since the focus is on housing flexibility and user participation theories, numerous home prototypes from all over the world using the concept of flexibility were examined. Technical data was obtained from builders/developers, contractors, housing agencies, Internet, libraries, manufacturers and/or professors.

Aggregate building components contribute to the overall flexibility of the home. The author structures all findings in an order of precedence (i.e. from general building structure to specific details). Principles and product evolution are briefly explained within each category of the building system, followed by products comparison, then future trends. At least four products are reviewed in each category if applicable; their technical data are processed and presented in a predetermined format. All products are subjected to performance evaluation based on their economy, installation difficulty, durability, maintainability, privacy/safety rating, practicability and appearance (Yamin 1990). After all products have been separately evaluated, an analysis on the compatibility of mixed products is studied in the conclusion.

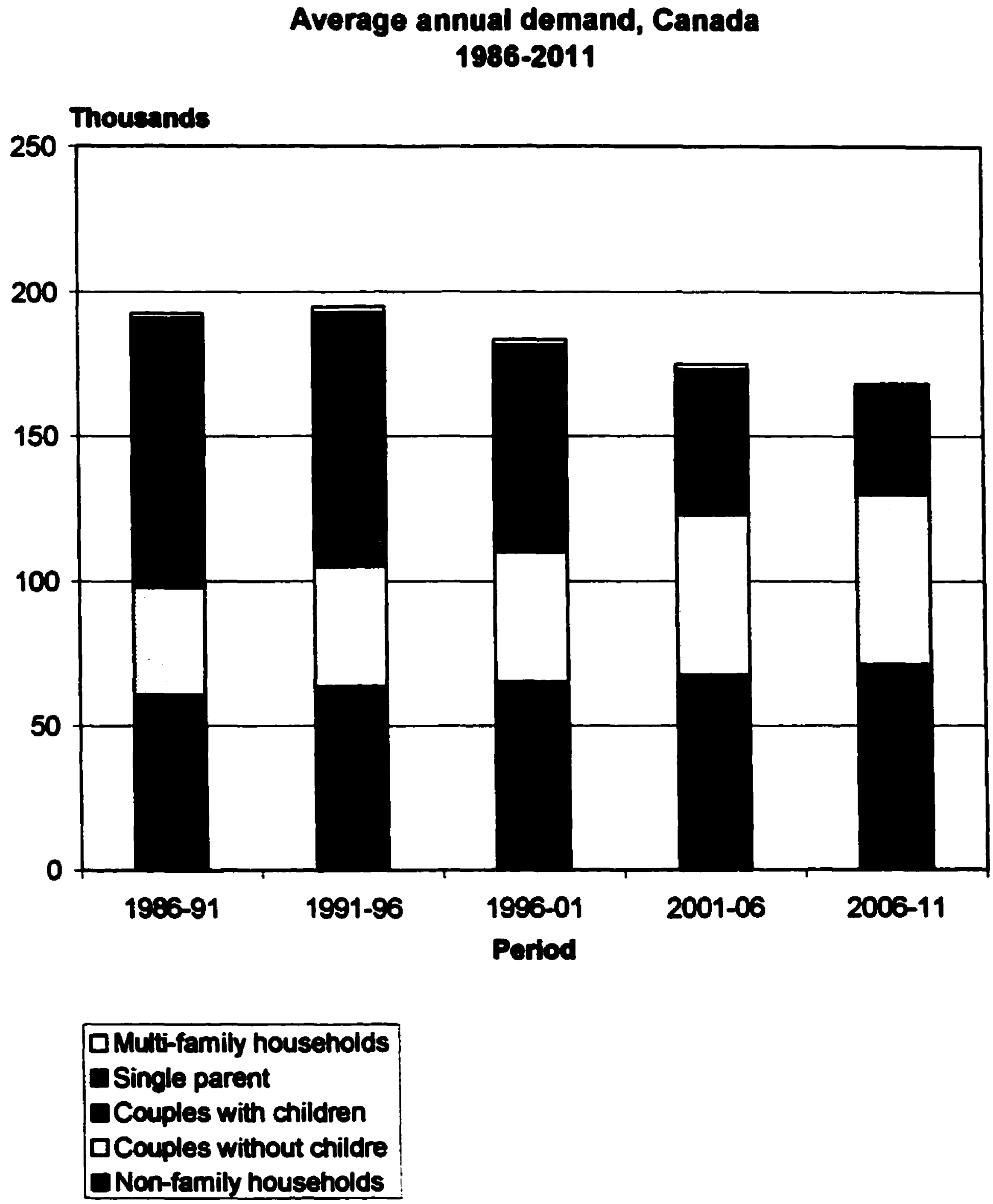

Figure 1.1: Housing Demand by Type of Family (Source: CMHC 1991)

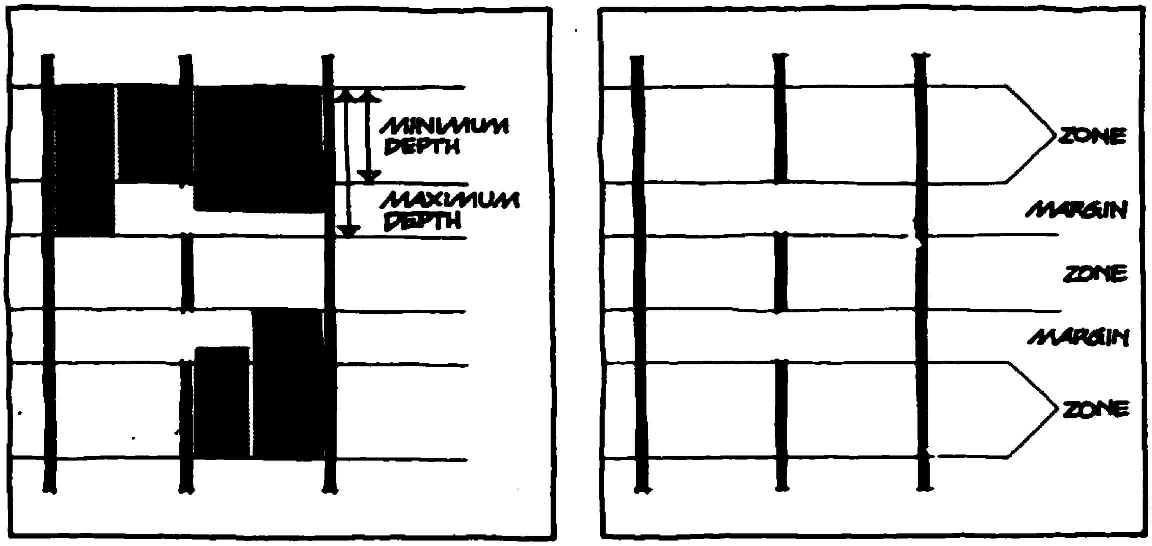

Figure 1.2: The Zones and Margins within a Support. Zones are spaces within a Support, which has certain characteristics. A Margin is an area between two zones, with the characteristics of both zones. Zones and Margins are areas within a Support in which certain kinds of spaces are located according to specific rules. (Source: Habraken, et al. 1976)

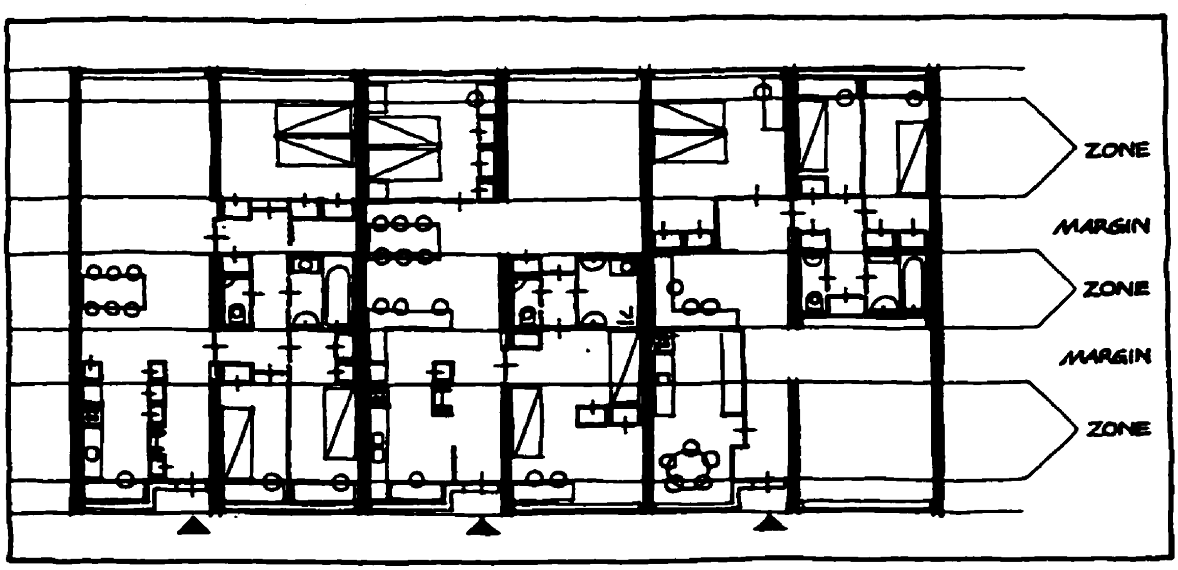

Figure 1.3: A drawing of interior layout showing Support, Zones and Margins. This example shows that the spaces in the Support are placed in the Zone/Margin system according to certain conventions. (Source: Habraken, et al. 1976)

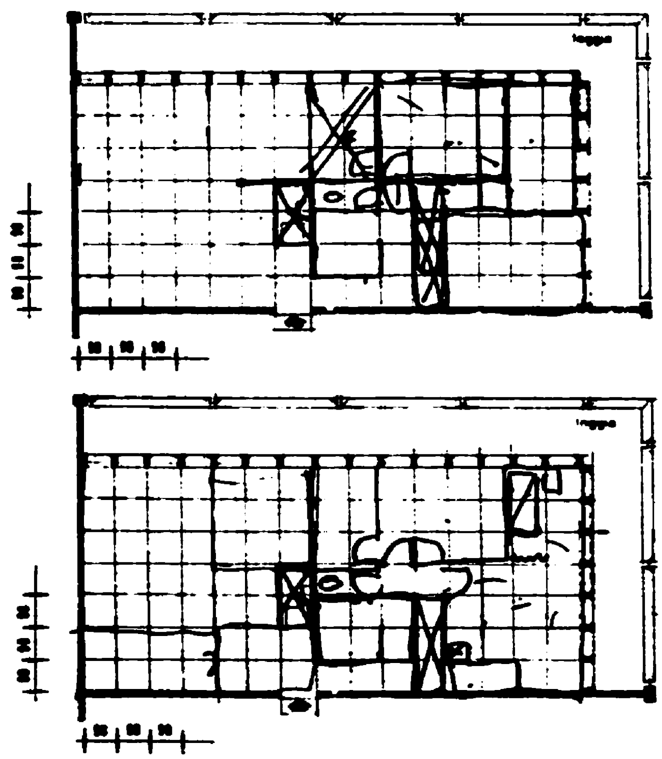

Figure 1.4: Plan developed by occupant (with guidance of the architect); after 45 and 60 minutes work. (Source: Martel and Ignazi 1974)

CHAPTER TWO

THEORY AND PRACTICE OF HOUSING FLEXIBILITY AND USER PARTICIPATION FROM 1900 TO PRESENT

This chapter examines housing flexibility and user participation literature that has directly influenced the invention of new flexible building products. The author reviews theories pioneered by John Habraken, as well as examples of housing flexibility using their concepts.

2.1 HOUSING FLEXIBILITY THEORIES AND ITS EVOLUTION SINCE 1900

The use of flexible building products depends on how flexible a building was planned to be. However, there is no standard on how flexible each project should be. The level of flexibility is specific to the condition and nature of housing at the time of planning, and the intention of the people who have the power and influence over decisions. Therefore, before one can decide on the right level of flexibility for a project, it is essential to understand the concept of housing flexibility, to know how it works, and to learn from past experiences.

The concept of housing flexibility is divided into pre-occupancy flexibility and post-occupancy flexibility. Pre-occupancy flexibility refers to the freedom to choose among options in order to adjust the dwelling to suit individual needs prior to moving in. Post-occupancy flexibility refers to the ability to adapt a building to changing needs after the dwelling is occupied. Flexibility can be measured by the capacity for buildings, building programs, or building technology to respond to subsequent change.

2.1.1 HISTORICAL BACKGROUND FROM 1900 TO 1970

Housing flexibility is not new; it can be traced back to 1927. Innovations such as Jean Prouve's houses in 1938 at Meudon, France were designed on 1m detachable modular panels to offer the tenant more choices of interior layout (Rabeneck 1973) (Figure 2.1). Mies Van der Rohe developed his steel-framed apartment house for the Weissenhofsiedlung exhibition at Stuttgart, Germany. The interior partitions were plywood panels that could be installed wherever the tenant chose, giving the tenant an infinite choice of room layouts within his 70 m^2 of space (Giedion 1959). Another example, Smithsons' Appliance House of 1958, was based on cubicles with connections for food preparation, sanitation, communication, storage, and maintenance appliances (Figure 2.2).

When integrated building systems were separated into distinct components, more choices were created and, installations or modifications were made easier. Around 1970, Spender and Rogers produced flexible partitions such as zip-up enclosures: the unobstructed floor plan allows alteration of the plan in a day (Figure 2.3). However, trouble began when these innovations became perceived as solutions to problems in housing and production. Designers were so obsessed with Gropius's idea of factory-made houses, they neglected the true housing needs at the time. These innovations became no more than mechanical toys inspired by technology (Rabeneck 1973).

Since 1960, flexibility researchers have become more aware of the increasing demand for innovative housing which was caused by rapid changes in the number of families; family size, composition, and structure; and a family's expectations in terms of comfort and efficiency. Getting the right fit for this new generation of family became crucial as the traditional housing solution became obsolete. It is the first time that capacity for change became accepted as a goal of architecture and planning.

It is essential to establish standards in order to maintain the efficiency of production and maintenance, and to reduce costs. Flexibility was not only promoted to reduce costs and to impose standards, but also "to provide a private domain that will fulfill each occupant's expectations" (Rabeneck 1973). Flexible buildings could offer choices to occupants: ...everyone should be able to fit out his house as he wishes, including the right to make mistakes as part of that freedom." (Rabeneck 1973)

2.1.2 THE SAR METHODOLOGY

In the early 1970s, the SAR (Stichting Architecten Research) under the direction of John Habraken, pioneered the development of a new systems concept for housing. The SAR developed architectural design methods for use in housing design. The SAR methodology is a system of dimensional rules for deciding the fit, location, arrangement, and rearrangement of structural elements, party walls, services, windows, and doors, many of which can be arranged and rearranged independently of the shell. It establishes a dimensional framework with which standardization can coexist with variety. These methods were based on a distinction between "Support" and "Infill". For Habraken, flexibility represents the amount of incremental transformation of incremental transformation a physical setting can undergo in order to ensure good fit through time. It is a basis on which to rationalize the production of houses and to reconcile both standardization and variety (Hamdi 1991) (Figure 2.4 & 2.5).

The "Infill" is the part of the building which can be determined for each dwelling. The "Support" is the part of the building which is fixed. The "Infill" can be changed without causing a change in the Support. But if the Support is changed, the Infill must be adjusted. Because a building is clearly divided into distinctive systems, different parties can be in control of Support and Infill during its design and construction, and subsequent modifications can be done without loss of efficiency or coherence (Kendall 1995).

The Support generally includes the load bearing structure, all common circulation spaces, a portion of the mechanical systems, and, sometimes, the building's envelope. The Infill includes the non-load bearing interior walls, and building systems on the distribution level such as fixtures, equipment, and all plumbing, wiring and duct work. The distribution of technical systems between Support and Infill will vary in each project depending on how the maximum efficiency can be achieved (Kendall 1995).

2.1.2.1 USER PARTICIPATION

User participation is an essential tool in redefining the relationship between people and their living environments. Habraken believes that user participation helps the designer to serve the public better. It also makes the design and the production of buildings more efficient and more dynamic, and the architecture more relevant (Hamdi 1991). For Habraken, "a support structure is a construction which allows the provision of dwellings which can be built, altered and taken down independently of the others". Supports are designed to accommodate what will happen inside, therefore, the inside is allowed to grow, to develop, and to change from time to time (Hamdi 1991).

Housing decisions used to be made between public (the government) and private (the community groups) sectors. Habraken was able to introduce individuals (dwellers) as new players in the decision-making by separating Support and Infill. The community ensures that the structure of a building, the Support, conforms to bylaws, building codes, and design guidelines which are established by the government. Individuals are responsible for what is within the Support: the Infill. Nonetheless, Habraken's intention was to exploit the potential of modern, factory-based mass production... (Hamdi 1991).

2.1.2.2 COMMENTS OF THE S.A.R. METHODOLOGY

However, after Habraken's lecture to the Royal Institute of British Architects in April 1972, there was criticism that the SAR methodology and the system of grids and zones would restrict creativity in architecture design. Many were skeptical about his calls for more flexibility, adaptability, and greater user involvement, as well as his assumption that "the more variety housing can assume in the support structure, the better" (Habraken 1982). Habraken argued that his methods would challenge conventional professional roles, as well as methods of finance, building and management, but would never compromise artistic expression in architecture.

As Trenton (1972) describes, there was skepticism about whether Support addressed contemporary concerns: "Families living in mass housing are inherently conservative, neither wishing for the flexibility we believe essential, nor suffering from the problems posed in the book[3]." In addition, he suggests that more problems will arise if individuals are only responsible for internal layout, and not for participating in the design of their communal environment (Trenton 1972).

Habraken tried to improve the efficiency of design, designer and building. User participation to him was essential in achieving efficient and healthy housing. As mentioned in the Housing Without Houses (Hamdi 1991), "Habraken was describing an architecture of the everyday environment that was responsive to change, dynamic, easily readable, additive, resilient, and reliable."

How much flexibility is appropriate, and is it more expensive to make buildings flexible? As buildings have become more and more complicated, it seems that flexibility is essential in the planning. Modern technical ingenuity also allows buildings to be made more flexible without becoming too expensive. However, a limit on the degree of flexibility in every project is imposed by user's needs and budget. It may be less economical to build with maximum flexibility because support has to anticipate any possible changes in the future (e.g. a special structure is needed to accommodate building services and variations in the internal layout; structure has to be stiffer to take unanticipated load; special connections are required to hook up existing building services and other components).

Finally, flexibility is used as a design strategy to create an infinite number of choices. It is a concept aimed at providing a better fit among people, location, finishes, and costs. However, these endless possibilities would only be rational when they are within the constraints of materials and systems, as well as legal and regulatory structures. What should then be ideal flexibility? Heath (1984) addresses this question as follows:

[3] "Supports: An Alternative to Mass Housing", Architectural Press, London (1972).

> Flexibility then is easy to provide where the quality of the environment required is not too rigorously specified, where the level of servicing is low, where, it follows from this, changes in the nature of the use of space are not very great. If these conditions are met, and frequent changes are expected, flexibility is the obvious design approach. As we move away from these conditions, the premium paid for flexibility increases; and if we find that we are in fact building an additional floor of the building for each floor of usable space provided, as in the "interstitial floor" concept then it may be more rational to look at other solutions."

Although the intention of user participation is flexibility, it should not be restricted to arranging materials within a given space envelope, much as one does when arranging furniture or decorating. This kind of participation has little to do with shifting patterns of control and responsibility and even less to do with user satisfaction. Flexibility should not be used as tool for enabling good and economical management by public authorities, builders, and manufacturers; the social and political impact should never be neglected, because users are the constituents of housing and the true beneficiaries of the housing revolution.

The variety in dimensions, in design, in additional materials or components, and in technology should be carefully analyzed. It is the differences between people that promote flexibility. Nevertheless, the question remains: how much flexibility should one be provided with to design, construct and modify physical buildings.

2.2 ASPECTS OF FLEXIBILITY AND FACTORS CONTROLLING FLEXIBILITY

Although flexibility may increase the planner's and user's control over layout, and in providing countermeasures to numerous obstacles, it can be by people who have decisive power. No matter who or what imposes limitations, we should first examine what can be flexible and what can cause restriction to flexibility.

Physically, the overall building flexibility is created by the flexibility of its systems and components. Because these elements are interrelated in a certain order, the overall flexibility must be looked at from a broader perspective. A building is constructed from the outside to the inside, and from the basic to the specific. This sequential process suggests that flexibility is controlled by elements from structural level to the Infill level.

Flexibility may also exist in the home delivery process. It includes planning and designing a flexible home from installation to occupation. Therefore, operationally (i.e. the procedures for making flexibility possible), flexibility is controlled by a decision-maker who determines the feasibility of a design under specific conditions.

2.2.1 TYPES OF PHYSICAL FLEXIBILITY AND DEFINITIONS

There are six types of physical flexibility as outlined by Eric Dluhosch in Flexibility/Variability and Programming (1974). Within each, there can be different degrees of manipulation depending on the size and type of an object. Therefore, the level of flexibility depends on the degree of control people have over these factors.

1. THE MATERIAL FLEXIBILITY:

The material flexibility refers to the inherent ability of a material or substance to yield, deform, be molded, bent, compressed, extended, twisted, or altered as a result of the direct application of exterior forces, without causing the loss of the basic integrity of the entity affected. Apart from these physical properties, the degree of manipulation is proportional to the size, weight, and other quantifiable qualities of the products being fabricated.

Example: flexible hose connections in place of rigid pipes.

2. MECHANIZED FLEXIBILITY, OR FLEXIBILITY OF JOINTS AND CONNECTIONS

This generally refers to components or sub-assemblies joined by means of hinges, loops or slides. This type of flexibility is restricted to the designed displacement limits, and the control of joint and connection tolerances. In terms of use, the designer/user is responsible both for ease of manipulation and the degree of maintenance.

Example: drop-leaf table, doors or windows.

3. FLEXIBILITY BY ADDITION AND/OR SUBTRACTION

Similar to the above, except that objects and assemblies may be combined with others in a pre-designed way, for example, a kit-of-parts. This type of flexibility is predetermined due to overall dimensional fit and tolerance coordination.

Example: book shelf kits, modular furniture.

4. LOCATIONAL AND/OR POSITIONAL FLEXIBILITY

Space and dimension determine this level of flexibility. The use of any space or objects need not necessarily fit in a predetermined way, but must be capable of being accommodated in various spatial situations and/or positions. This may constrain choice, or allow for a given range of choices. This type of flexibility requires study of possible alternatives, which must be anticipated by the designer without constraining the user. It also requires a careful study of alternative settings with respect to changing content.

Example: dining room transformed to study or bedroom, etc.

5. DIMENSIONAL AND/OR MODULAR FLEXIBILITY

This may be either imposed or designed. If imposed from outside toward inside of a building, the other types of flexibility have to be adjusted in order to accommodate the dimensional and/or modular system. In the reverse order, an optimal dimensional and/or modular system must be selected by the designer to accommodate all types of flexibility, and to provide a medium for manufacturing and assembly compatibility and/or coordination. To gain control over this type of flexibility, it requires designer's extensive knowledge of measurement systems, modular control, and prevalent practices in the industry in terms of compatibility and adaptability of various components and assemblies. For increased user control, the modular system should be designed unobtrusively, and the matching and/or fitting of items should be comprehensive and easy to achieve.

6. INFRASTRUCTURE FLEXIBILITY

For human comfort and energy saving, it is necessary to plan and program for flexibility in terms of all the mechanical, electrical, HVAC and plumbing infrastructure elements of housing. This concerns not only design improvement and maintenance factors, but also opens up the whole problem of conversion and/or modification of all or some of the existing service infrastructure systems in a building. This type of flexibility is influenced by a material's properties, the degree of installation work as well as performance ratings.

Depending on strategies and/or other limiting conditions, the above types of flexibility can be selectively incorporated into a project to meet the decision-makers' demands for overall flexibility. Heaf (1976) summarized three basic building design strategies to control overall flexibility:

I. Plan for periodic replacements of building components to meet new requirements.

II. "Built-in flexibility for change in the arrangement, equipping and servicing of space - including the possibility of expansion."

III. "Generalized structures are designed to accommodate diversity of use and frequent change through the exercise of the hierarchical separation" (Heaf 1984).

2.2.2 PROCEDURAL FLEXIBILITY

According to Canadian Wood-Frame House Construction (1997) by CMHC, a complete house life cycle can be divided into planning, designing, construction, occupation, renovation, and demolition. There are a series of processes involved in each stage. Within each process, there can be many sets of rules or methods to follow. Procedural flexibility refers to the availability of alternatives to deal with situations during the home delivery process. Whether or not to opt for flexibility is a decision made by governments, financial institutions, builders, designers, and users. However, there are different controlling factors at all stages of a project, and a hierarchy in the decision-making process and among its decision-makers. The presence of physical flexibility will enable the decision-makers to choose whether to use a flexible home design or not. The following section will examine the factors which influence this decision-making process.

2.2.2.1 THE PARTICIPANTS

The present home delivery process involves parties such as the builder/developer, government, supplier, manufacturer, sub-contractor, client, and financial organization (Charney 1971) (Figure 2.6). Decision-making among these people is a looped process, or a "Closed System", according to Roberts (1970) (Figure 2.7). This means that any participant may influence the construction of a home. Furthermore, any change one participant introduces will bring about changes in the whole process. As Friedman (1988) points out, "Innovation and change of the above process are difficult since they tend to break down a traditional routine process in which each party is familiar with the tasks he has to perform. The introduction of flexibility in a manner which will confront the mainstream will not be welcome and will most probably fail." He recommends that: "flexibility must be compatible with existing industry customs rather than confront them. And it should make use of existing routines rather than suggest new ones." In other words, flexibility may be accepted when used as an alternative or modification to the existing home building practice. The implementation of flexibility in housing construction should meet the traditional home-building industry's standards, while, at the same time, help participants to attain their goals (Friedman 1988).

Decision-makers are classified into 3 categories (Charney 1971, Kaynak 1981, Friedman 1988). It is necessary to examine their roles in order to study the decision for flexibility and the implications when flexibility is introduced:

1. CONTROLLING AGENCIES

Government (federal, provincial, and municipal) agencies regulate housing policies through financial means, codes, standards, by-laws, and master plans. Local, provincial, national and global economies are the government's biggest concerns. In fact, the Canadian government's intervention in the housing market has traditionally been motivated by the need to stimulate economic activities through the construction of homes (Rose 1980). Because the construction industry employs over 10% of the total labour force (Kavanagh 1978), the government's decisions and policies concerning housing have had a great influence on the country's economy, as well as on its health and safety (Friedman 1988). It has been suggested that, due to bureaucracy (Rose 1980, Charney 1971), the government tends to favor traditional practices and organizations in the industry, and to provide standards that are based on the minimum needs of the user. In fact, Donald I. Hovde (undersecretary of U.S. Department of Housing and Urban Development) believes that the maze of zoning and building regulations have prohibited some of the best innovations from getting a fair trial (National Institute of Building Sciences 1984). Unless there appears to be a political advantage or the pressure for action on the government in power is very strong, it is unlikely for a government to support any social intervention such as introducing flexibility in home construction (Rose 1980). In this regard, housing flexibility is viewed as an option. Until it is seen as a solution to housing problems, and until all participants collaborate, it will have little or no influence on governmental decision-making.

2. FINANCIAL INSTITUTIONS

Financial institutions lend money to builder/developers for the execution of a project, or to users for the purchase of a unit. They control builder/developers and users through financial means, while the government and market responses control them. Their objectives are to ensure the maximum return on their investments. According to Friedman (1988), adopting flexibility systems may help financial institutions increase their returns. By lowering the cost of units, decreasing the rates of mobility, and providing loans for flexibility components (as suggested by Warshaw (1974)), they can attract more first-time homebuyers, while increasing the value of property (which is designed to be adaptable), and offering additional financial services. However, since flexibility in housing is still not popular in North America, financial institutions are hesitant to support it. This is because they fear that it will reduce other financial opportunities by, for example, decreasing the number of mortgages due to a lower mobility rate and an increase in do-it-yourself activities (Friedman 1988).

3. PARTICIPANTS IN THE SUPPLY PROCESS:

- **The Builder/developer** conceives and carries out a project. During the production phase of a project, they generally make recommendations on building materials and products to keep a project within the estimated construction budget (Yamin 1990). Their objectives are to control costs by keeping overhead to a minimum (Montgomery 1977), to ensure quality standards are met, and to ensure that the project be delivered on time (Gould 1997). Gould (1997) writes:

> "As changes occur due to changes in scope or unexpected events, the need for tight control of cost and schedule becomes increasingly important. Keeping the cost within acceptable budget constraints and maintaining control over key milestone completion dates for coordination with outside parties is critical to the owner."

Implementing flexibility can help to achieve these goals by: 1) outfitting a house to suit a customer's needs without extra costs in labour, time and material; 2) offering easy adjustments or replacements during the guarantee period; 3) speeding up the sale of units before/after construction thanks to adaptable interior layout; 4) staying competitive with market demands and competitors; 5) saving time by using pre-fabricated components; and 6) establishing the image of being "innovative" which may promote sales (Friedman 1988). Despite the above advantages, builder/developers are concerned that flexibility will cost them more. The potential draw backs are: 1) increased housing prices and construction time; 2) losing potential customers (since not all people accept the idea of flexibility); 3) additional investment requirements to comply with local codes and practices; 4) difficulty in funding; 5) difficulty in adapting flexibility system in terms of operation (Friedman 1988). Complex management demands may also make them unwilling to implement building flexibility. Since builder/developers are responsible for arranging financing, advertisements, project management, office management, and numerous other tasks, the stress of switching from their existing practices to another should be taken into consideration as a factor influencing the adoption or rejection of innovative products (Sternthal 1994) (Figure 2.8).

- **The Project designer** plans and designs the physical layout, and usually specifies the building materials and products for a project. The objective of a designer is to take a proposal from a builder/developer and prepare a series of plans (complete and technically accurate design) for action. Because they have to work under financial and time pressures, many traditional housing designers often repeat the same styles without responding to true user needs (Montgomery 1977). This lack of communication between designer and user is the result of the builder/developer's strategy for saving users' money (Zeisel 1974). The use of a flexibility system may provide a designer alternative ways of cutting costs without scarifying variety. In addition, they can expand their knowledge by becoming an advisor for a household in the planning of interior layouts, or by becoming a researcher for developing new interior arrangements and construction techniques. However, role switching requires that a designer familiarize himself with a user's economic status in order to select flexible-housing alternatives, and with technical systems that allow flexibility (Friedman 1988).

- **The Project executor** builds a project according to a design. This includes the general contractor and subcontractor. Their practices have become highly specialized due to competition within the building process (Charney 1971). Because these firms or companies are usually small (i.e. number of workers that can be kept working continuously) and financially limited, specialty contractors are vulnerable to the decisions of builder/developers (Friedman 1988). In the case of a fixed price contract, the contractor must maintain tight control over the budget and schedule the work in order to guarantee a profit on the project (Gould 1997). Although they do not make the decision for flexibility, they install it: there are contractors who work specifically on flexibility systems. Implementing flexibility suggest that construction work may become even more specialized and diversified. Contractor companies may become smaller in size and weaker financially. Also, they may have to adopt new methods in order to stay competitive. The possible advantage is that they can be more independent in their work (Kendall 1993). For firms that are based on traditional methods, they need to modify their existing work habits in order to adopt flexibility construction (e.g. contractors that are presently involved in the installation of dry walls may specialize in the installation of flexible partitions) (Friedman 1988).

- **Manufacturers/suppliers** who produce or supply goods for construction in the home building industry, are usually the ones who have introduced and promoted new materials and systems (Charney 1971). If new products are accepted by the public, then it opens the market up not only for new construction, but for renovations and upgrades (Friedman 1988). However, the creation and promotion of innovation involves substantial risks. Establishing standards within the industry requires additional investment in marketing. Promising products and systems may be rejected if they call for major alterations in the construction methods and techniques. Manufacturers should carefully select the appropriate degree of improvement, keeping in mind market trends, and the limits of the existing industry's practice.

4. USER IN THE DEMAND PROCESS:

The occupant of a dwelling is the user in the demand process. Before housing flexibility is introduced, the decision for home occupation is made based on the user's needs. According to Bennett (1979), the user's needs can be classified into three categories: The Social Needs[4], The Physiological Needs[5] and The Psychological Needs[6] (Rosen et al, 1979; Blachère, 1970; Parson, 1972). Kaynak (1981) summarizes factors from these three categories which influence the decision to buy a home as in Table 1:

In most cases, the user has to adapt to a new environment when moving from one place to another. Certain factors from those listed above may be compromised in order to fulfill others. Implementing housing flexibility will increase the number of needs that can be met. This is because the dwelling unit can be outfitted according to the user's specifications before and after construction. However, many people shy away from the flexible home because they do not anticipate that they will stay in one place for very long. In addition, they are unwilling to plan their own layout either because they do not have the

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[4] **Bennett (1979) defines The Social Needs as "the basic human requirements that are produced by political, economical and cultural standards of society".**

[5] **Bennett (Ibid.) defines The Physiological Needs as "the basic physical requirements that are generated by survival and daily living".**

[6] **Bennett (Ibid.) defines The Psychological Needs as "the perceived human requirements generated by social pressures, reactions to the environment, and mental attitudes and states of mind".**

skill, or because they do not believe that flexibility offers any special advantages or savings (Friedman 1988).

In conclusion, the degree of housing flexibility is controlled by the physical property of the materials, and the decision-makers in the home delivery process. Home building environments and technologies in different countries reveal different approaches to designing flexibility. In the next chapter, the international experiences in the application of flexibility in contemporary housing design will be discussed.

The Social Needs Individual or Household Characteristics (Socio-Economic Features)	**The Physiological Needs** Housing Unit Characteristics (Physical Features)
Education Ethnicity Income Household size Profession Age of family head	Number of rooms Age of house Size of living space Price Modernity Integral Garage Air Conditioning Spaciousness Durability of construction Oil Heating Layout
The Psychological Needs	
Neighbourhood Related Characteristics	Social Bonds
Distance from work Distance from school Accessibility Distance from shopping Quality of public services Near by parks and open spaces Bus Service Level of traffic noise Safety of the area Property Tax Location	Planned duration of residence School aged children Social composition of the area Presence of friends and relatives

Table 1: Major factors involved in home-buying decisions (After Friedman 1988)

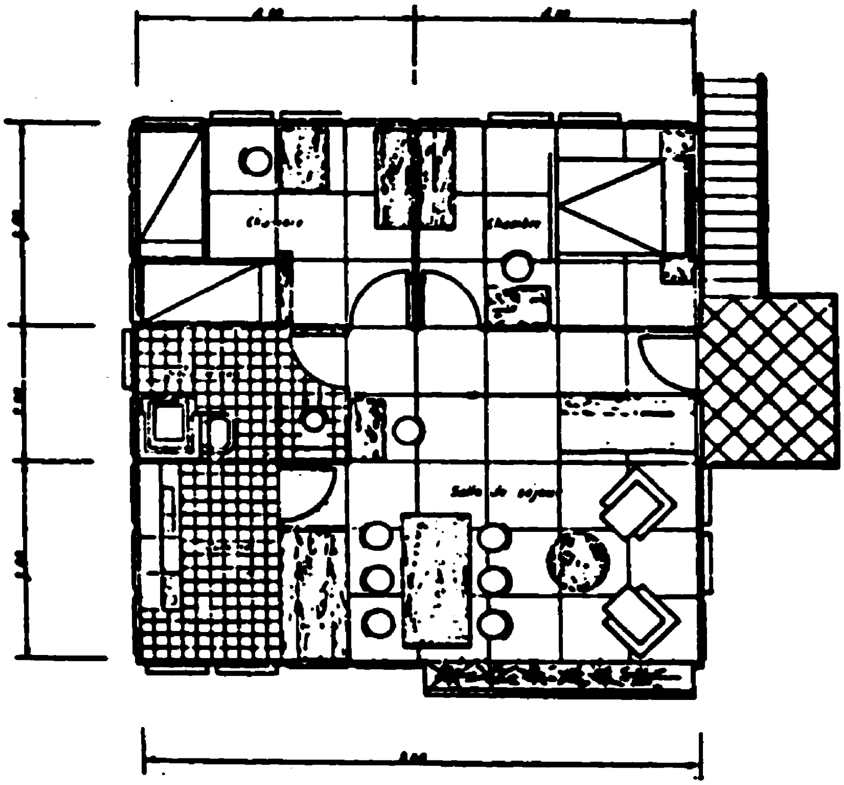


Figure 2.1: Prouvé's Meudon houses are planned on 1m module with all panels interchangeable (Source: after Rabeneck, et al. 1973)

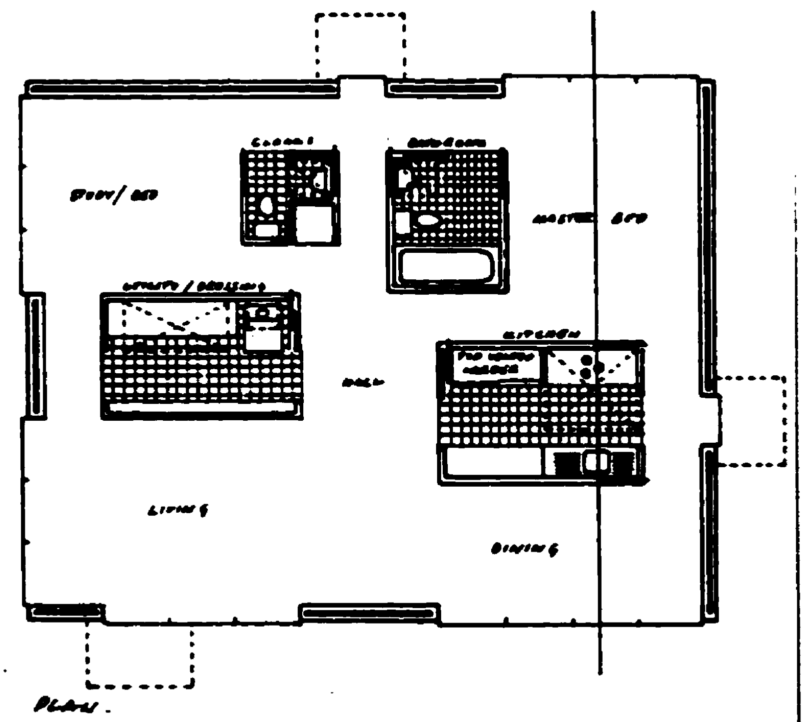
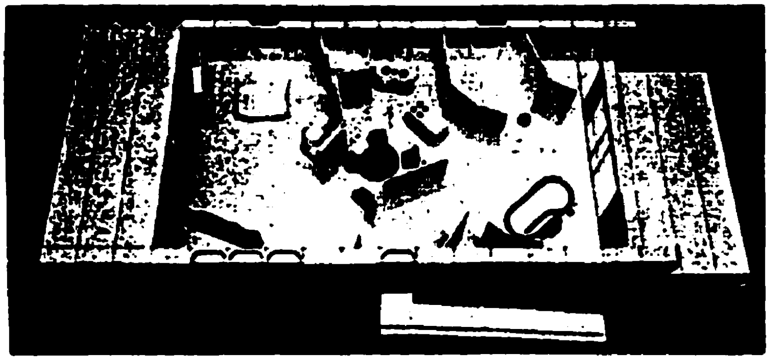
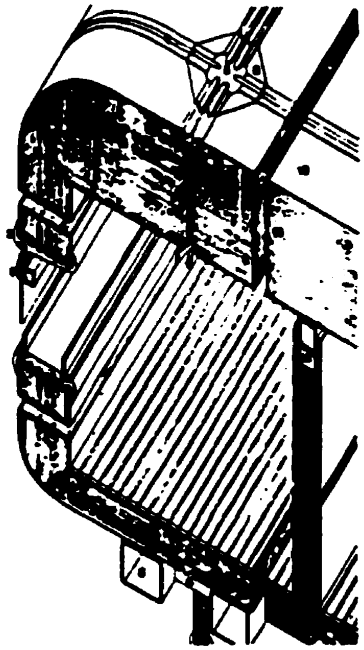
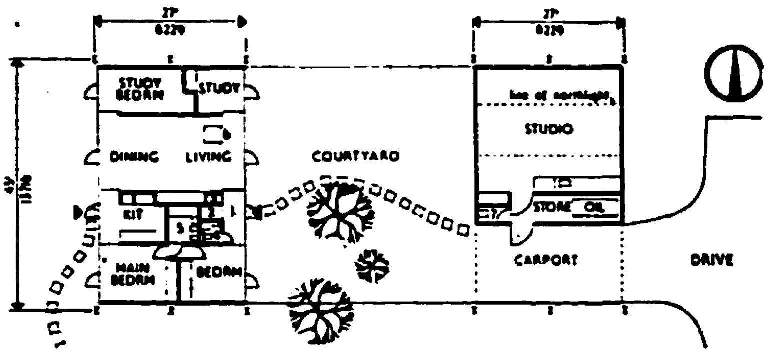


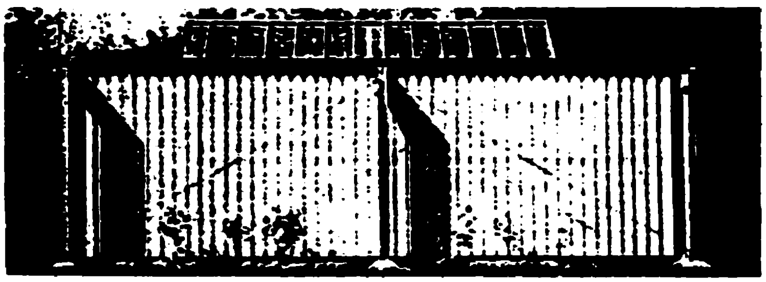
Figure 2.2: Smithson's Appliance House of 1958 was based on cubicles with connections for food preparation, sanitation, communication, storage, and maintenance appliances (Source: after Rabeneck, et al. 1973)





Rogers zip-up house. (AD 3/70)





Spender House. (AJ 6/10/71)

Figure 2.3: The Rogers and Spender houses are made up of 45 ft clear span steel portal frames, to provide unobstructed space. This design allows alteration of the plan in a day. (Source: after Rabeneck, et al. 1973)

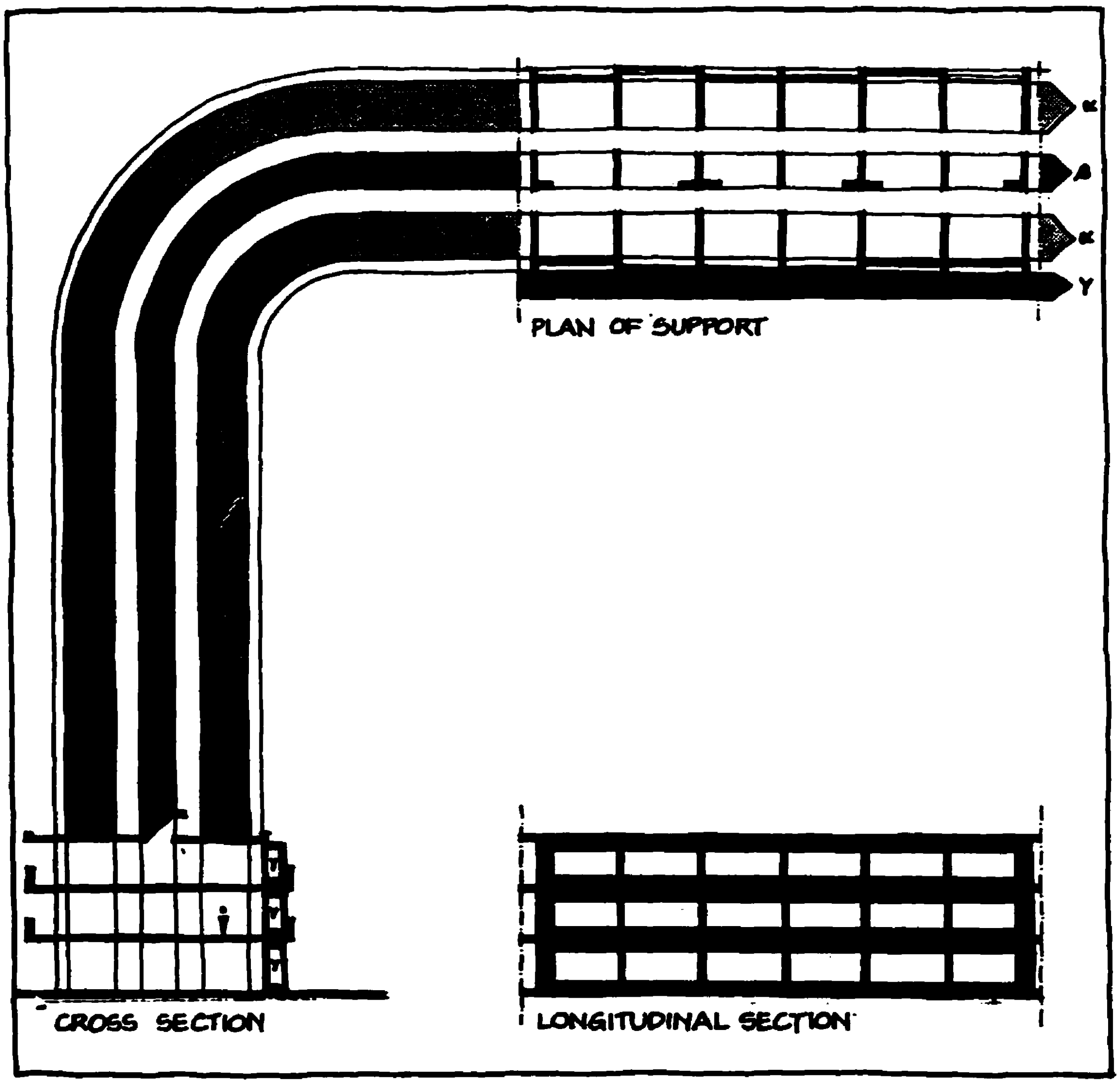


Figure 2.4: The Support. A Support is that part of a habitable structure which the resident has no control. The Support generally includes the load bearing structure, all common circulation spaces, a portion of the mechanical systems, and, sometimes, the building's envelope. (Source: Habraken, et al. 1976)

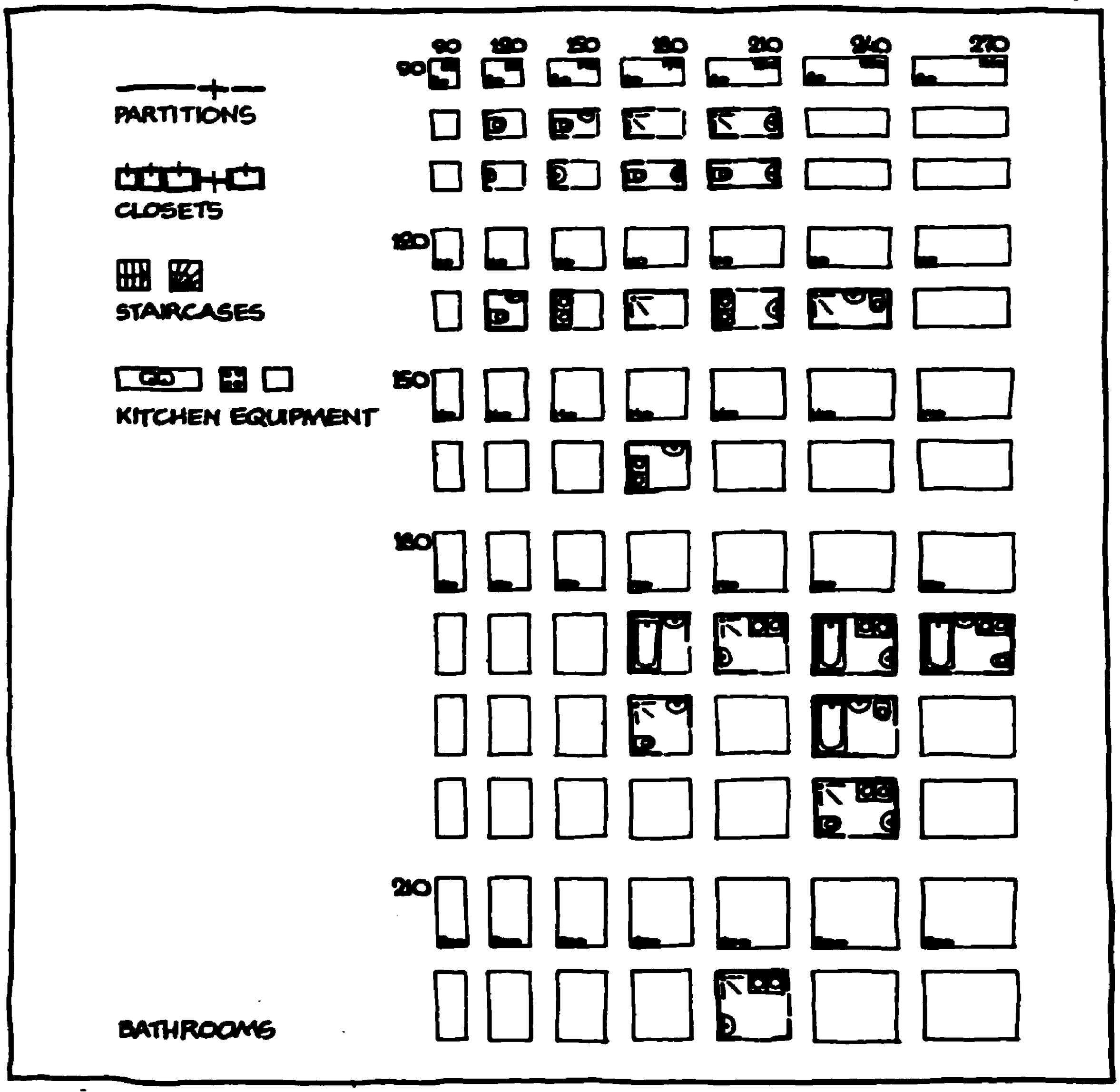


Figure 2.5: The Infill (or Detachable Units). Detachable units are movable components over which the resident has individual control. The Infill includes the non-load bearing interior walls, and building systems on the distribution level such as fixtures, equipment, and all piping wiring and duct work. (Source: Habraken, et al. 1976)

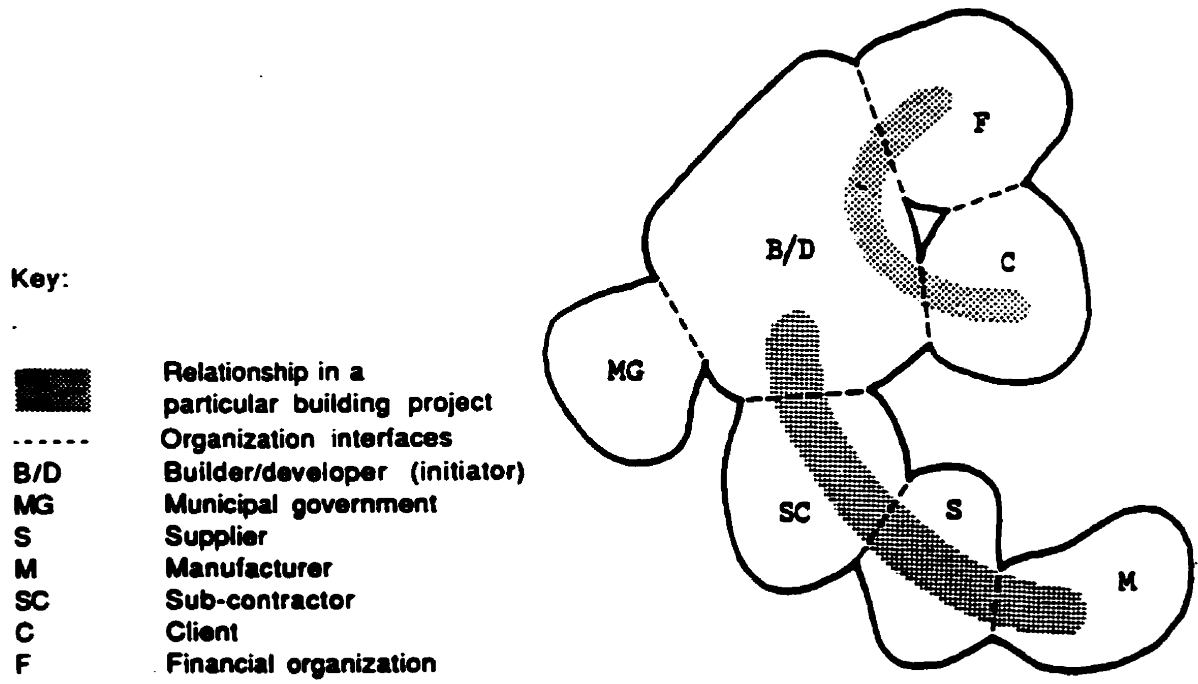


Figure 2.6: Organizational and project interface in speculative home-building (Source: Charney 1971)

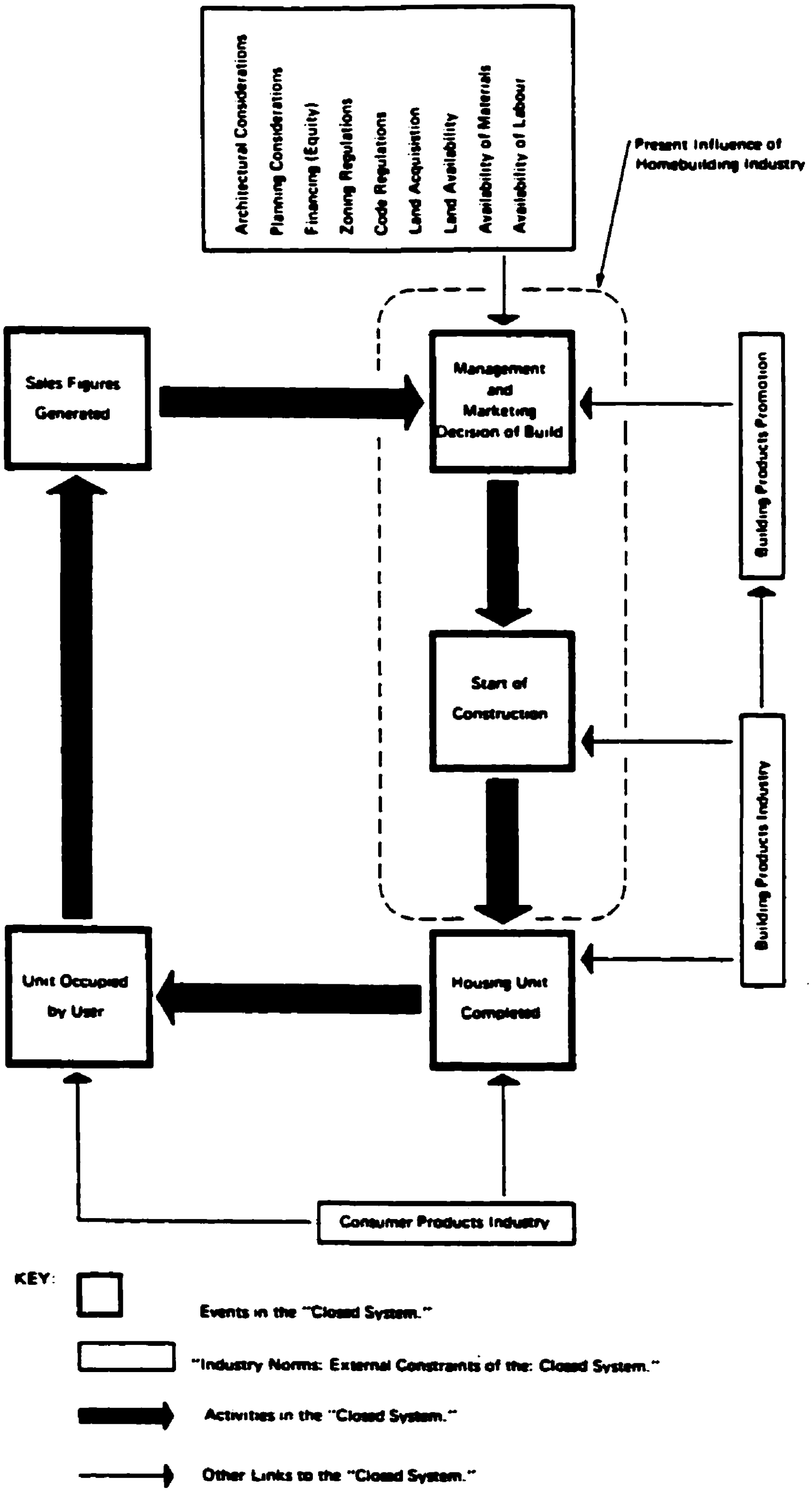


Figure 2.7: The "Closed System" of decision making events occurring in the homebuilding industry (Source: Roberts 1970)

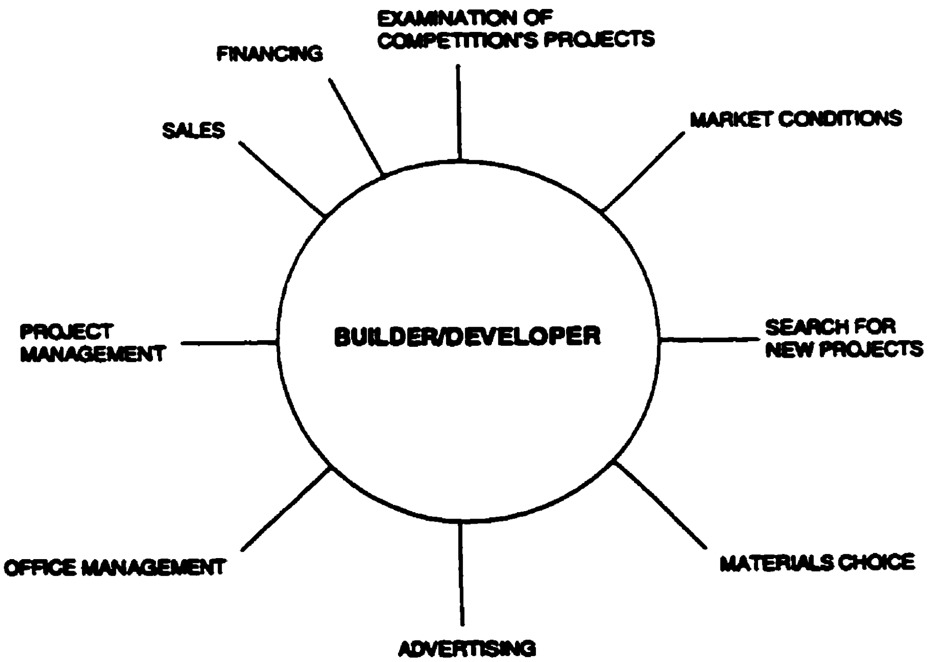


Figure 2.8: Builder's/Developer's administrative duties (Source: Sternthal 1994)

CHAPTER THREE

APPLICATION OF FLEXIBILITY IN CONTEMPORARY HOUSING DESIGN: THE INTERNATIONAL EXPERIENCES SINCE 1980

Lessons in flexible homes prior to 1980 helped to develop new solutions for the 80's and 90's. The modular systems were costly and technically complicated for the ordinary user. In addition, a majority of users did not stay long enough in their units to benefit from their custom layout or from its flexibility. Recent technological innovations tackle these problems by making detachable components more user friendly, and revising numerous construction methods and production processes to make housing more flexible and economical.

3.1 NETHERLANDS

In the Netherlands, a series of housing projects incorporated user participation by using the concept of Infill and Support. The Matura Infill System is an economical prefabricated package for building fit-out. It is a commercially based system modified to disentangle and to regulate building services for residential-use. The Matura Infill System utilizes sub-systems and parts that are available on the market. All sub-systems are integrated into two elements: the "Matrix Tile", and the "Baseboard Profile." These provide flexibility in design, fast installation on site, and changeability in the future for concrete building. The Matrix Tile is laid on top of the floor slab. It is basically a modular floor panel that has grooves in it, to provide room for the distribution of primary building services such as sewage, water, heating, electricity, and all kinds of piping and wiring. The Baseboard Profile is the secondary distribution system running wires for appliances. The Matura Infill System is more economical, and its advantages include quick installation, a wider choice of floor plans, and the ability to separate the Infill works into teams (Figure 3.1). It is unlikely that the Matrix Tile can be used in North American low-rise wood frame buildings because of the limited floor to ceiling clearance (Kendall 1996).

3.2 SWEDEN

Customized kits of manufactured building parts are largely used in Sweden. Today, more than 96 percent of all houses in Sweden are built of wood, and 80 percent of these are produced industrially (Arnold in Kendall 1986). Due to limited daylight hours and long winters, it became necessary to speed up the process of housing construction. In addition, efficient labor methods and the elimination of nonproductive time are required due to high wage rates, a high living standard, and delays caused by weather and construction management (Figure 3.2).

Since World War II, the Scandinavians have developed a procedural system for the design of manufactured housing that equally accommodates all the parties involved in the building process: architects, researchers, manufacturers, building contractors, financiers, government and consumers. This joint participation has made new house ownership easy and attractive for the consumer. Initial unit costs have been lowered and made more predictable by reducing the amount of labor and cutting construction time. In fact, manufactured houses in Sweden cost 25 to 40 percent less to build than those built on site. Houses can be built in less than one month, and still exceed the quality of site-built houses. The manufactured Swedish houses come with complete packages of components: exterior and interior finishes, equipment, fixtures, appliances, and built-in furnishings. The manufactured house accommodates design flexibility to satisfy the requirements of each customer (Figure 3.3). The house is also flexible enough to meet municipal regulations and site-specific restrictions. The customers actively participate in the design of their own houses. They may choose to purchase a house that is not completely finished, then finish the interior on their own at a later stage. In fact, approximately 90 percent of manufactured housing is customized to suit a particular household's needs. Computer programs have been developed by manufacturers to facilitate customers' selection of their ideal home. A wide range of choices is available on computer for the various finishes, fixtures, colors, and other components. After the selection of building type and components, the computer will generate drawings and schedules that are customized to suit the client's needs (Arnold in Kendall 1986).

There are three basic types of housing prefabrication systems that are used extensively in Scandinavian countries. The modular volume system consists of volumes that provide rooms. This type of system is most suitable on remote sites or in areas where skilled construction is not readily available. The drawbacks are the dimensional restrictions for transportation, and the need for a high-capacity crane to hoist them into place (Figure 3.4).

The large panel system is the most popular system in Scandinavia. It consists of large-size prefabricated panels such as walls, floors and roofs. Construction of the panels is very similar to standard wood stud construction. The advantages of the large panel system include the high tolerances and precise fittings of all system components. The drawback is the need for a long-reach, fine-control crane. Houses built with this type of system can be erected in as little as 11 days. (Figure 3.5)

The small panel system consists of modular panels that are approximately four feet by eight feet in size, and usually of wood stud construction. These panels can be erected more easily and require less skilled personnel. It takes as little as 11 days to build a house using the small panel system. This type of system requires more on-site labor, but it permits a greater degree of flexibility during construction. (Figure 3.6)

3.3 JAPAN

In Japan, recent developments in Support and Infill focus on the quality and performance of building components. These include improvements to the mechanical system's performance, and provisions for a wide range of high quality products for use in dwelling interiors, such as partition, floor and ceiling systems; unit baths, fixtures and kitchens; and quick connect cabling and piping systems. But there are problems: the entanglement of complex building systems, renders the Infill system uneconomical. The housing industry also aims to develop new components, production methods and supply methods for detached housing. Strong emphasis is placed on recent technical efforts, the objective of which is to make buildings more adaptable to accommodate changing preferences, life styles, and technical standards. Yet another emphasis has been on the development of production methods that are not heavily dependent on skilled labor. A recent national mandate to reduce the cost of housing in Japan has prompted the industry to re-examine a number of interrelated aspects. These include regulations effecting domestic and imported products and services, administrative and approval procedures, labor skills and availability, and the range of choice and quality levels of consumer housing products (Kendall, 1995).

3.4 HOUSING FLEXIBILITY IN NORTH AMERICA

3.4.0 INTRODUCTION

Housing design and construction have constantly evolved to suit people's needs. This evolutionary process took a giant leap after the Great War, because the demand for housing far exceeded the supply. In fact, "the return of ten million American war veterans in 1945, coupled with the stagnant state of construction as a result of the Depression years created a housing crisis…" (Friedman and Niessen 1991). However, the supply shortage continued into the 1950s, because the family structure had changed and homebuyers were more diversified and specialized. In response to this problem, the housing industry looked to technology for the development of new building types and construction materials. The objective was to provide attractive, low cost homes in a rapid, cost effective manner (Friedman and Niessen 1991). Although during the post-war years (1945-1959) homes were built to solve the housing crisis, the goal of housing innovation also changed at this time. In addition to being economical, innovations took into consideration the dweller's individual taste, comfort and convenience (Bloodgood 1984). The demand for low-cost housing during the post-war period, plus the trend toward personalizing individual space, catalyzed the development of affordable, flexible and adaptable houses.

House construction has become more flexible in many respects. Changes in structural details, and the availability of different materials, have allowed a certain degree of flexibility in planning and physical construction. Planning innovations include designs for efficient use of space, plus designs for flexible and adaptable interiors (Friedman and Niessen 1991). New planning proposals often generated innovations in physical construction and vice versa. This can be seen in roof/floor/wall construction, as well as in mechanical/electrical/plumbing systems. In this section, the evolution of housing flexibility innovations in North America will be examined in broad detail. A study of innovative flexibility building components will follow in the subsequent chapter.

3.4.1 PLANNING

3.4.1.1 DESIGN FOR ADAPTABILITY

One driving force behind residential building construction during the post-war period was the escalation in demand for affordable homes. To cope with economic constraints at the time due to high labour and material costs, the industry proposed numerous design strategies to keep housing prices low without compromising livability (Friedman & Niessen 1991). They learned from past experiences that by making the space smaller, simplifying traditional building construction, and reorganizing layout, costs could be reduced. Their approaches included maximizing interior space by minimizing interior construction, using building products that can be mass-produced, centralizing building services, and introducing multipurpose rooms[7] that serve various spatial functions. These

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[7] Eric Dluhosch (1974) referred to this type of physical flexibility to as locational/positional flexibility. The use of space must be capable of being accommodated in various situations and/or positions.

cost reduction strategies generated design flexibility and adaptability in North American wooden light frame housing.

Most of the post-war affordable homes were designed to be simple and small for economic reasons. This is understandable because the housing industry was trying to keep up with demand, especially from many low-budget, first-time homebuyers. However, the need for space became evident as young families grew. Many could not afford the high cost of bigger houses in the suburbs. These people looked towards expanding their homes by converting unfinished space in the attic and/or garage into living space[8]. The Cape Cod Cottage and the Levitt houses were good examples of designing for vertical expansion (Figure 3.7). Others, however, chose external expansion over internal expansion since it interferes less with the structure of a building and with the occupant's daily activities[9] (Friedman and Niessen 1991). The "Expandable House", designed by Robert Elkinton, showed that additions and conversions to an existing building can be done without doing major modifications to the supporting structure (Figure 3.8). In the project, "The Expandable Bungalow", architects Gill and Bianculli pushed the concept further by concentrating building services to facilitate future extension (Figure 3.9).

3.4.1.2 DESIGN FOR FLEXIBILITY

Long term spatial needs were also anticipated by designing for interior flexibility. The principle was to provide an open floor plan to allow occupants to define their spaces according to their particular needs. In contrast to the traditional home building, architects replaced fixed partitions with movable walls, mobile partitions (accordion walls, drapery) or modular closets to create a space of variable functions and requirements. For example,

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[8] Likewise, this is locational/positional flexibility. Designers studied possible settings with respect to changing family context.

[9] This is flexibility by Addition and/or Subtraction. Objects and spaces may be combined with others in a pre-designed way.

Haydn Philips designed a minimum interior fixed wall in his "Flexible Interior for Small House" to maximize open space for indoor flexibility (Figure 3.10). Vincent J. Scully, Jr. demonstrated in the project "One Room House" that centralizing building services (plumbing, HVAC), kitchen and bathroom would help to reduce construction inflexibility due to system entanglement. However, the need for numerous mechanical devices to use the movable partitioning system drove up the price (about 1 time more expensive than the expandable house) (Friedman and Niessen 1991). For that reason, Vincent proposed movable storage units instead of mobile partitions to attain privacy, additional storage space, and better economy (Figure 3.11).

In the following years, much effort was spent to produce designs that would satisfy the home owner's needs in terms of cost, quality and efficiency. Certain mass-produced building products were designed for interior flexibility at a reduced price. The modular or panelized construction of prefabricated houses and mobile homes permitted a systematic method of building expansion . Windows, doors, wall panels and other building parts were standardized so that planning for flexibility was made more predictable and economical. However, some flexibility designs became obsolete when numerous appliances, fixtures and building systems[10] were introduced into homes. Resolving technical difficulties such as systems integration, became the main focus of North American housing and building technology research from the 1960's to the 1980's (Kendall 1994).

Planning for multiple occupancy was another strategy to cut housing costs. Increasing residential density could help communities socially and economically. It would also help to reduce urban/suburban sprawl, preserve resources and save energy (Berkus 1984). The Next Home is the latest example of a flexible/adaptable house that is capable of converting a single family dwelling into a multiple family dwelling. The open floor plan

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[10] Wires, pipes, and ducts servicing appliances, fixtures and building systems are fixed within ceilings/floors and walls. Therefore, flexibility is restricted by the difficulty of relocating these elements.

lets occupants decide their own interior arrangement. A catalogue of prefabricated interior and exterior building components offers flexibility and variety in the selection before and after construction. Future expansions, in terms of both spatial requirements and building services upgrades, are anticipated in the design in order to meet long-term user needs (Friedman 1993).

In recent years, new strategies for residential building flexibility have been developed worldwide. North America responded with the Open Building flexibility concept borrowed from its office and retail sectors. The development, design, construction, and buildings management are separated into three levels: base building, fit-out and FF&E (furnishings, fixtures and equipment). This distinction between building components helps to bring greater efficiency and control to large, complex projects (Dekker and Kendall 1996). In Canada and United States, some pioneering individuals in the housing industry are exploring the benefits of the Open Building concept.

3.4.2 CONSTRUCTION

The level of housing flexibility and adaptability depends on the physical limits of building structures and materials. Setting up an open floor plan, for example, would require alterations in the traditional roof, floor and ceiling construction in order to anticipate additional load due to increased span. Economy is another factor fueling the development of new building designs and materials. It helps to explain the industry's attempt to mass-produce new housing products targeted at a broader public. As a result, house design and construction are becoming more economical and flexible.

3.4.2.1 ROOF

Before prefabricated roof trusses were commonly accepted in residential building construction, homebuilders used joist and rafter systems to support the roof. Traditional roof construction was complicated, labour-intensive and time consuming. Moreover, the structure needed to be supported halfway by load-bearing partitions, which constrained interior flexibility. After the Second World War, the shortage of materials and labour, plus the high demand for housing pushed the development of efficient house construction. The prefabricated roof trusses were created to take greater load and stretch longer (spans the entire width of house), use half the amount of wood, and reduce costs by eliminating extra framing for the interior load-bearing wall. Over the years, roof trusses were improved to be stronger and cheaper. They are even sometimes designed to give usable space in the attic (CMHC F 1989).

3.4.2.2 FLOOR/CEILING

In contrast to conventional solid wood structural members, composite wood/steel beams and joists help to increase floor and ceiling spans. They were created and evolved in response to the need for longer spans. One type of long span joist is with wood flanges and sheet metal truss webs (Figure 3.12). Others are made of engineered wood in the forms of a conventional joist, I-beam or truss. The open web design allows services (plumbing/ ventilation/electrical) to pass through, which increases flexibility for fixtures placement, as well as system addition and upgrade (Jones 1984).

Increased span means increased open space, which means increased flexibility. However, laying board sub-floor (originally used to transfer load from one floor joist to another) was considered cumbersome and inefficient. So it was replaced by plywood to improve installation and savings. Plywood panels are manufactured in standard sizes and various grades. Because of its modular dimensions, it helps to organize floor, wall and roof construction in terms of joists, studs and trusses spacing. Therefore, floor area, size and ceiling height can be predetermined and costs can be controlled (Jones 1984). Furthermore, the general application of plywood for house construction (whether structural, decorative or both) made installation work much more efficient and flexible.

3.4.2.3 WALL

Traditional wall plastering was replaced by gypsum wallboard. Panelization has progressed from small modular panels, through panels that are room size, and finally up to whole walls. The prefabricated wall panels have framing and sheathing incorporated, interior and exterior finishes, insulation and openings, plus services are fitted out as options. In the 1940s, a new type of pre-finished plastic coated plywood was created for interior finishes (Friedman and Niessen 1991) (Figure 3.13). Recent movable partitions are pre-finished and may have mechanical devices attached to permit connection to walls, floor and ceiling. Some are equipped with service ducts for wiring, which allows for future system additions or upgrades without having to remove the gypsum panel.

3.4.2.4 MECHANICAL/ELECTRICAL/PLUMBING SYSTEMS

The demand for comfort and sanitation has prompted the development of mechanical, electrical and plumbing systems. These systems control lighting, water supply and waste disposal, temperature and air quality, as well as appliances and electronics that are needed to support human life, work and entertainment. Since traditional systems were too stiff to make connections, changes were made to ameliorate installations during house construction and renovation. These improvements included the use of plenum duct systems, the nearly universal use of circuit breakers, and the shift from metal to plastic supply and waste piping (Jones 1984).

3.4.3 SUMMARY AND CONCLUSION

In summary, housing flexibility is generally used as a strategy to cut home building costs in North America. Because all building systems are interrelated, designing flexibility in one area normally requires design flexibility in another (e.g. variable interior space needs movable partitions, which need an open floor plan, which needs flexible building services, which need truss beam/joists, and so forth). It seems like North American housing flexibility innovations are following this hierarchical model for a complete building upgrade. When the most basic building components are updated with flexibility design, this hierarchical renewal process can be reversed to achieve a higher degree of overall housing flexibility. In order to determine the next highest level of flexibility, we must examine the basic building components and check whether their innovative flexibility designs coexist or contradict each other.

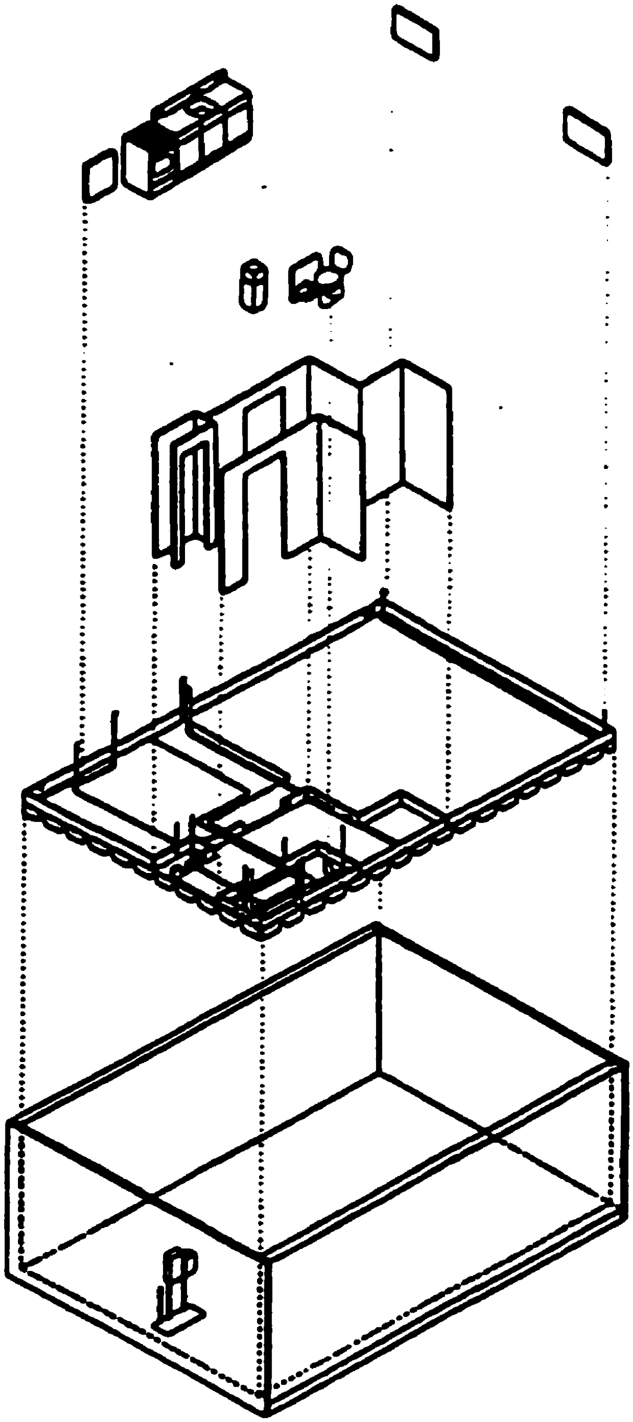


Figure 3.1: Conceptual drawing of "Matura Infill System" and space to be fitted out. Lower system is comprised of "Matrix Tile," piping, "Baseboard Profile" and cabling. Upper system elements include partitions, equipment, cabinets and finishes. Pipes, cables and upper system elements are off-the-shelf building products. (Source: Kendall 1996)

Figure 3.2: A Swedish manufactured home. Panels, complete with interior and exterior finishes, can be prefabricated for virtually any style of house. When construction is complete, there is no visible difference between panelized and conventionally constructed houses. Shown is a demonstration model. (Source: Kendall 1986)

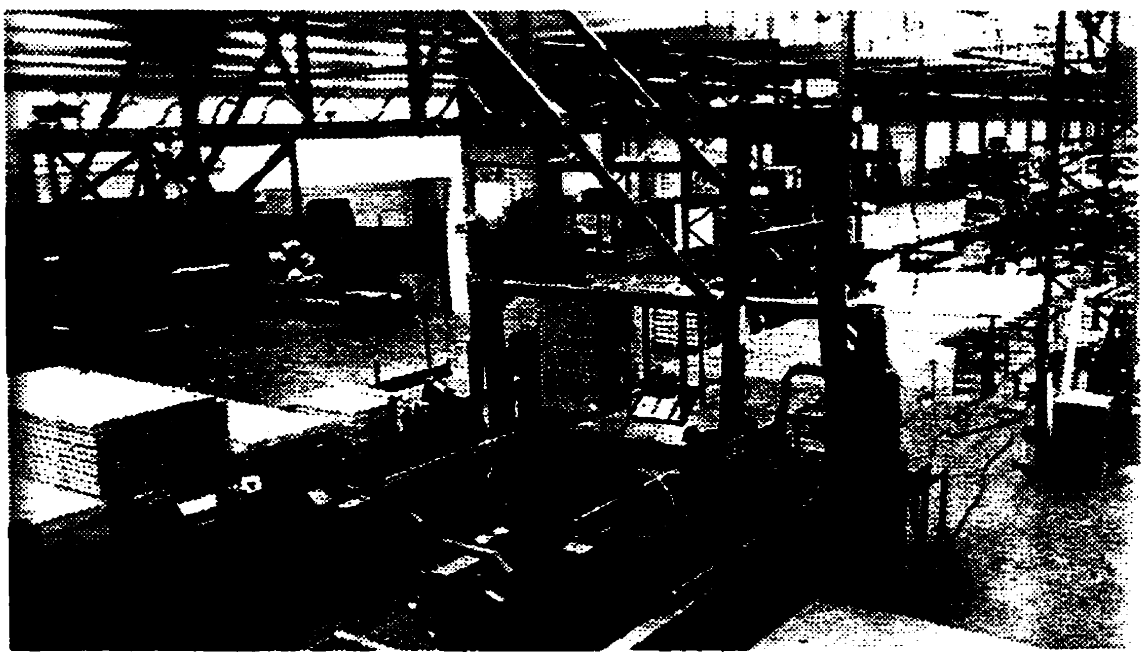


Figure 3.3: A manufactured-house factory in Scandinavia. Manufacturers say they are capable of precise methods of joinery and fabrication not attainable in the field and claim to waste less than four-tenths of 1 percent of raw material. (Source: Kendall 1986)

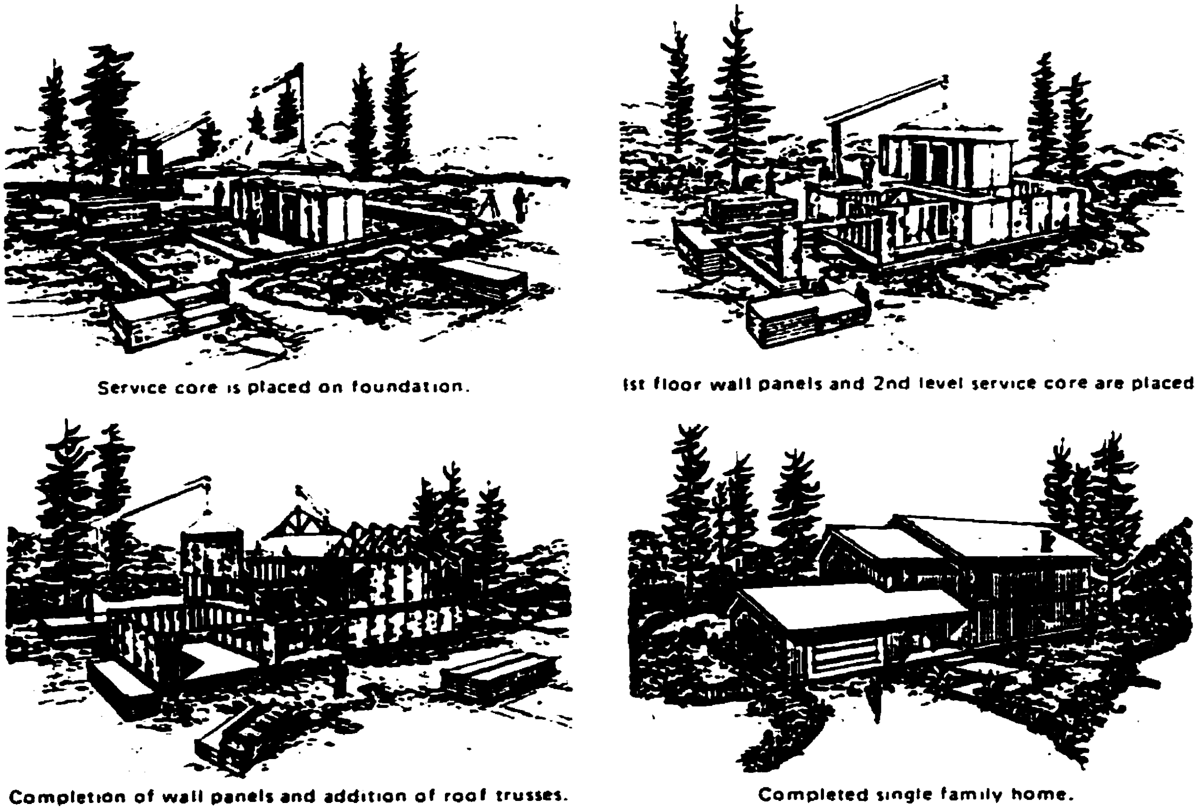


Figure 3.4: Site construction sequence of a modular volume system. (Source: U.S. Department of Housing and Urban Development 1973)

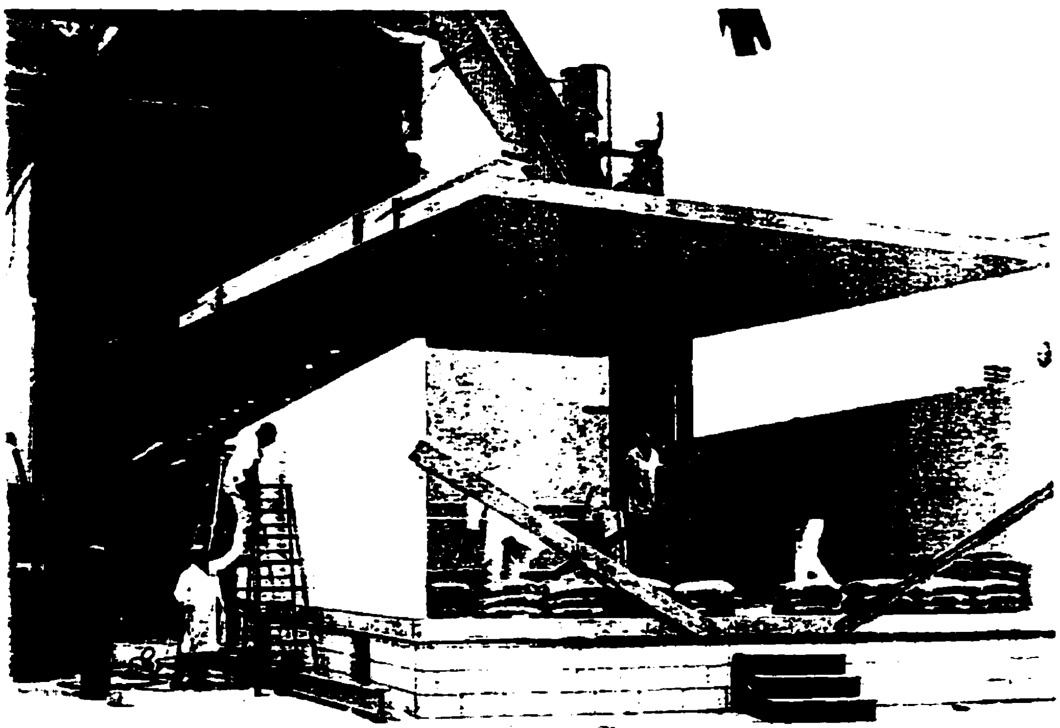


Figure 3.5: Full size shell assembled from flat panels. (Source: U.S. Department of Housing and Urban Development 1973)

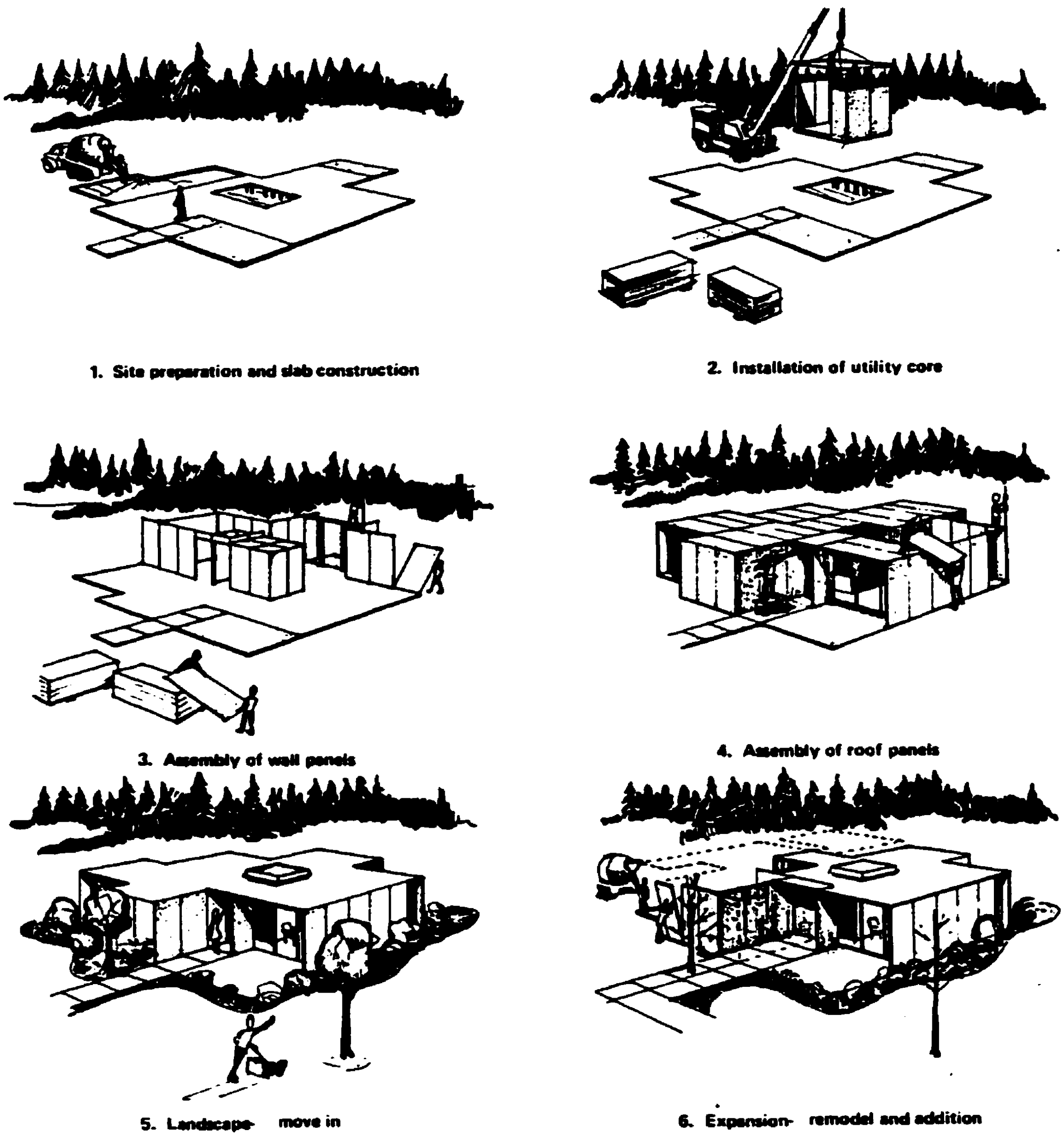


Figure 3.6: Construction sequence of a small panel system. (Source: U.S. Department of Housing and Urban Development 1973)

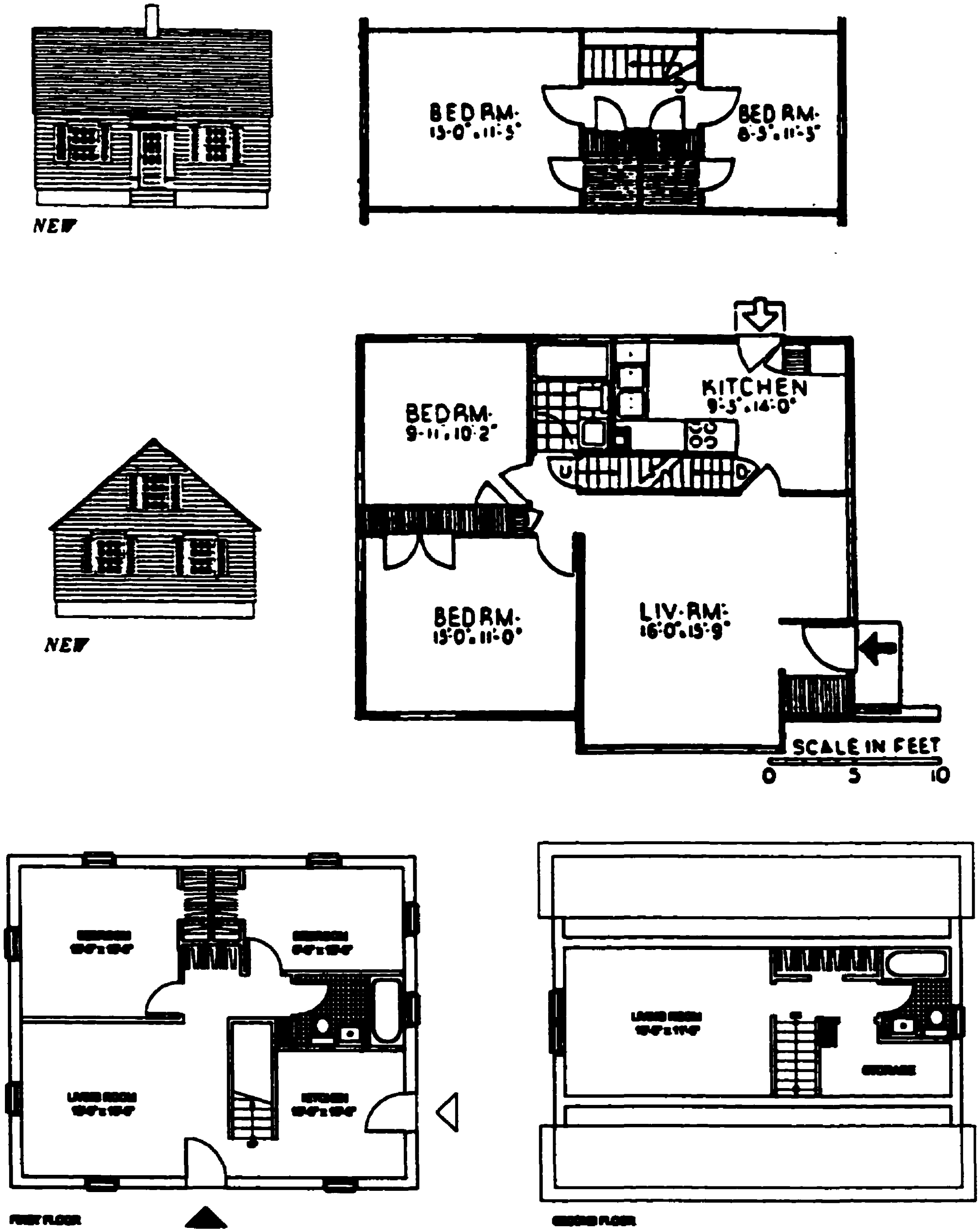
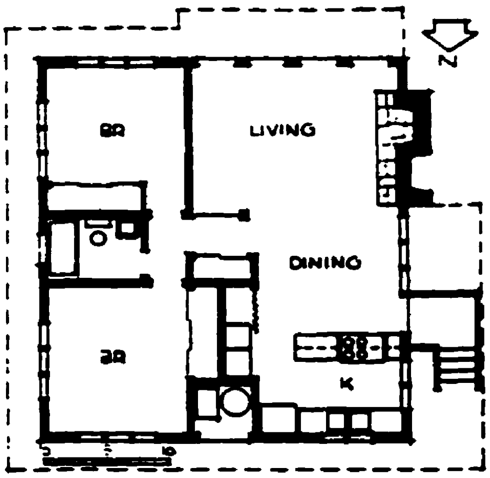
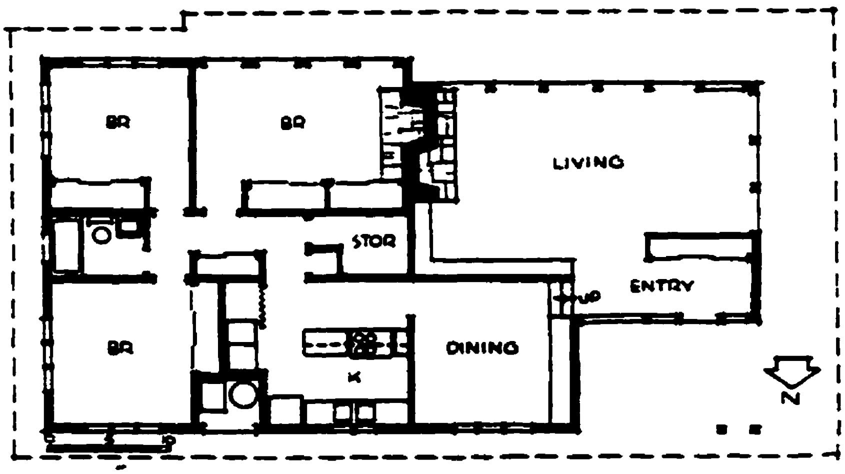


Figure 3.7: On top, the Cape Cod Cottage. At bottom, the Levitt house. These houses provided space in the attic for storage, or the later addition of a bedroom, storage space, and an extra bathroom. The idea was to allow families to grow without having to immediately seek larger housing. (Source: Friedman & Niessen 1991)



ORIGINAL PLAN



EXPANDED PLAN

Figure 3.8: The Expandable House 1954. A minimum number of fixed features are used to accommodate future growth with minimal disturbance. Therefore, a living room can easily be converted into a bedroom. Note also the inclusion of the double fireplace in the original version, which allow this conversion of functions to take place without any changes to the masonry. (Source: Friedman & Niessen 1991)

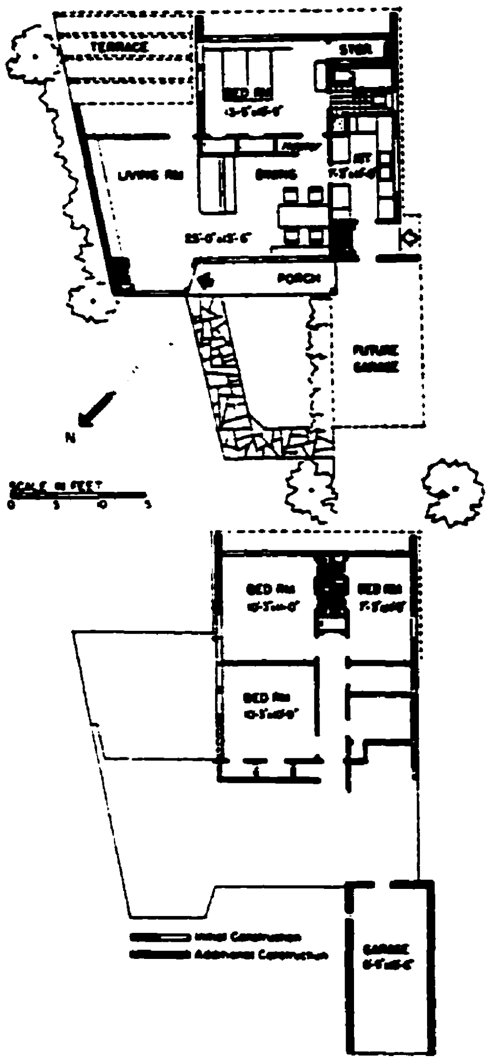


Figure 3.9: The Expandable Bungalow. In order to design a small house that could be expanded according to a pre-determined plan, the designers arranged the circulation in order to provide for a minimum disturbance to spaces during expansion. Furthermore, the bathroom is centralized allowing it to conveniently serve additional bedrooms. Heating is also located centrally, minimizing the amount of ductwork necessary to heat the house. (Source: Friedman & Niessen 1991)

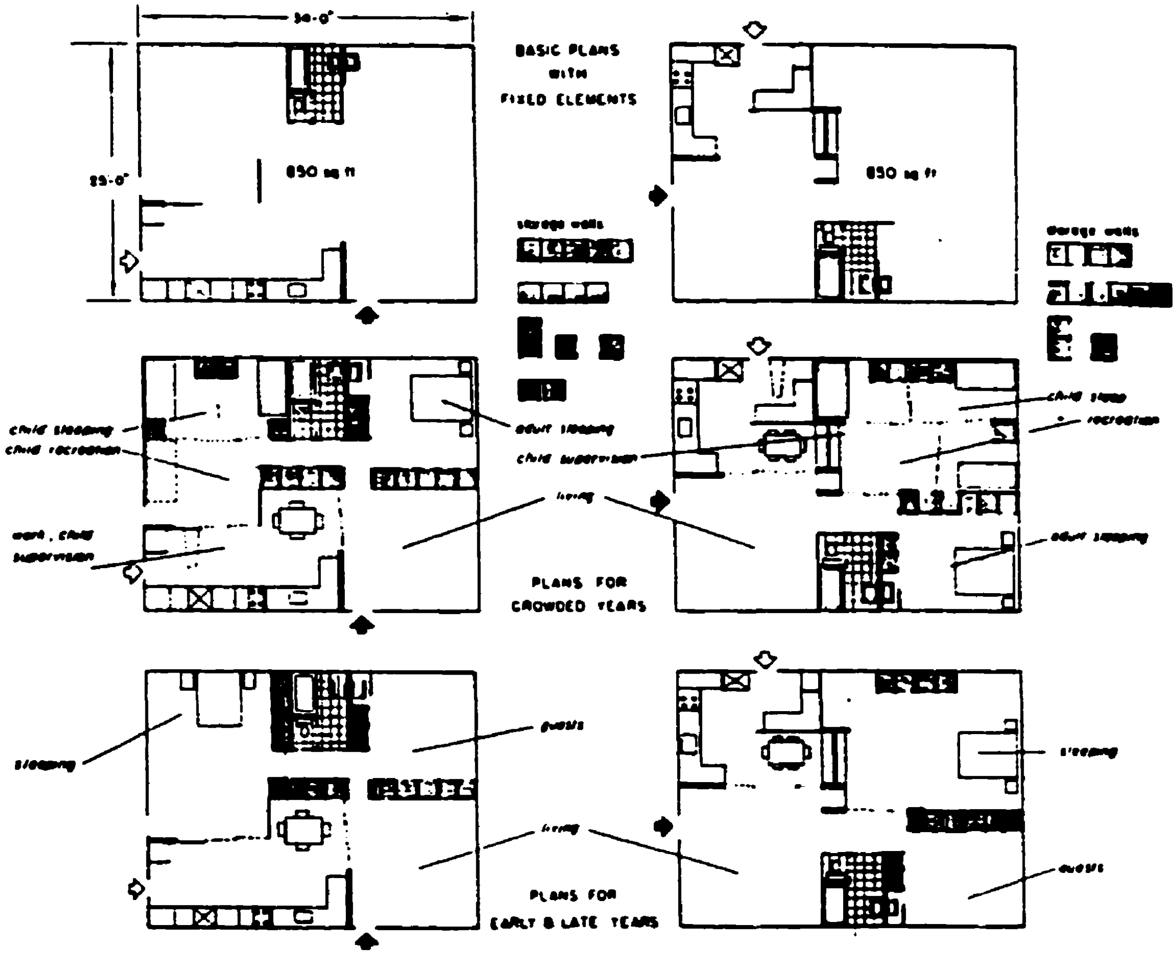


Figure 3.10: Haydn Philips, Flexible Interior for Small House, 1950. For maximum flexibility, the floor plan is created with a minimum number of fixed elements. (Source: Friedman 1995)

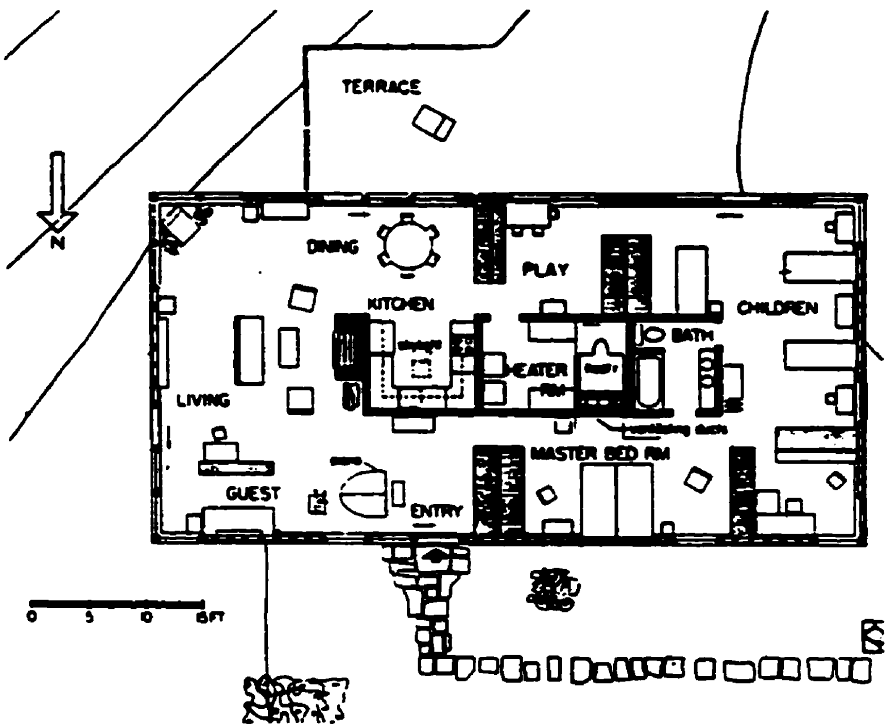


Figure 3.11: Vincent J. Scully, Jr. The One Room House, 1951. To avoid a mechanical movable partition system and yet retain the benefits of flexible partitioning, privacy is created inside the one room house, with the use of 6'3" high movable storage units. The necessary utilities are kept to a minimum in the interior of a masonry core in order to maximize the living space. (Source: Friedman & Niessen 1991)

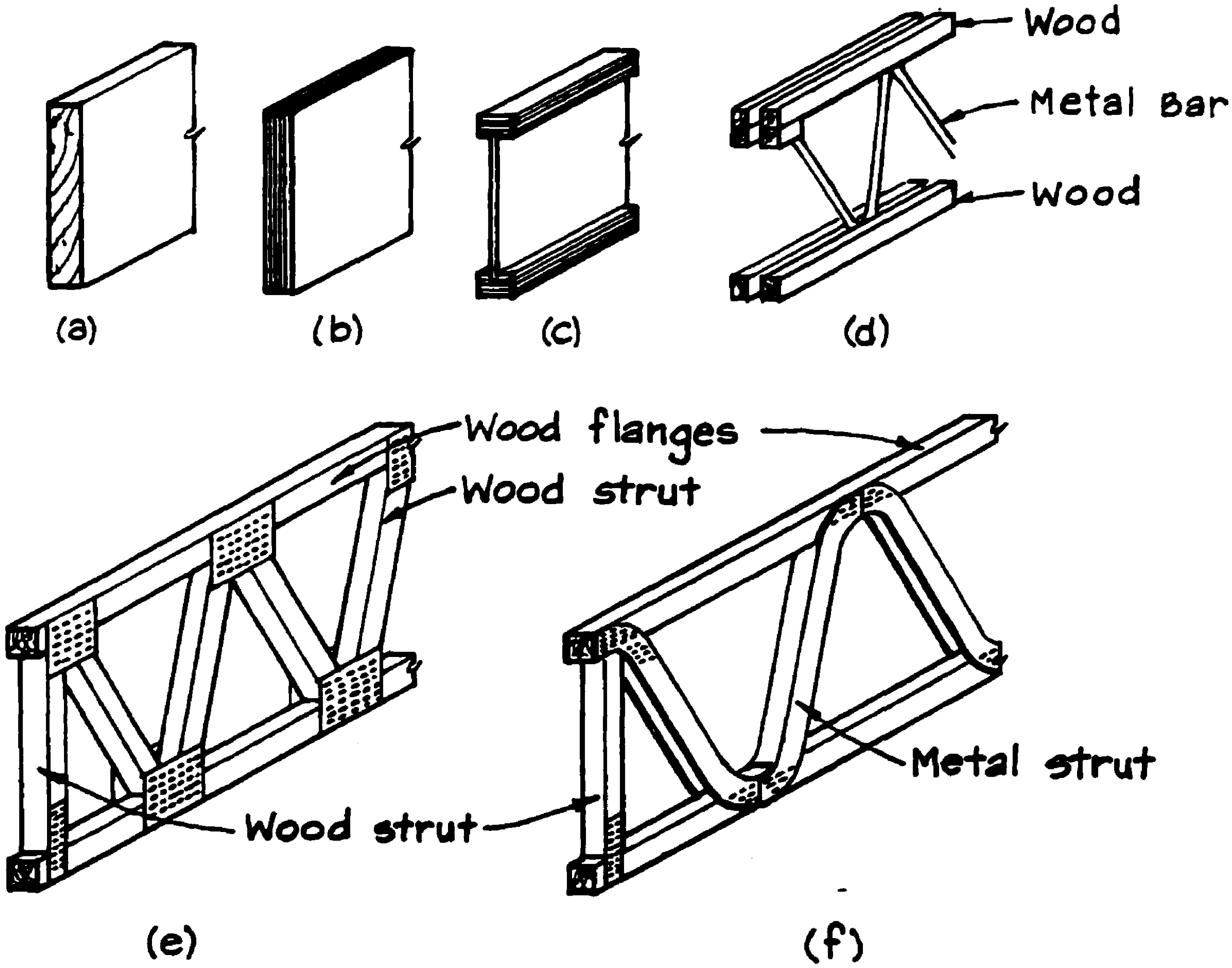


Figure 3.12: Construction lumber: (a) dimension; (b) veneer; (c) I-section; (d-f) open web joists. (Source: Dietz 1991)

Figure 3.13: Plastic Coated Plywood manufactured by Kimberly-Clark Corp., 1946. The new, pre-finished material of plastic and plywood was promoted as a finish for kitchens and bathrooms because of its moisture resistant qualities. According to the manufacturer, it is also durable enough to serve as a floor finish. (Source: Friedman & Niessen 1991)

CHAPTER FOUR

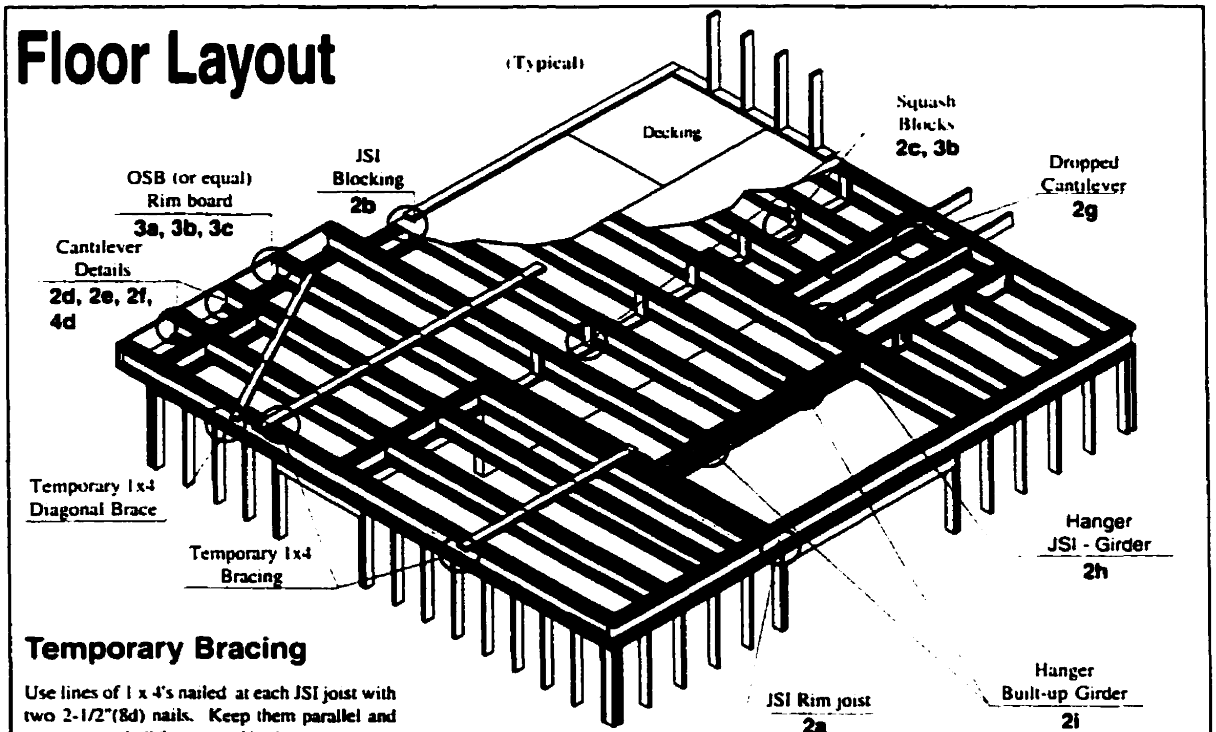
NEW PRODUCTS THAT ENABLE HOUSING FLEXIBILITY

4.0 INTRODUCTION

The prime objective of home-flexibility is to let occupants determine their own layout before and after construction. The level of flexibility is proportional to how independent building systems are. There is more flexibility when there is, less interference between Support and Infill. In general, Support and Infill consist of six primary systems. This report only covers the floor, roof, partition, electrical, plumbing and HVAC (Heating Venting Air Conditioning) systems. What really controls the level of flexibility are these systems' principles, material properties, installation and, often, their costs. The discovery of new materials and the application of new technology will allow for more flexibility. Notice, however, that inflexibility in one system will cause a chain reaction of inflexibility in the lower systems. This chapter examines the technical aspects of traditional building systems and components that restrain flexibility. In addition, the most recent innovations are investigated to show how flexibility can be improved.

For aesthetic reasons, building services are hidden within structures. They are also hidden in order to provide open space for higher flexibility. But inflexibility is encountered when building elements associated with one particular space must be kept. Displacing one space with another often means moving its services with it. Therefore, flexibility depends not only on how easily one space can be reconfigured, but also how freely services can be swapped from one room to another. It is often a limitation in flexibility that sets the design principles. For example, the kitchen, washroom, and laundry room must be located close to each other in order to reduce costs. The arrival of tomorrow's home technology also shows that traditional homes have difficulty coping with flexibility. People in the 21st century are more and more dependent on energy and information. Due to technological constraints, electronics and computers, they need all kinds of cables and wires to establish their network capabilities. Flexibility is required to accommodate these additional services without compromising the flexibility of other building systems.

4.1 FLOOR FRAMING



Temporary Bracing

Use lines of 1 x 4's nailed at each JSI joist with two 2-1/2"(8d) nails. Keep them parallel and approximately 8 feet apart. Use long pieces, not short blocks. Lap the ends (side by side) to keep the line continuous.

To prevent endwise movement of continuous 1 x 4 bracing, provide a bay braced by sheathing, diagonal bracing, or blocking at its ends and at 25 foot intervals (maximum) between ends.

Remember, the continuous 1 x 4 bracing is not effective unless attached to the braced bay. Use particular care in removing temporary bracing when applying sheathing. Remove the bracing as you go.

2 x 2 X-bridging is NOT recommended.

Note: Continuous solid blocking adequately fastened to a braced end wall will greatly improve floor performance.

4.1 FLOOR FRAMING

4.1.0 INTRODUCTION

Distinguishing between the Support system and the Infill system is a method of achieving housing flexibility. One approach is to design an open space so that the building structure can avoid interference with its interior volume. Speaking from the standpoint of flexibility in North American wooden light frame house construction, the objective of floor and roof construction is to increase the unsupported span; therefore, permanent structures such as beams, columns and load bearing partitions can be taken away. This is infrastructure flexibility according to Eric Dluhosch (1974). Today, wood engineering is the industry's route to building flexibility: roof span has been increased by the use of trusses. Due to the invention of engineered wood products, and the use of composite materials and metal anchors/connectors/hangers, joist span has increased. There are many types of long-span joists. This section studies four typical long-span joists and their degrees of flexibility.

4.1.1 BASIC

"The structural shell must be erected before other works can begin. It consists of the foundation, floors, walls and roof" (CMHC 1997). The construction process suggests that flexibility should begin with the building structure. In North America, dimension lumbers are mostly used in traditional wood light frame construction. Their sizes are proportional to the amount of load they take, as well as wood species and grades. Because dimension lumbers are solid, they use considerably more wood when taking larger loads. Therefore, in terms of construction economy, stretching long distances will not be feasible without making the intermediate supports. The consequence is that interior flexibility is compromised after construction. Moreover, this inflexibility may cause material wastage and higher labour costs if major renovations are needed in the future.

4.1.2 TYPES OF JOIST

In contrast to dimension lumber, engineered wood products provide equal or superior performance. They make better use of forest resources by using less wood, and using wood from small, fast growing trees. Chips or slices of wood are bonded with chemicals (mostly special glue) to form laminated timber, wood I-joists and structural composite lumber. Dimension lumber and other laminated timber are sometimes combined in the making of new-engineered wood products using glue or mechanical fasteners. The most common example is the engineered roof/floor truss. It is generally a parallel-chord truss with metal or wood webs. Wood I-joists consisting of lumber flanges and plywood, waferboard or oriented strandboard webs are also being used more frequently. These products provide greater flexibility in design by virtue of their larger spans and their capability to house services (i.e. the web area can be cut to make access for plumbing, wiring and ducts). In addition, when used for the roof structure, they can accommodate higher insulation levels (CMHC 1997).

4.1.3 JOIST SPAN

Providing a stiffer structure is one prerequisite when designing an open floor plan. Wood I-joists become good alternatives to dimensional lumber because they can take a larger load by using less material, and may even permit a wider spacing between members leading to even further reductions in material requirements (CMHC 1997). However, engineered wood joists are manufactured in certain dimensions only. There are several factors to consider when deciding the joist span: maximum deflection allowable by code, amount of dead/live load, floor sheathing type and thickness, joist spacing, species/grade of material, provision of joist strapping and bridging, as well as size of joist. Dimensional lumber joists have nominal sizes from 2 x 6 inches to 2 x 12 inches. Their average spans range from 8 feet 7 inches to 21.5 feet (CMHC 1997). Engineered wood I-joists have spans from 13 feet to 27 feet. The special V-joists have spans from 12 feet to 20 feet. The metal web space joists have spans from 12 feet to 30 feet. While the wood space joists have spans from 10 feet to 30 feet. Below is a summary chart of joists' maximum spans (Figure 4.0):

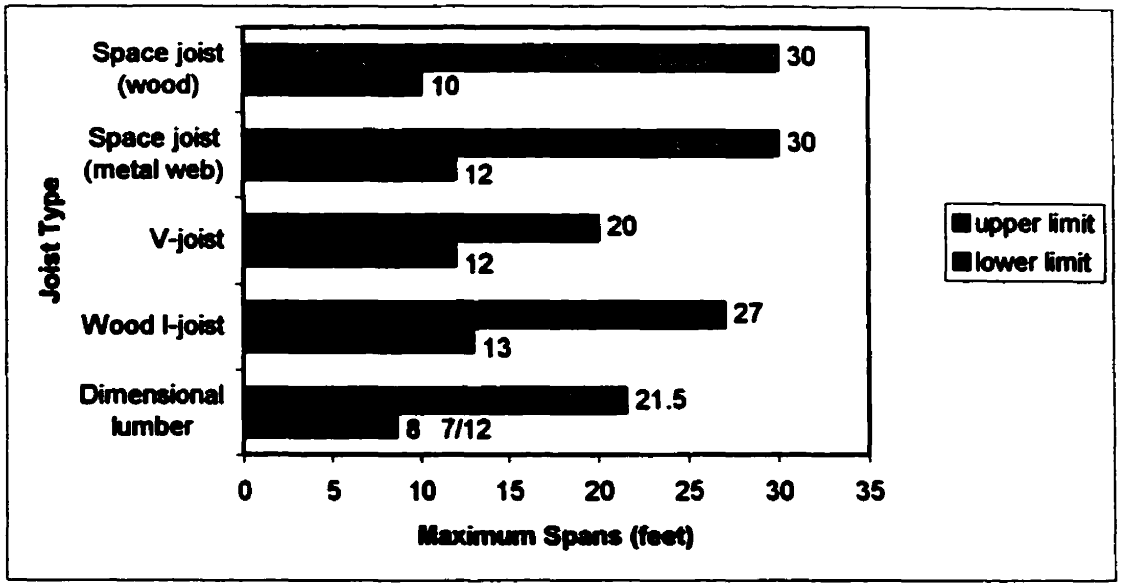


Figure 4.0: Engineered wood joists maximum spans.

4.1.4 JOIST SIZES

Many manufacturers use floor span to determine joist sizes and spacing. These two factors have significant influences on construction economy; either narrowing joist spacing or deepening the joist can change the spans. If the spacing is narrower, more material and labour will be needed to install the floor. If the joist is deepter, which means the floor/ceiling structure would be "thicker", the more material and labour will be needed to construct the exterior building envelope. The second alternative seems to be more reasonable to house pipes, wires, ventilation ducts and other add-on building systems. It also has higher post-construction flexibility because it has less structural members spanning across, meaning that there are fewer obstacles (especially cutting holes) when new building services are to be added. Optimum structural layout is achieved when the equilibrium between budget and needs is attained. Below is a table showing typical sizes of joists (Table 2):

	Joist Depth (inches)	Nominal Sizes (inches)	Joist Spacing (inches)
Dimension Lumber Joists	6, 8, 10, 12	2x6, 2x8, 2x10, 2x12	12, 16, 24
Wood I-joists	9 ¼, 9 ½, 11 ¼, 11 ½, 11 7/8, 12 ½, 14, 16	Flange Sizes: 2x3, 2x4	12, 16, 19.2
V-joists	9 ½, 10 ¼, 12	N/A, Classified by joist depth	12, 14, 16, 19, 24
Space Joists (metal web)	9 ¼, 10 ¾, 11 ¼, 12 ¾, 14 ¼, 15 ¾	Flange Sizes: 2x3, 2x4	12, 16, 19.2
Space Joists (wood)	9 3/8, 13, 16	Flange Sizes: 2x3, 2x4	12, 16, 19.2, 24

Table 2: Typical joist sizes.

4.1.5 LOAD/SPAN COMPARISON WITH REFERENCE TO JOIST DEPTH

Generally speaking, engineered joists are not much stronger than dimensional lumber below a 16 feet span (Table 3); they are also less suitable due to their higher costs. The differences become apparent when spans exceed 16 feet because conventional dimension lumbers do not stretch beyond that extent (Figure 4.0). The width of a house generally takes advantage of plywood modules of 4 feet. Therefore, homes often have overall widths of between 16 feet and 32 feet. Any width in this range can be supported with either one row of simple-span engineered wood joists, or two rows of dimension-lumber joists with columns and beams or load bearing partitions (Figure 4.1). Loading conditions and construction details must be specified in order to compare the load/span of various joists. Let us assume the following: 40 PSI live load, 15 PSI dead load, L/360 maximum allowable deflection, 5/8 inch OSB or plywood nailed subfloor, 10 inch joist depth (minimum size for all engineered wood joists) with 16 inch spacing, plus all necessary strapping and bridging. The spans are summarized in table below:

Joist Types	Spans (feet)
Dimension Lumber Joists	14'-10"
Wood I-joists	14'-11"
V-joists	15'-0"
Space Joists (metal web)	16'-2"
Space Joists (wood)	20'-0"

Table 3: Joist spans

Wood space joists are the strongest of all. Other joists have spans roughly between 15 feet and 16 feet. Note that dimension lumber joists and V-joists are manufactured in standard lengths, therefore, cutting to fit is often unavoidable. Other engineered wood joists can be made to user-specified dimensions, which eliminates field cutting. Also, most of these joists can be trimmed at both ends for on-site adjustment, which increases flexibility during construction.

4.1.6 PRICE

The price further explains whether one type of joist is suitable for a project. It is therefore important to check the cost of each joist. This subsection discusses only the cost of materials (the joists themselves) regardless of their relative installations, but hardware costs and shipping. Assume all joists are 9.5 inches deep and have 16" center-to-center spacing.

Below is a comparison of prices:

	Cost per each			
Joist Types	12'	15'	16'	18'
Dimension Lumber[11]	$15.27	$18.84 (14')	$23.83	N/A
Wood I-joists[12]	-	$28.5	-	$36
V-joists	-	$30	-	$36
Space Joists (metal web)	$22.56	$27.90	$32.64	$46.80
Space Joists (wood)	-	$22.65	-	$41.58

Table 4: Cost of joists

4.1.7 PRODUCTS

4.1.7.1 WOOD I-JOIST

In contrast to dimension lumber, the joist in "I" profile has a higher moment of inertia and resistance because it consumes less material. The I-section structure, which is extensively used in current steel construction, can also be produced in wood by gluing or nailing. The wood I-beam was not popular before the Second World War because of abundant wood resources and high fabrication labour. The earlier models were usually made of plywood web and sawn lumber flanges that were glued and nailed to the top and bottom of a web (Figure 4.2). Initially it was meant to replace the solid lumber beam; however, it was eventually replaced by the laminated beam that takes even less time to produce (Götz 1983). Nevertheless, the technology was kept for the development of engineered wood I-joists for their inherent advantages. The strength and quality were

[11] Retail price obtained from Rona Entrepôt, Brossard, Canada. March, 23rd 2000.

[12] Jager Industries Inc.

improved by using laminated veneer lumber (LVL) flanges and Oriented Strand Board (OSB) webs, which are more resistant to water damage.

Engineered wood I-joists have several advantages over traditional dimension lumber joists. Besides offering long spans, they are lightweight; thus, they reduce the builders' job-site labour and material needs while providing roof and floor systems that are rigid and uniform. The design varies from company to company. Jager's Super I-joists are manufactured with 2 inch x 3 inch or 2 inch x 4 inch sawn-lumber flanges and structurally enhanced Oriented Strand Board (i.e. high-density OSB) webs (Jager Industries Inc. 1999) (Figure 4.3). This configuration uses up to 35 percent less wood fibre. The result is a superior wood floor system that can carry greater loads with less bounce and virtually no shrinkage. The Jager I-joists are available in five different series and depths ranging from 9 ¼ inches to 24 inches. They can be cut to exact lengths or shipped in long lengths for field cutting (Figure 4.4). TrussJoist MacMillan Ltd. (1999) modified the design of I-joists further by using laminated veneer lumber (LVL) for flanges. Available in three flange sizes from 1 ½ inch x 1 ¾ inch to 1 ½ inch x 3 ½ inch, the I-joists have a slightly superior performance to those made of sawn lumber flanges. In addition, they are a better use of wood resources.

Framing I-joists is not much different than dimension lumber. The joists are connected using deeper metal hangers/connectors (Figure 4.5). Two I-joists can be nailed together to form a girder with the addition of filler blocks. Nailing web stiffeners to increase their designed spans or loads can also reinforce wood I-joists. This is flexible because joists can be reinforced where the point load is instead of reinforcing the entire member. The web stiffeners fit in the web area, and their total thickness does not extend beyond the width of the flanges. Therefore, I-joists will not restrict the flexibility of other building components, and they also reduce the costs of material and labour (Figure 4.6).

Another advantage of I-joists is that they allow plumbing, electrical and mechanical services to pass through. However, there are guidelines for hole cutting. Any hole smaller than 1.5 inches may be located anywhere in the web. A maximum size hole is only permitted at mid-span of the joist. There is also a minimum clear distance between holes if more than one hole must be cut in the web. Moreover, flanges can not be cut or notched. The guidelines are summarized in the table and chart below (Figure 4.7):

4.1.7.2 V-JOIST

V-joist is a prefabricated joist made from OSB boards that are "welded" (glued) together using reinforced polyester resin (Les Systèmes V-Joist Inc. 1990). The bottom of the joist has a steel bar embedded in the weld to increase its tensile strength. The "V" shape joist can be cut to desired lengths at the factory. However, field cutting is questionable without the use of a special saw that cuts both wood and steel. The V-joist system has four principle components: the joist, polystyrene insulated rim joist (which has an R-value of 20), laminated veneer lumber (LVL) beam, and joist cap hanger (Figure 4.8). The floor will have a uniform and stable performance thanks to its monocoque construction, and because of the shape of the joist and the way it is engineered. The V-joist resists vibration, thus it is silent. It also has good lateral stability; therefore, temporary bracing during construction can be avoided. V-joists are manufactured in three depths (9.5 inch, 10.25 inch, 12 inch) and five standard lengths (12 feet, 14 feet, 16 feet, 16 feet, 19 feet, 24 feet). The web can also be cut to make access for plumbing, electrical and mechanical services. Similar to I-joists, guidelines for cutting apply. A chart showing the size and location of openings is summarized in Figure 4.9. Nevertheless, the V-joist is a non-conventional floor framing system. It lacks flexibility in certain ways: joists cannot be connected sideways, or nailed together in parallel to form a girder. They cannot be reinforced midway, nor can they be cantilevered or extended. Building intermediate supports (e.g. load bearing partitions or columns) for V-joists may be complicated and time consuming because of the triangular shape of the joist. Moreover, the joists are not connected using regular metal joist hangers that are widely available on the market; instead they use special joist cap hangers. This may cause inflexibility for construction or renovation when the system becomes obsolete or parts become unavailable. In summary, the V-joist has a good span, but it lacks flexibility in terms of variation in the structural layout.

4.1.7.3 METAL WEB SPACE JOIST

1. SPACEJOIST

The metal web space joist consists of two parallel wood frames connected by high tension galvanized steel plates in the form of a truss. The web is made from individual forged plates with teeth, which are pressed into the sides of the top and bottom flanges. Metal web space joists are light yet strong. Their maximum unsupported span can reach 40 feet (Truswal Systems Corporation 1993). They can also be used for floor, roof or wall construction. When used as rafters in roof construction, they can help to create habitable space in the attic (Figure 4.10). The open web area can be filled with insulation, or accommodate pipes, electrical wires and ventilation ducts. The entire space joist floor system can even serve as return for heating systems if permitted by local building codes. The maximum dimensions for ducts are provided by Jager SpaceJoist in figure 4.11.

Most manufacturers use computer software to calculate the load pattern of space joist systems. Therefore, joists can be custom built to bear the special loading condition of a project. The metal web space joists manufactured by Jager Industries Inc. are categorized by the size of top and bottom flanges, depth and grade. There are two flange sizes (2x3 & 2x4), five joist depths (9.25 inch, 10.75 inch, 11.25 inch, 12.75 inch, 14.25 inch, 15.75 inch) and three grades available. The joist length is determined by the user. The metal web space joist is a more flexible framing system than other engineered wood joists because there are many ways to connect the joist to other structural members. The space joist can be supported at the bottom end of the top flange. This type of connection increases the speed of installation; in addition, the structure is more stable during construction. It can also be supported by sitting on top of the sill plate, beam or load bearing partition. Otherwise, it is connected to beams in the web via joist hangers (Figure 4.12). Two space joists can join together side by side to form a girder. Moreover, dimension lumber can be inserted into the cavity between plates in a web to make a cantilever extension or reinforcement. These inserts are nailed in place; therefore, it is quick and easy to strengthen the joist where the point load is (Figure 4.13). With the block insert, it is possible to connect joists sideways. This application is used to construct stairwells (Figure 4.14). For increased working flexibility on site, metal web space joists are available with ends that can be trimmed. This design feature allows the joist to be adjusted (i.e. cut to length) when the actual foundation wall is off, without disturbing its structural integrity. Up to 12 inches on both ends are trimmable (Figure 4.15).

The biggest concern about space joists is their fire resistance: the metal web loses its strength under high temperature. In fact, most building codes regulate fire ratings for space joists in residential construction. A one-hour fire rating can be achieved with two layers of ½ inch gypsum board screwed to the bottom of joists. This added ceiling thickness, however, might somehow restrict the accessibility of plumbing, wiring and other mechanical services. It also suggests that suspension-ceiling systems may not be usable because they will not provide sufficient fire protection. Apart from fire resistance, sound protection is also an important consideration. The space joist floor system has a minimum STC rating of 42 without sound absorbing insulation. Because of its open web design, the sound rating can be improved to STC 55.

2. TRUSS JOIST

Another type of metal open web joist is manufactured by Trus Joist MacMillan Limited (2000). It uses double Laminated Veneer Lumber (LVL) for flanges, and tubular steel for webs that are bolted to the top and bottom chords (Figure 4.16). The truss joists are between 14 inches and 72 inches deep. The flanges have four dimensions (1.5 inch x 2.3

inch, 1.5 inch x 3.5 inch, 1.5 inch x 4.75 inch, 1.5 inch x 5.5 inch) and are pre-stressed for increased performance. The tubular steel has five diameters (1 inch, 1.125 inch, 1.25 inch, 1.5 inch, and 2 inch) to choose from according to user requirements. The spans range from 14 feet to 70 feet, while the minimum 14 inches deep joist has a span of between 14 feet to 20 feet. The load/span characteristic of a truss joist is similar to other engineered wood joists.

The truss joists have several profiles, and they can be used for roof trusses (Figure 4.17). The installation resembles that of the space joist. It also shares many other characteristics: it spans longer, is easily and quickly installed, and allows passage for plumbing, electrical and mechanical services. However, it lacks the flexibility and variety in terms of joist connection or extension. The truss joist system is not suitable in the basement because the top flange is set on top of the supporting structure at both ends. As a result, it reduces floor to ceiling clearance (Figure 4.18). Like I-joists and SpaceJoists, bracing for truss joists is required during erection to prevent lateral buckling of the flange members.

4.1.7.4 OPEN WEB WOOD JOIST

Open Joist 2000 was derived from the glued wood truss beam that was developed in the 1950s for use in both light and heavy wood frame construction (Open Joist 2000, 1996). The top and bottom flanges, as well as the bar web have incisions and are finger-jointed using special glue (Figure 4.19). The maximum allowable span is 98 feet. The utmost depth can reach 10 feet; however, depths in between 1 foot to 2.5 feet are the most popular (Götz 1983). The Open Joists 2000 are manufactured in three standard depths: 9 3/8 inch, 13 inch, and 16 inch. The sawn-lumber flanges have two standard dimensions: 2x3 and 2x4. Minimum joist length is 10 feet, and the maximum is 30 feet. The joist can be supported either by sitting on top of the sill plate, bearing wall or beam, or by using a joist hanger.

Unlike SpaceJoist or truss joist, Open Joist 2000 must provide backer blocks[13] at both ends; this prohibits the joist from being hung from the bottom ends of the top flanges. Job site length adjustments of 11 inches will minimize material waste and assure a security buffer for the builder (Figure 4.21). Open Joist 2000 also exhibits a variety of structure combinations: two joists can join together side by side to form a girder; the web area can be reinforced with plywood on both sides for stair stringer support (Figure 4.22), a point load (Figure 4.23), and a cantilever that supports load bearing wall (Figure 4.24). A 2" x 10" solid lumber can be inserted and nailed to the webs for a dropped cantilevered balcony (Figure 4.25), or a solid lumber cantilever perpendicular to the joist (Figure 4.26).

The installation of Open Joist 2000 is similar to Space Joist and so are the precautions. The webs and flanges cannot be cut, while the backer blocks can not be cut to less than 1 ¾ inches. Continuous bridging must be provided at mid-span for increased lateral stability and load distribution because these joists are deep. Moreover, because the outermost web bars are designed going downward, Open Joist may not be used as rafters in roof framing (Figure 4.27).

4.1.7.5 PREFABRICATED ROOF TRUSS

Following the end of the Second World War, a high demand for housing, and a shortage of materials and labour urged builders to call for efficient ways of building. Pre-assembled components or new types of materials were used to boost production. For the first time, prefabricated roof trusses were widely incorporated in many post-war housing constructions. They were designed to replace joist and rafter systems because traditional roof support construction was complicated, labour intensive and time consuming. Another disadvantage of traditional roof framing was that intermediate supports were needed. This

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[13] Backer blocks: Blocks of wood or other material used to fill in and reinforce the web of a wood I-joist, space joist or truss joist. Backer blocks are typically used where a hanger will be attached to the joist, allowing for the attachment and support of another structural member (Bianchina 1997).

required more materials and labour, and restrained indoor flexibility. Roof trusses eliminated most of the drawbacks associated with the old joist and rafter system. They were engineered because their physical behaviour was predictable. Truss members were held together by bolts, metal connectors, and, later, by "Gri-P-Late" and "Gang-Nail" (Figure 4.28 & 4.29). Gri-P-Late and Gang-Nail are generally gauge metals that have teeth. They were pressed into the wood with a hydraulic press, eliminating the need for nails (CMHC A 1989). Recently manufacturers have entered the computer age, and trusses can now be designed to fit many roof shapes, stretch many widths, and bear any specified load. They can even be simulated and tested on the computer before they are actually produced. Trusses use about 50 percent less wood, span the entire width of a house, and their low cost, fast installation and custom built characteristics increase flexibility before and during construction. However, there is one potential drawback. Post construction flexibility is restricted as the space (or attic) in the middle of some low-pitched trusses may not be usable. This situation worsens when an airtight building envelope must be kept between the trusses and the ceiling.

4.1.7.6 COMPUTERIZED DESIGN SERVICES FOR ENGINEERED LUMBER

Today, the use of computer software is getting more and more common in the construction industry. In the near past, there were specialized computer programs for cost estimation, as well as for some construction-related tasks such as accounting and payroll (Bianchina 1997). The CAD (Computer-Aided Design) programs came later. However, due to the high cost of the programs and of the intensive training required to operate them, these were more common in large architecture firms. The popularization of personal computers and "user friendly" computer programs, which began in the late 1980s, has enabled many users to do design and analysis in a way that would not have been possible in the past. As a result, builders and remodelers will benefit as computer software increases flexibility and productivity.

Increasingly, a number of engineered lumber manufacturers are incorporating their products in their software. These computer technologies are capable of putting the power of some very sophisticated engineering right into the hands of the average contractor (Bianchina 1997). They can even suggest the types of material (from manufacturers' inventories) that are most economical to builders. For example, the Trus Joist MacMillan's TJ-Xpert computer software is basically an interactive product catalogue that includes floor and roof design, and contains data concerning I-joists, beams, blocking, and hangers. It provides a complete analysis of floor and roof systems. It calculates structural loads, distributes the loads to the individual members while sizing them, and it develops a complete material list and framing plot (Bianchina 1997).

The design process begins by inputting dimensions for the house floor plan into the computer. The computer will create the most cost-effective layout that meets current building codes. However, the computer-generated design may not be the best one for the builder to actually work with on site. This is because the computer may mix different spacings depending on the span. Therefore, inexperienced users need to work with a consultant to correct any irregularities. With suggestions from a structural designer, the original design can be refined using the computer. The whole process can take approximately three to four hours for a typical house. The program will then print out a drawing of the structure's layout. Each structural member on the drawing is identified with a specific code letter or number. The drawing is also keyed to a set of detailed framing instructions. These show how each section should be assembled, what hanger to use where, safety precautions specific to the use of members during erection, and the nailing schedule for each section (Bianchina 1997) (Figure 4.30 & 4.31).

For optimum flexibility, the design can be modified anytime. For example, by changing the maximum allowable horizontal member deflection from L/360 to L/480, the computer will instantly recalculate and update the structure's layout by changing the member size or spacing. Built-in pricing for the Trus Joist MacMillan's TJ-Xpert TJI products also allows the designer to instantly project the cost differential for the builder between the code minimum and any upgrades in framing, member size, or spacing. The "instant engineering" features of computer software, offer builders flexibility, and time/labour savings. The advantages are illustrated in the following example (Bianchina 1997):

> "Suppose the builder is right in the middle of laying out the second-floor framing, and the plumber points out that one of the joists sits where the toilet will be. The builder can call me here at the yard, and I'll pull his design up on the computer. Within minutes, I can tell him if it's okay to move the joist and increase the spacing to clear the plumbing. If the spacing can't be increased, I can have someone deliver him an additional joist so he can slip one in on each side of the pipes. Either way, he has an accurately framed building with a minimum of downtime." "Frustrating changes that occur during construction – moving a bathtub location, for example, or changing a lightweight fiberglass shower to a mud-set marble enclosure – can be easily accommodated. Here again, the builder only has to call the designer and specify the details of the change, and the design can be instantly altered to reflect the exact live and dead load requirements over the specific area involved."

The detailed material list is created after the design is finalized. This includes engineered lumber products, hangers and connectors. Quantity, dimension, model number, blocking panels, web stiffeners, reinforcing materials and plywood are listed as well. Once the list is complete, the computer will check the availability of materials and then their prices. This cost estimation feedback allows users to immediately calculate how changes in the building design will affect the price of the engineered lumber materials specified. It is, therefore, a decision-making tool that increases flexibility before and during construction (Bianchina 1997).

4.1.8 CONCLUSION

The Support structure itself is not flexible, but it grants flexibility to Infill Systems. It is generally permanent, therefore it cannot be easily modified to accommodate more flexibility. Traditional framing systems with dimension lumber joists, beams, columns and load bearing partitions already have some degree of flexibility built-in. If moving around spaces and their respective building services is frequently needed, it is necessary to separate the Support and Infill. Engineered wood products make this separation possible in wood light frame construction by reinforcing material strength and resistance. Different engineered wood structures have different degrees of flexibility. Open web joists allow the easiest passage of plumbing, electrical and mechanical systems. Computer software pushes the flexibility to the next level by speeding up the design process and visualizing changes in the loading pattern. Some Support structures offer a wider variety, and can be modified to suit specific space conditions. For example, the engineered wood I-joists, SpaceJoists and OpenJoists give contractors more flexibility during construction. Nevertheless, users do not have direct control over Support structures. The maximum level of flexibility can be explored only when Infill Systems match Support Systems' capabilities. The following sections will study the interaction of various building components between the partition wall, stairs, plumbing, electrical services and HVAC systems.

Floor framing: *(1)* **subfloor nailed with 2 in. (51 mm) nails to joists;** *(2)* **1 x 3 in. (19 x 64 mm) continuous wood strapping nailed at bottom with two 2 1/4 in. (57 mm) nails; and/or** *(3)* **2 x 2 in. (38 x 38 mm) cross-bridging at midspan nailed with two 2 1/4 in. (57 mm) nails;** *(4)* **header joist end-nailed to joists with three 3 1/4 in. (82 mm) nails;** *(5)* **header toenailed to sill plate with 3 1/4 in. (82 mm) nails 24 in. (600 mm) o.c.;** *(6)* **floor joists toenailed to sill plate with two 3 1/4 in. (82 mm) nails, one on each side.**

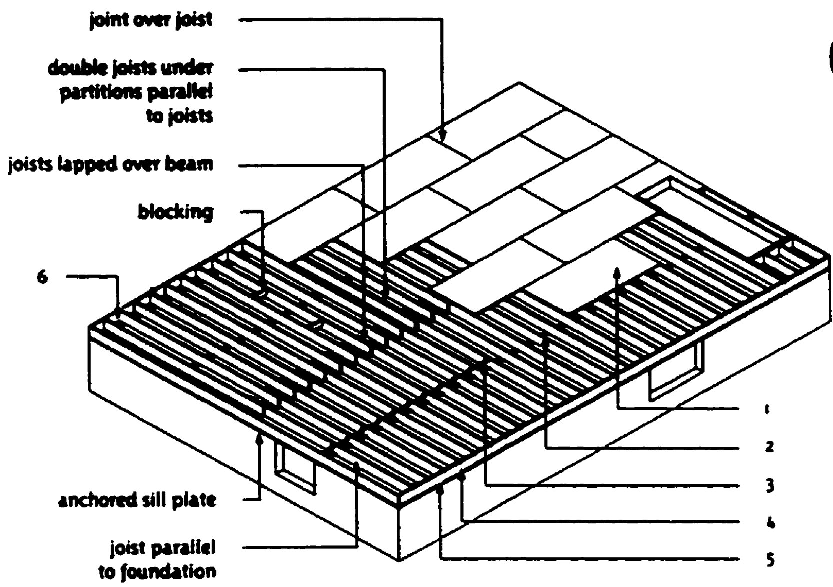


Figure 4.1: Floor framing. The width of a house generally takes advantage of plywood modules of 4 feet. Therefore, homes often have overall widths of between 16 feet and 32 feet. Any width in this range can be supported with either one row of simple-span engineered wood joists, or two rows of dimension-lumber joists with columns and beams or load bearing partitions. (Source: CMHC 1997)

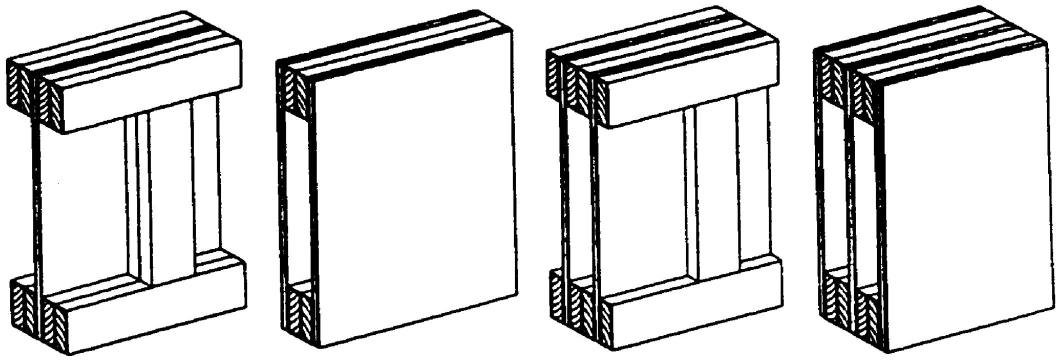


Figure 4.2: Earlier models of wood I-joist. These were usually made of plywood web and sawn lumber flanges that were glued and nailed to the top and bottom of a web. Initially it was meant to replace the solid lumber beam; however, it was eventually replaced by the laminated beam that takes even less time to produce. (Source: Gŏtz 1983)

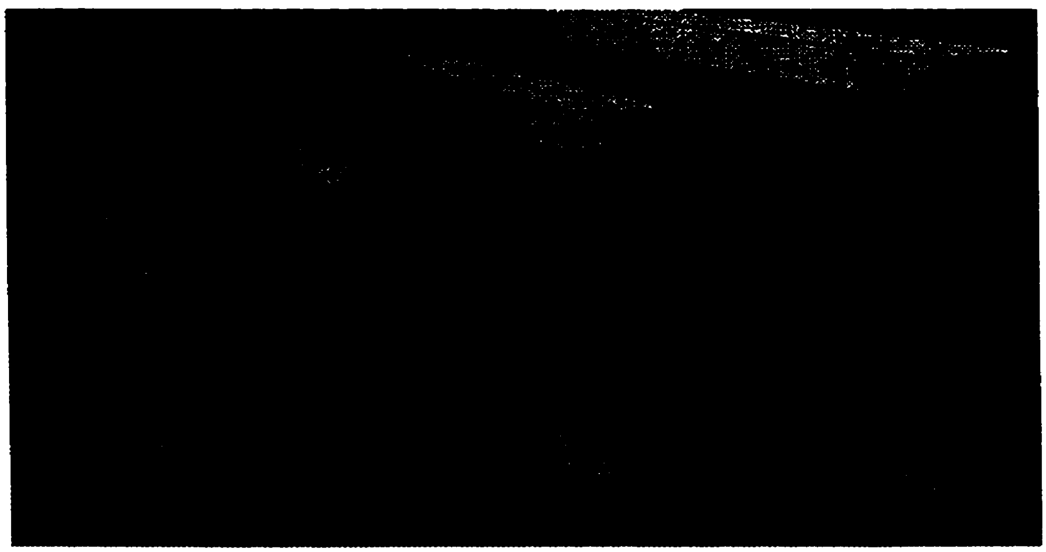


Figure 4.3: Jager's Super I-joists. Jager's Super I-joists are manufactured with 2" x 3" or 2" x 4" sawn-lumber flanges and structurally enhanced Oriented Strand Board (OSB) webs. This configuration uses up to 35% less wood fibre. The result is a superior wood floor system that can carry more loads with less bounce and virtually no shrinkage. (Source: Jager Industries INC. 1999)

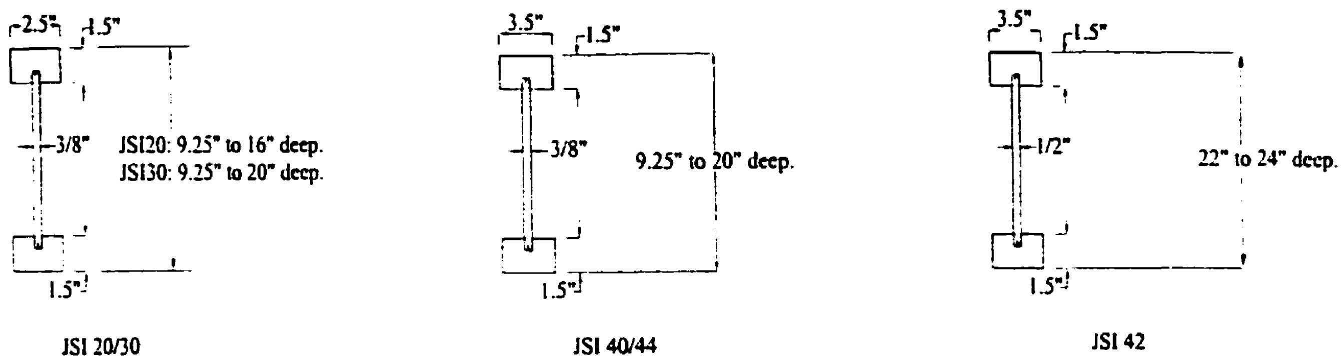


Figure 4.4: The Jager I-joists series. The Jager I-joists are available in five different series and depths ranging from 9 ¼ inches to 24 inches. They can be cut to exact lengths or shipped in long lengths for field cutting. (Source: Jager Industries INC. 1999)

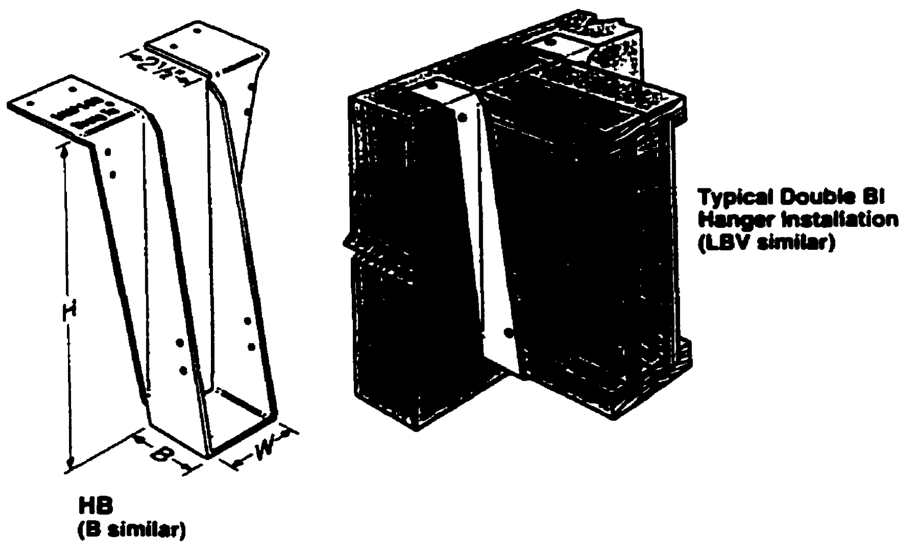


Figure 4.5: Joist hanger. Framing I-joists is not much different than dimension lumber. The joists are connected using deeper metal hangers/connectors. (Source: Simpson Strong-Tie Company, INC. 1997)

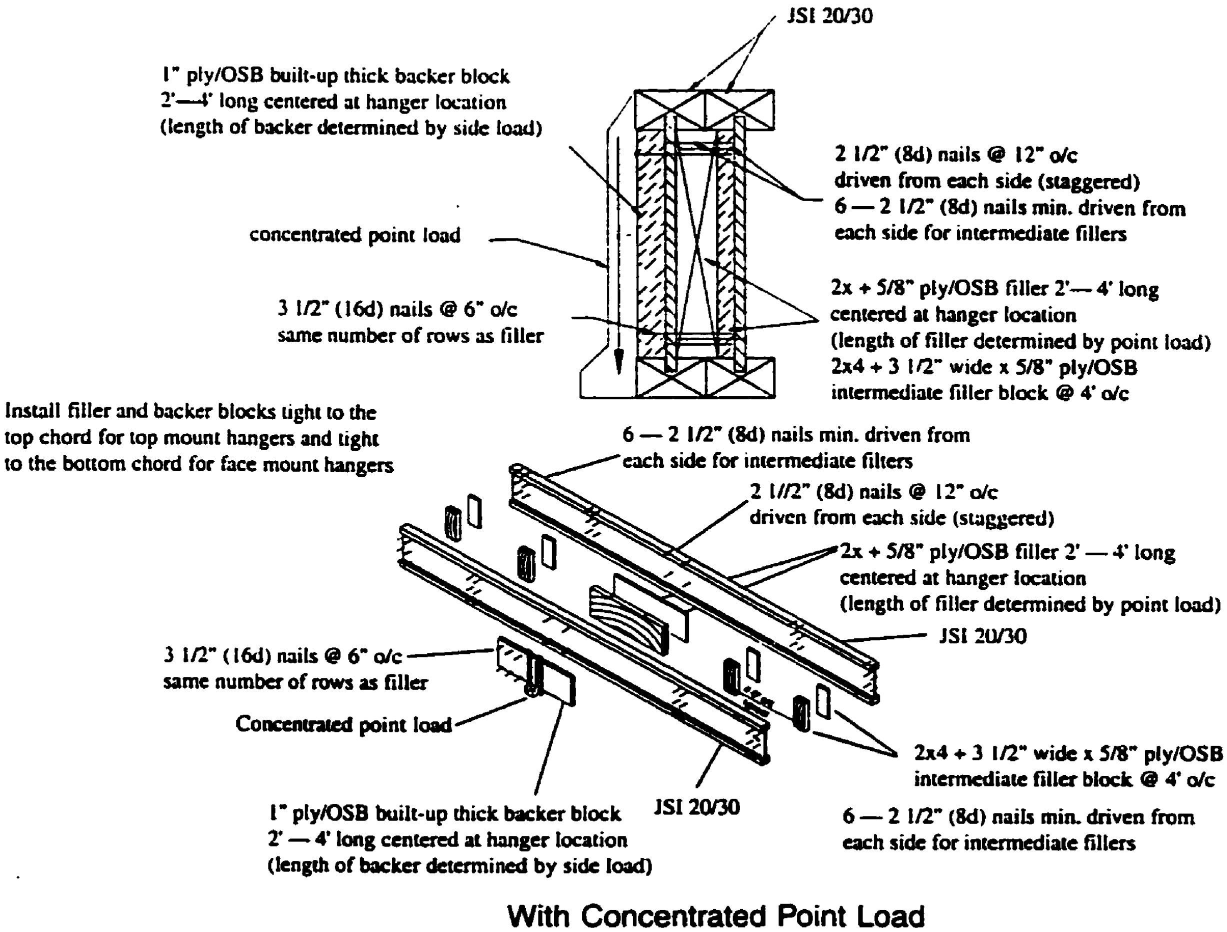


Figure 4.6: Girder fastening details. Two I-joists can be nailed together to form a girder with the addition of filler blocks. This example shows a build-up girder for concentrated point load. (Source: Jager Industries Inc. 2000)

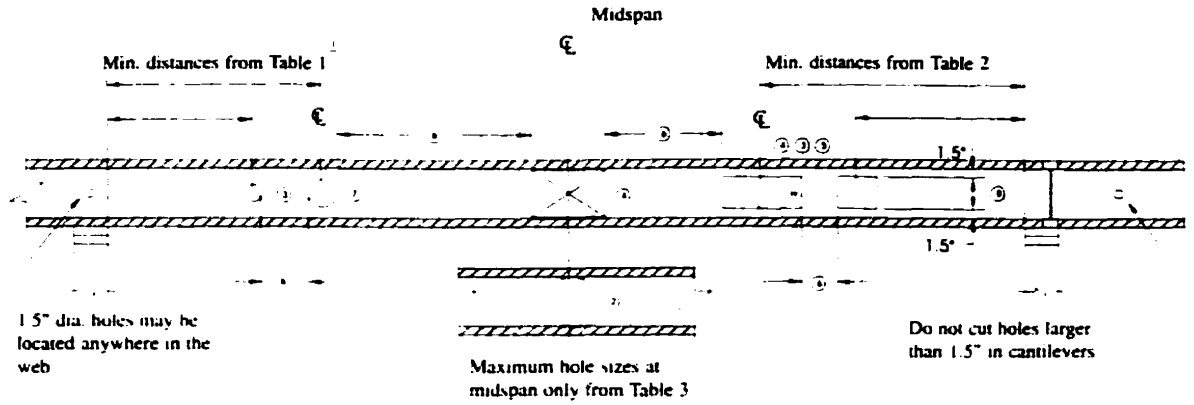


Table 1. Round Holes ①

Round Hole Diameter ③									
Hole Dia.	2"	3"	4"	5"	6"	7"	8"	9"	10"
Min. Dist.	1'-0"	2'-0"	3'-0"	4'-0"	5'-0"	6'-0"	7'-0"	8'-0"	9'-0"

Table 2. Square or Rectangular Holes ①

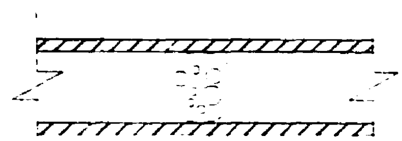
Square or Rectangular Hole Size ④⑤								
2"	3"	4"	5"	6"	7"	8"	9"	10"
1'-8"	3'-0"	4'-4"	5'-8"	7'-0"	8'-4"	9'-8"	11'-0"	12'-4"

Table 3. Max. Hole Sizes (Midspan Only)

Hole Type	JSI " Series	
	JSI 20/30	JSI 40/44
Round ②	12"	12"
Rect. (L x H) ④	12" x 9"	16" x 9"

General Notes

① All measurements are from centre-line of hole to inside-face of support. Min. distances are to be maintained from both left and right supports.
② Largest round hole size = joist depth - 3" to a max. of 12" dia. located at midspan.
③ Round Hole Formula: Distance from support (ft.) + 1 = Hole Dia. (inches)
④ Longest side of a square or rectangular hole is 3/4 of the allowable round hole diameter
⑤ Rectangular holes are based on the measurement of the longest side.
⑥ If more than one hole is to be cut in the web, the min. clear distance between holes must be twice the length (or dia.) of the largest adjacent hole.
⑦ Round holes may be located vertically anywhere in the web.
⑧ Square and/or rectangular holes must have minimum 1.5" edge distance, as illustrated above except at midspan locations where full web-depth holes are permitted, as per Table 3.
⑨ These charts are based on residential uniformly distributed loads. For other load cases, contact the nearest Jager office.
⑩ For other hole configurations not included in these charts, contact the nearest Jager office.



Multiple Small Holes
A group of small holes must fit inside a circle meeting the criteria for round holes in Table 1

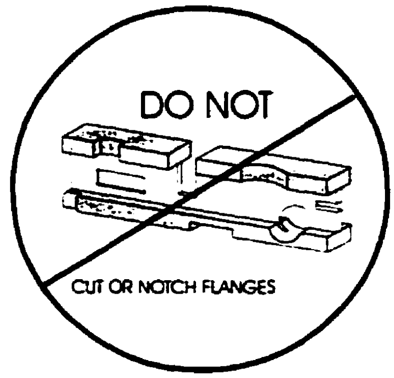


Figure 4.7: Hole cutting guidelines for I-joist. One advantage of I-joists is that they allow plumbing, electrical and mechanical services to pass through. However, there are guidelines for hole cutting. (Source: Jager Industries Inc. 2000)

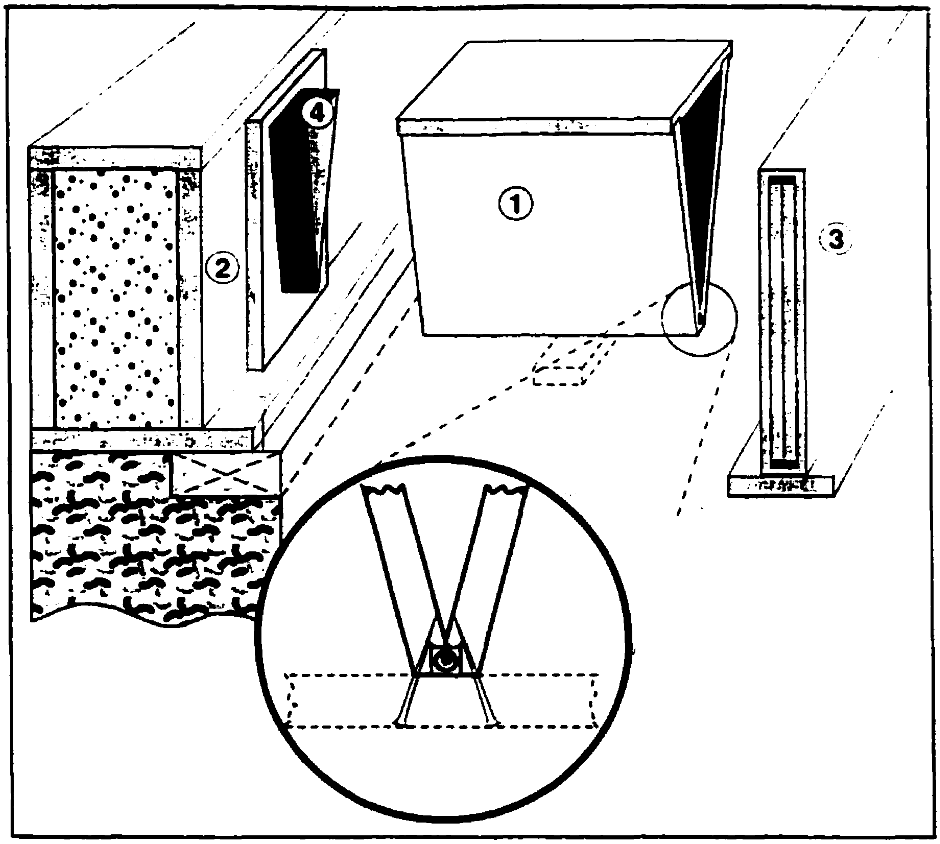


Figure 4.8: The V-joist system. The V-joist system has four principle components: (1) the joist, (2) polystyrene insulated rim joist, (3) laminated veneer lumber beam, and (4) joist cap hanger. (Source: Les Systèmes V-Joist Inc. 1990)

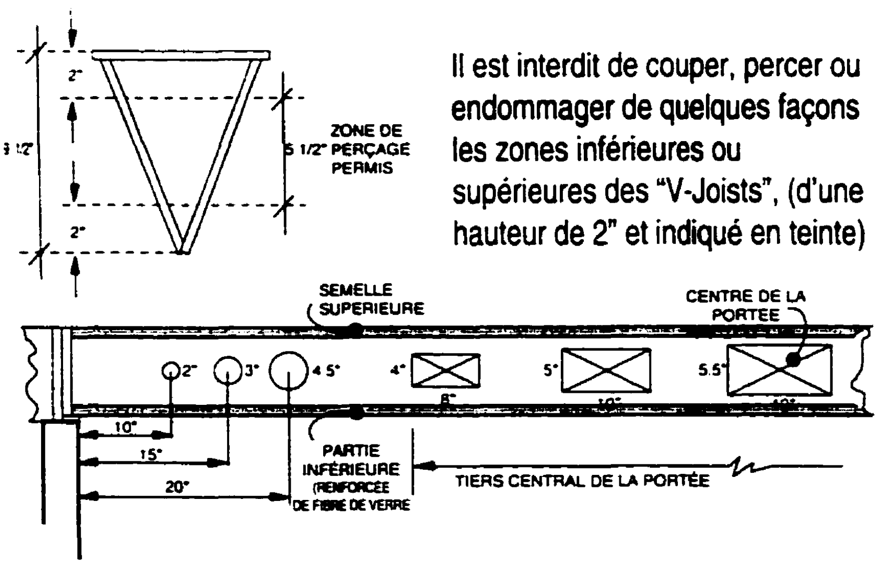


Figure 4.9: Hole cutting guidelines for V-joist. Similar to I-joists, the web of V-joist can also be cut to make access for plumbing, electrical and mechanical services. (Source: Les Systèmes V-Joist Inc. 1990)

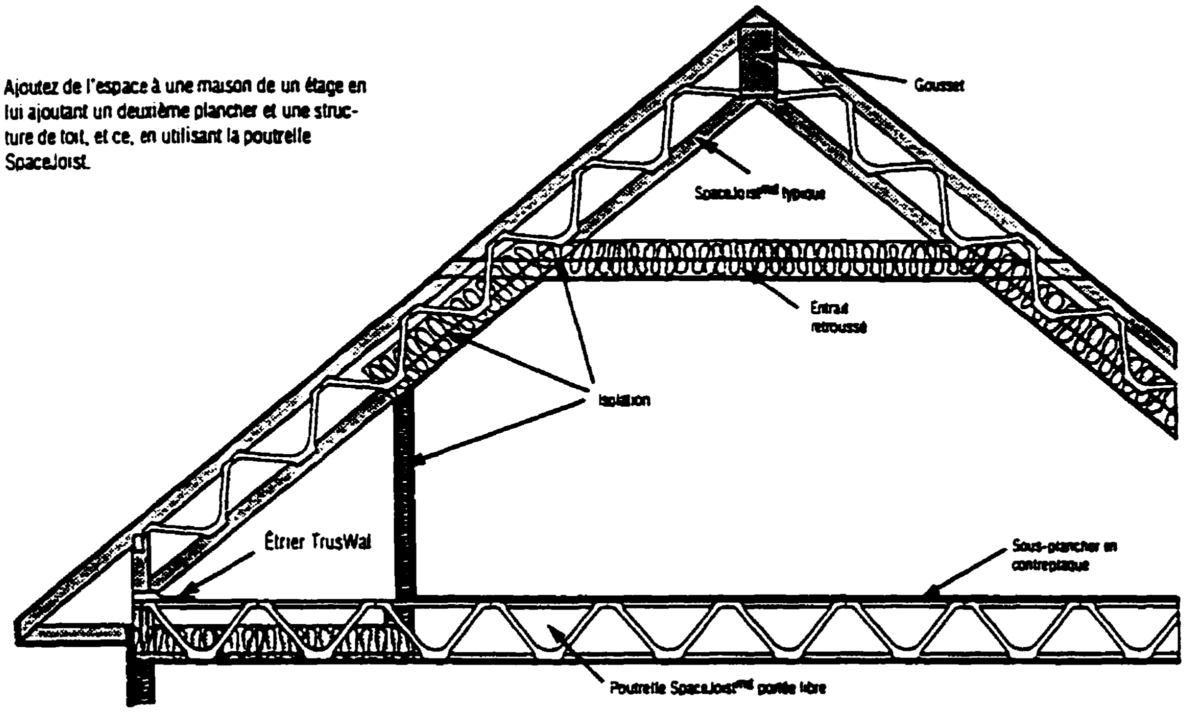


Figure 4.10: The Jager's SpaceJoist can help to create habitable space in the attic when used as rafters in roof construction. (Source: Truswal Systems Corporation 1993)

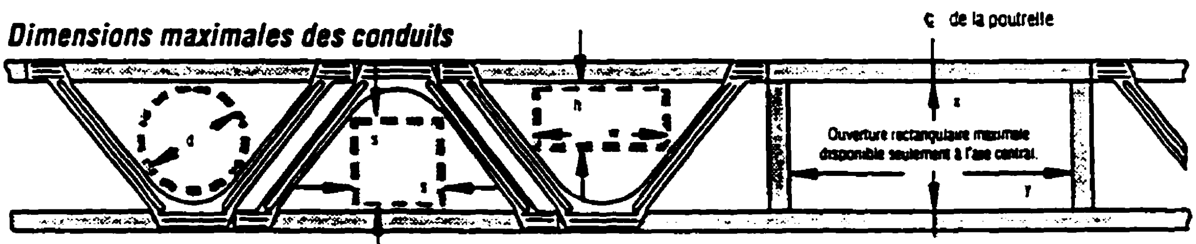


Tableau des dimensions des conduits (V•1)

Type de poutrelle	d*	h*	w*	s*	x	y
	Dimensions maximales - Pouces (Métrique)					
9V20	5.83" 148mm	3.72" 94mm	8.41" 214mm	5.1" 130mm	6.25" 158mm	24" 610mm
10V20	7.46" 189mm	4.73" 120mm	8.46" 215mm	6.07" 154mm	7.75" 196mm	24" 610mm
12V20	8.97" 228mm	6.42" 163mm	8.27" 210mm	7.23" 184mm	9.75" 247mm	24" 610mm
16V20	10.47" 266mm	7.09" 180mm	10.3" 262mm	8.4" 213mm	12.75" 323mm	24" 610mm

Tableau des dimensions des conduits (V•2)

Type de poutrelle	d*	h*	w*	s*	x	y
	Dimensions maximales - Pouces (Métrique)					
10V2	6.05" 154mm	3.83" 97mm	8.19" 208mm	5.22" 133mm	6.25" 158mm	24" 610mm
12V2	7.55" 192mm	4.75" 121mm	8.48" 215mm	6.09" 155mm	8.25" 209mm	24" 610mm
14V2	9.94" 252mm	6.28" 160mm	11.13" 283mm	8.03" 204mm	11.25" 285mm	24" 610mm
16V2	10.36" 263mm	6.92" 176mm	11.47" 291mm	8.33" 212mm	12.75" 323mm	24" 610mm

* Les dimensions spécifiées tiennent compte d'un dégagement de 1/8"

Figure 4.11: Maximum conduit dimensions for SpaceJoist. The open web area can be filled with insulation, or accommodate pipes, electrical wires and ventilation ducts, without cutting. (Source: Truswal Systems Corporation 1993)

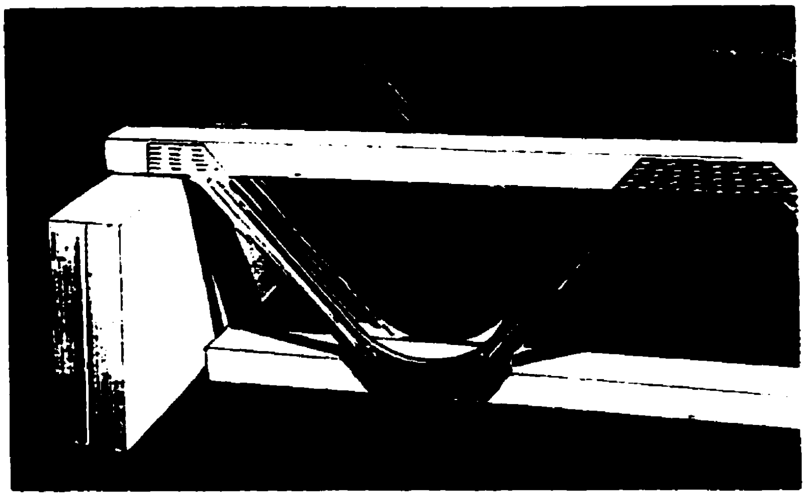


Figure 4.12: Installation of SpaceJoist. Metal web space joist is a more flexible framing system than other engineered wood joists because there are many ways to connect the joist to other structural members. For example, the space joist can be supported at the bottom end of top flange. This type of connection increases the speed of installation; in addition, the structure is more stable during construction. (Source: Jager Industries Inc. 1999)

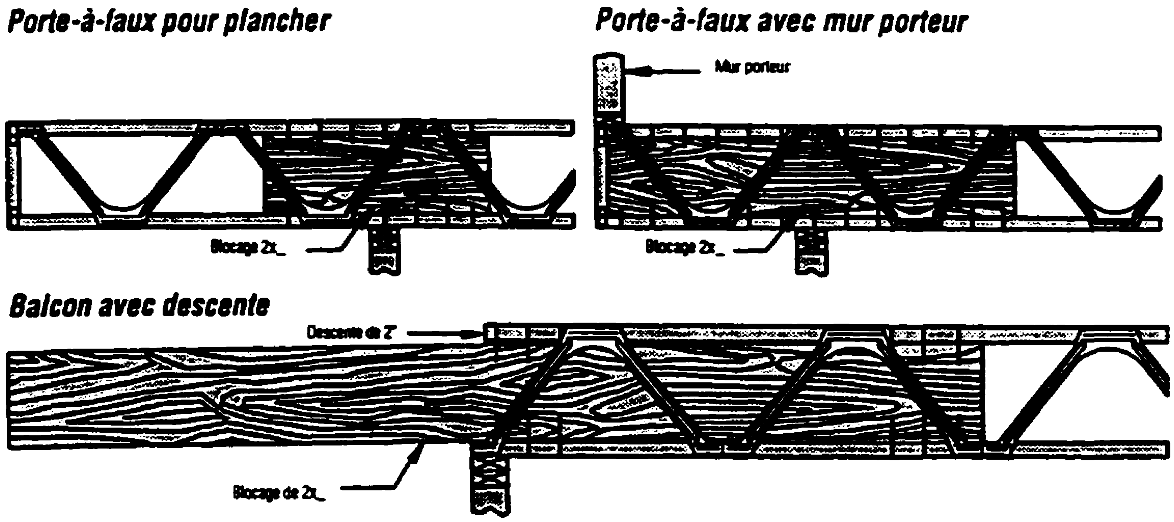


Figure 4.13: Reinforcement for cantilevered SpaceJoist. Dimension lumber can be inserted into the cavity between plates in a web to make a cantilever extension or reinforcement. These inserts are nailed in place; therefore, it is quick and easy to strengthen the joist where the point load is. (Source: Truswal Systems Corporation 1993)

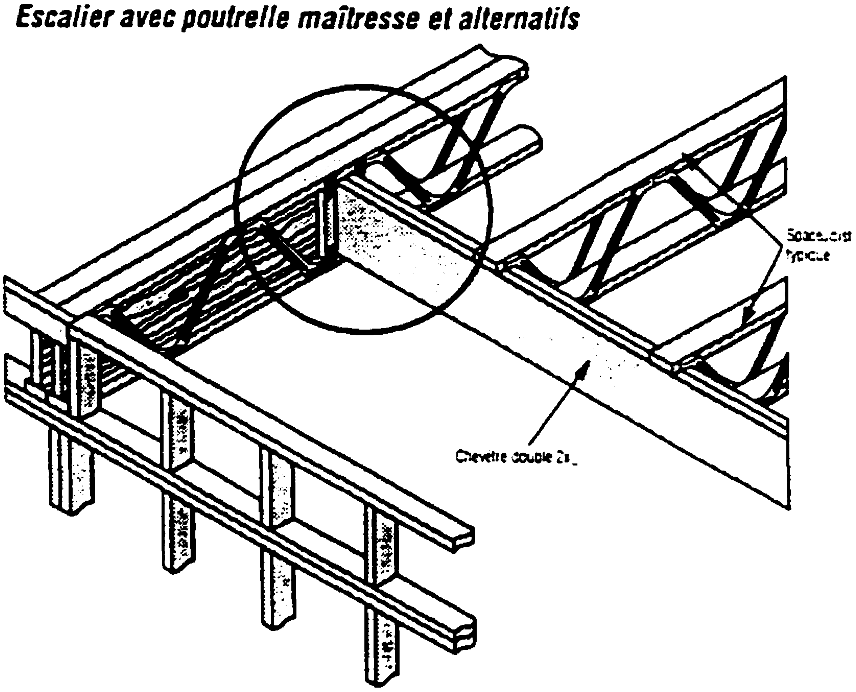


Figure 4.14: Staircase framing detail. It is possible to connect joists sideways with the block insert. This application is used to construct stairwells. (Source: Truswal Systems Corporation 1993)

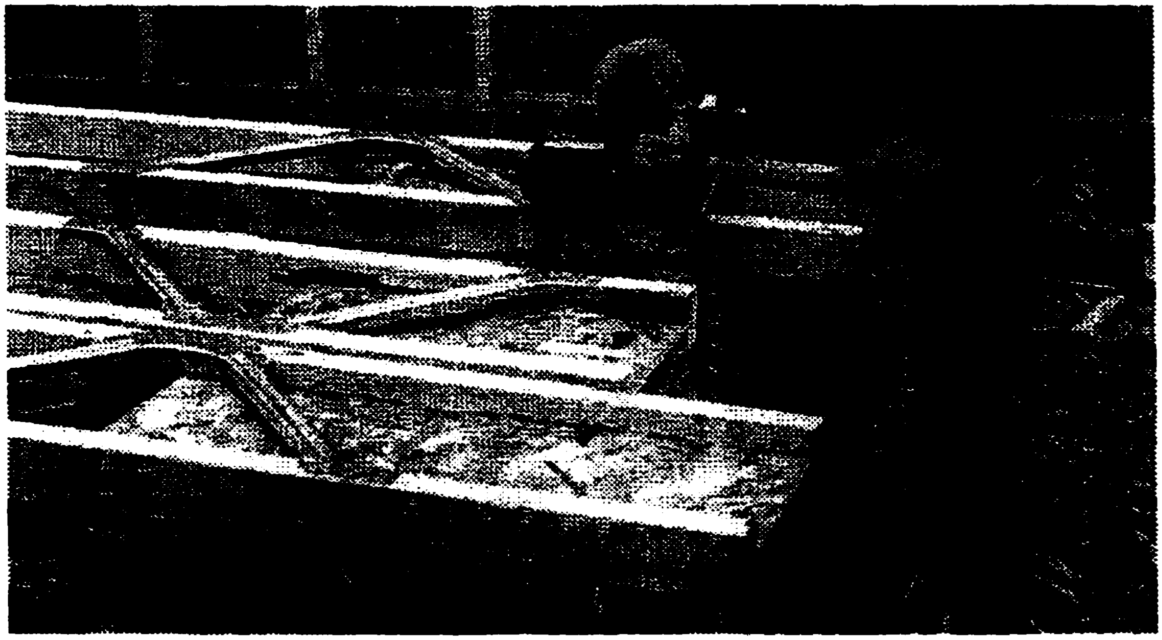


Figure 4.15: SpaceJoist with trimmable ends. For increased working flexibility on site, metal web space joists are available with ends that can be trimmed. This design feature allows the joist to be adjusted (i.e. cut to length) when the actual foundation wall is off, without disturbing its structural integrity. (Source: Lumber Specialties 1999)

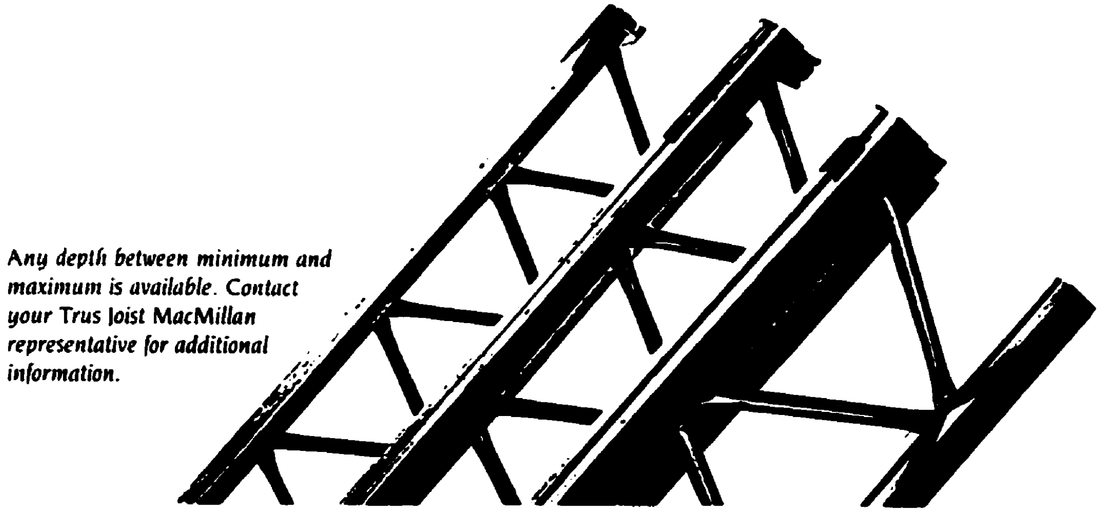
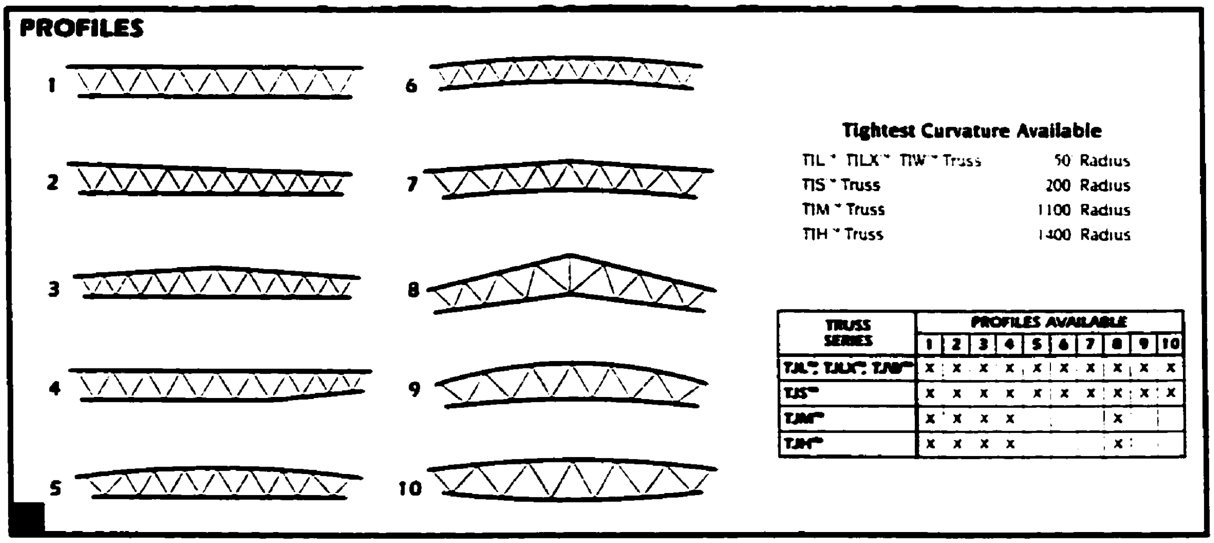


Figure 4.16: Metal open-web truss joist. The truss joist uses double Laminated Veneer Lumber (LVL) for flanges, and tubular steel for webs that are bolted to the top and bottom chords. (Source: Trus Joist MacMillan)



TRUSS SERIES	PROFILES AVAILABLE									
	1	2	3	4	5	6	7	8	9	10
TJL™, TJLX™, TJW™	X	X	X	X	X	X	X	X	X	X
TJS™	X	X	X	X	X	X	X	X	X	X
TJM™	X	X	X	X				X		
TJH™	X	X	X	X				X		

Figure 4.17: Different profiles of truss joist. The truss joists can also be used for roof trusses. (Source: Lumber Specialties 1999)

APPLICATION WITH NO BRACED END WALL

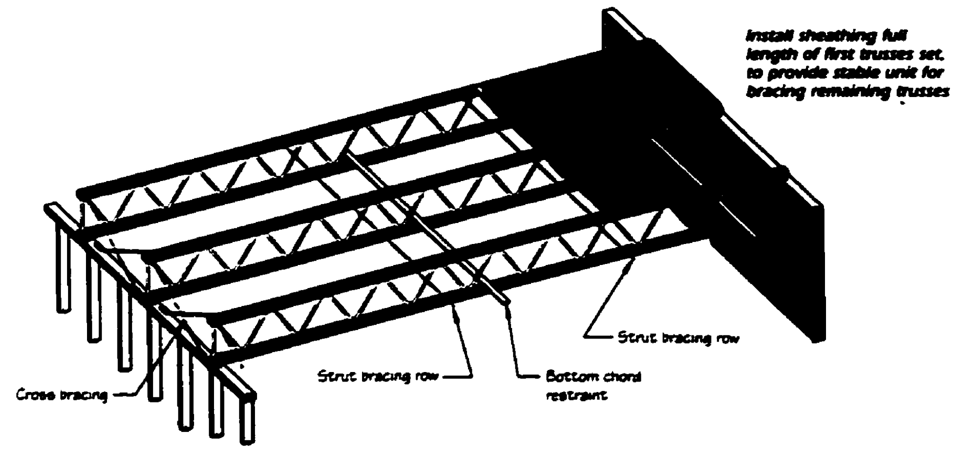


Figure 4.18: Installation detail of truss joist. The truss joist system is not suitable in the basement because the top flange is set on top of the supporting structure at both ends. As a result, it reduces floor to ceiling clearance. (Source: Trus Joist MacMillan)

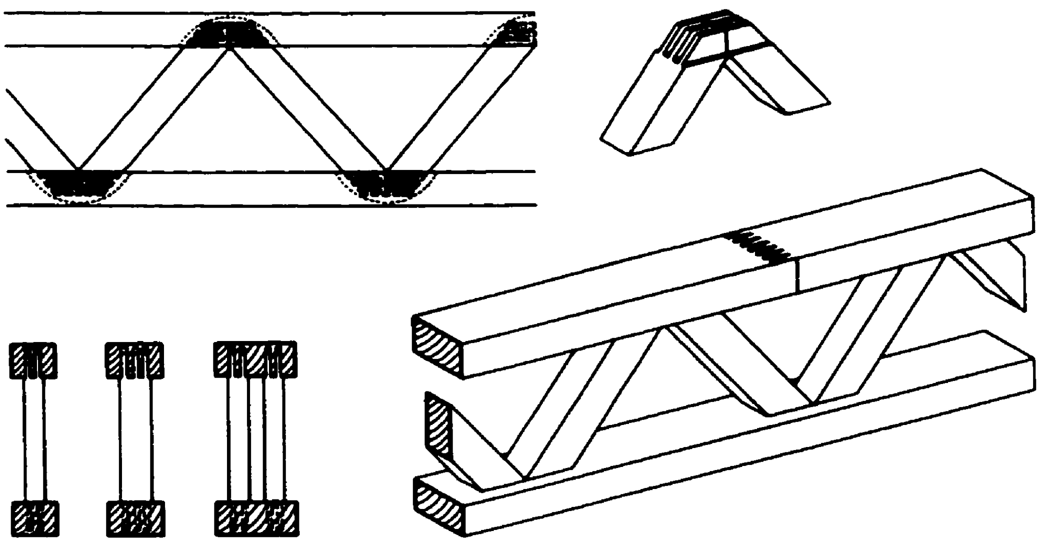


Figure 4.19: Open web wood joist. The Open Joist 2000 was derived from the glued wood truss beam that was developed in the 1950s for use in both light and heavy wood frame construction. The top and bottom flanges, as well as the bar web have incisions and are finger-jointed using special glue. (Source: Götz 1983)

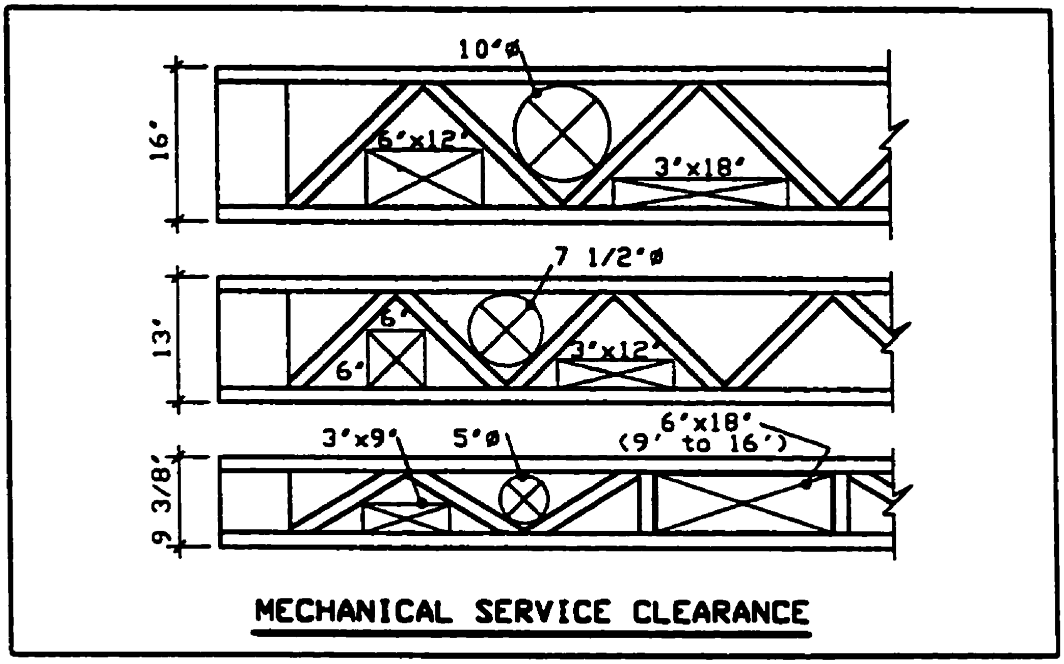


Figure 4.20: The open web design facilitates the installation of mechanical and electrical conduits. This design also prevents accident cutting of the structure by giving access to additional building services in future renovation. (Source: Open Joist 2000 1996)

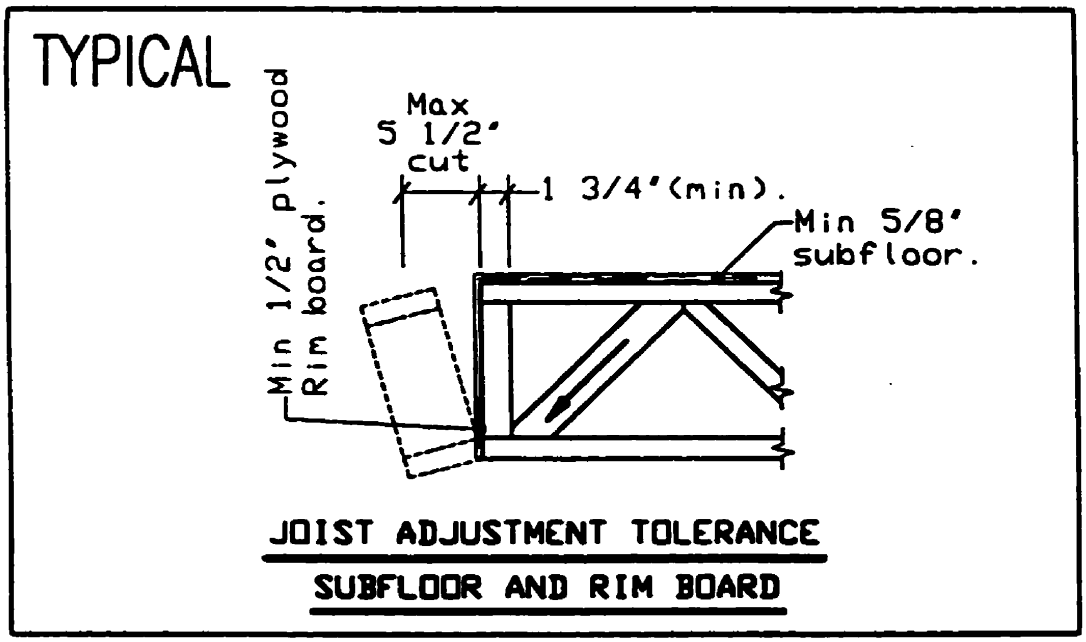


Figure 4.21: Job site length adjustments of 11 inches will minimize material waste and assure a security buffer for the builder. (Source: Ibid. 1996)

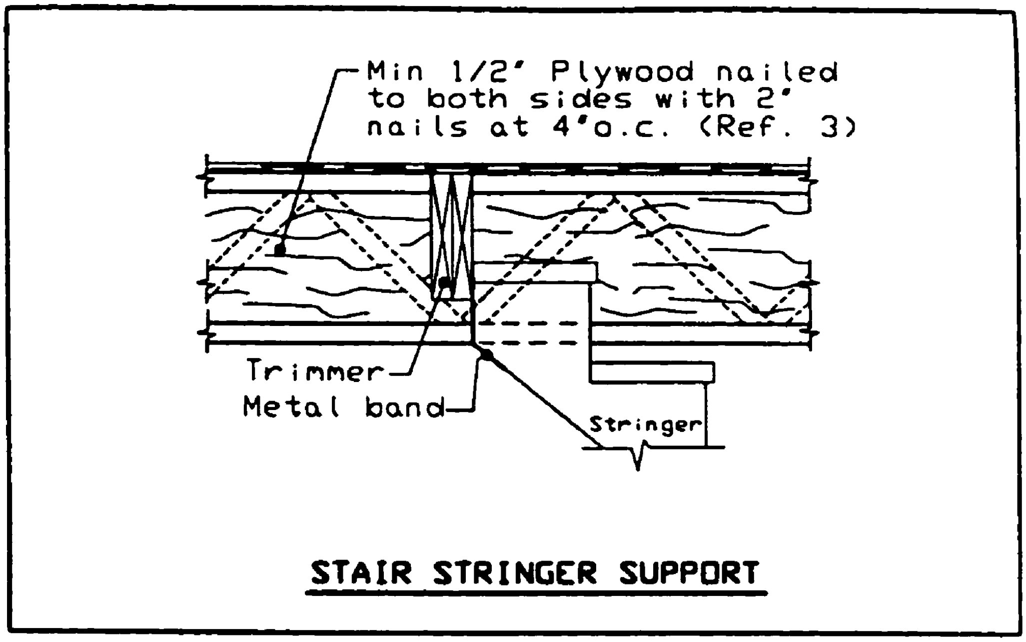


Figure 4.22: The web area of Open Joist 2000 can be reinforced with plywood on both sides for stair stringer support. (Source: Open Joist 2000 1996)

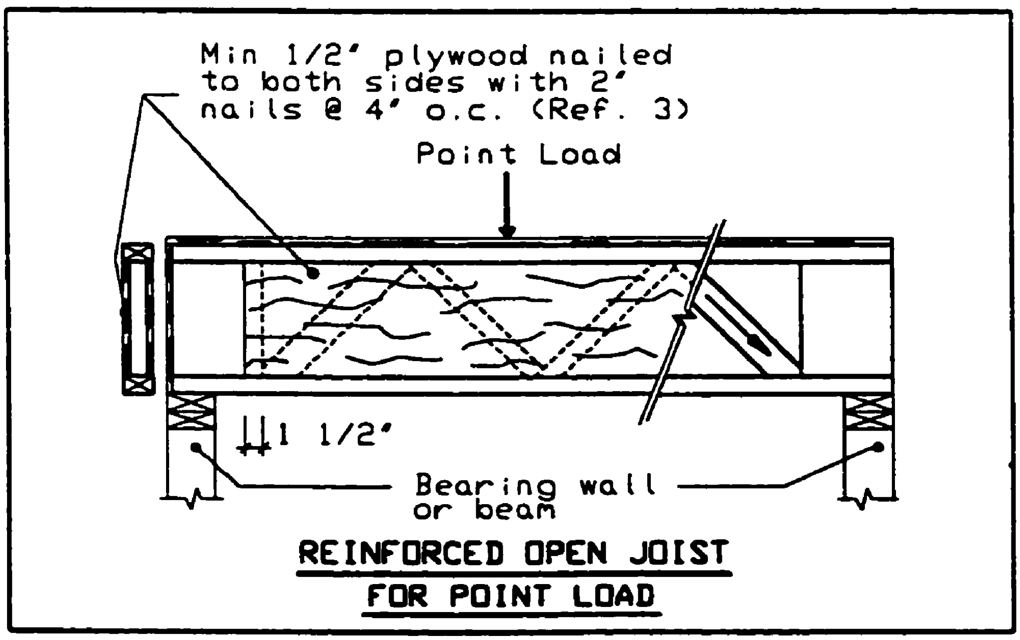


Figure 4.23: The Open Joist 2000 can also be reinforced for point load, and a cantilever that supports load-bearing wall. (Source: Ibid. 1996)

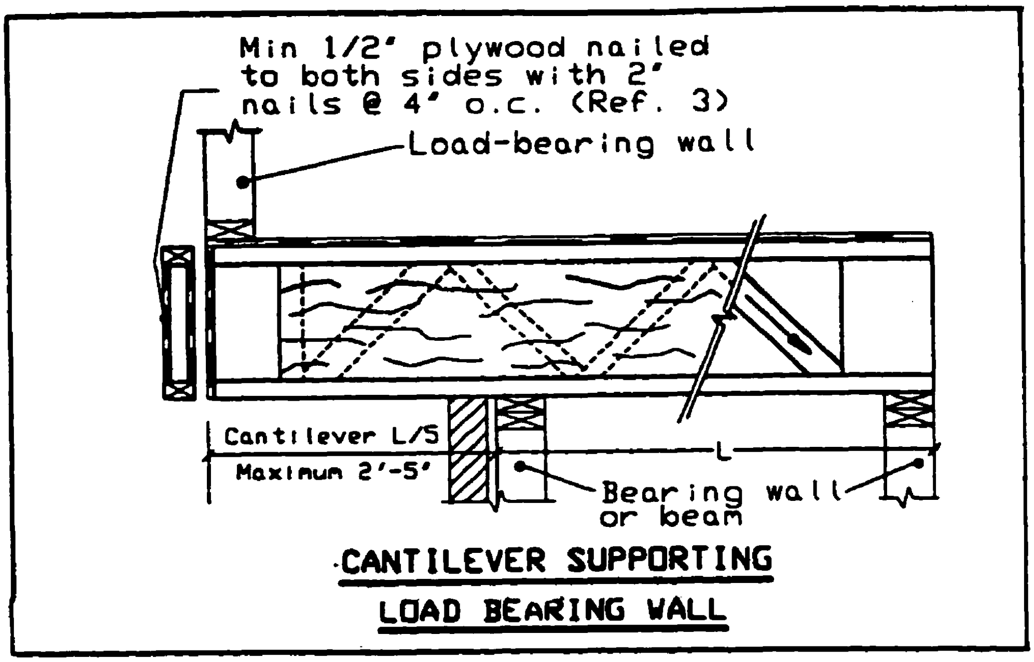


Figure 4.24: Reinforcement framing detail. (Source: Open Joist 2000 1996)

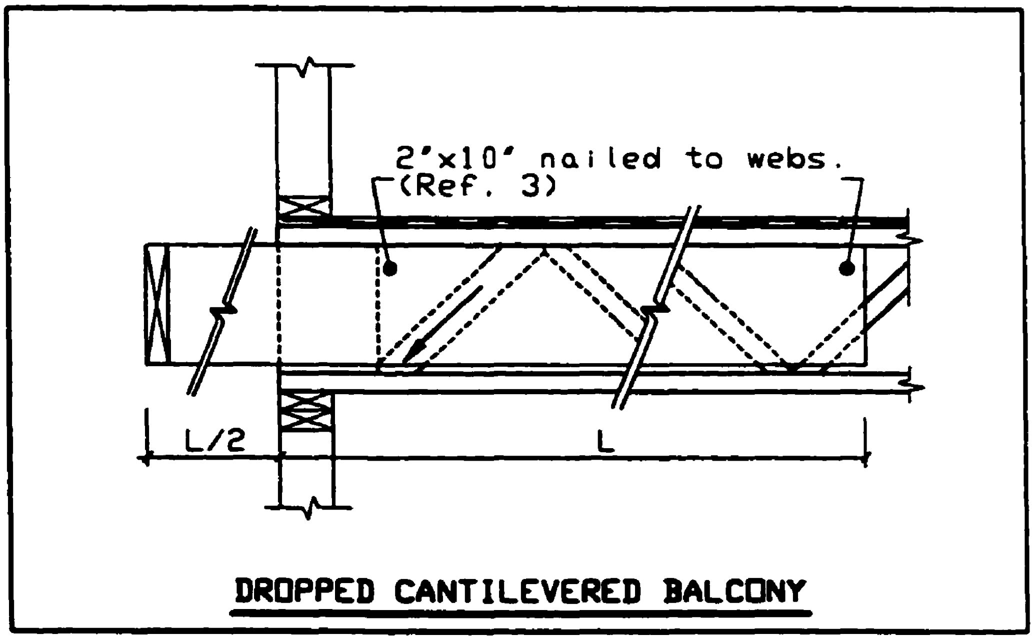


Figure 4.25: Reinforcement framing detail. (Source: Ibid. 1996)

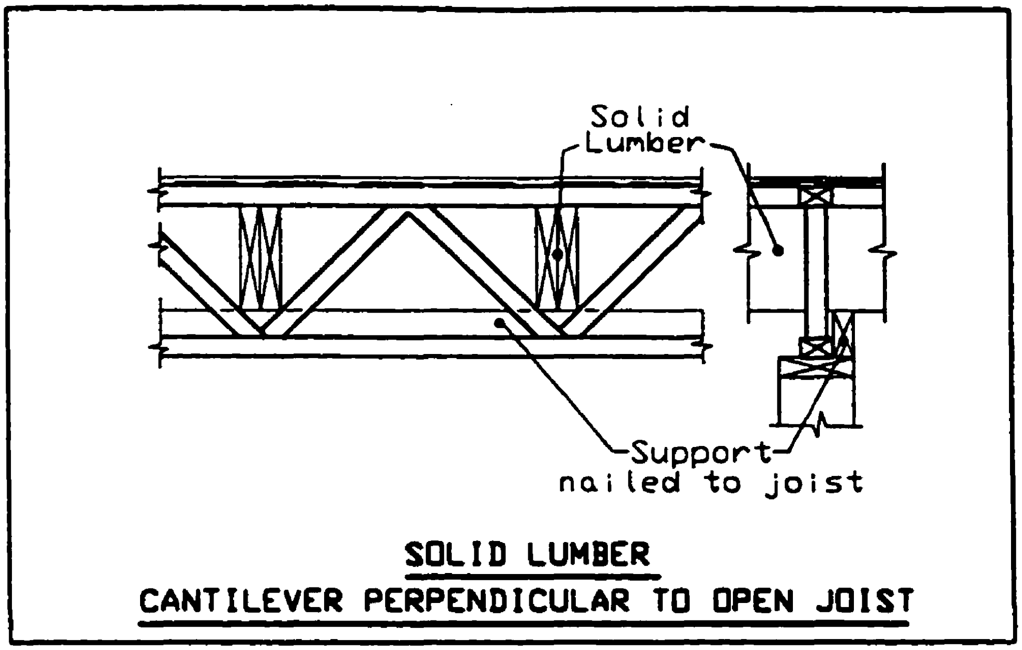


Figure 4.26: Reinforcement framing detail. (Source: Open Joist 2000 1996)

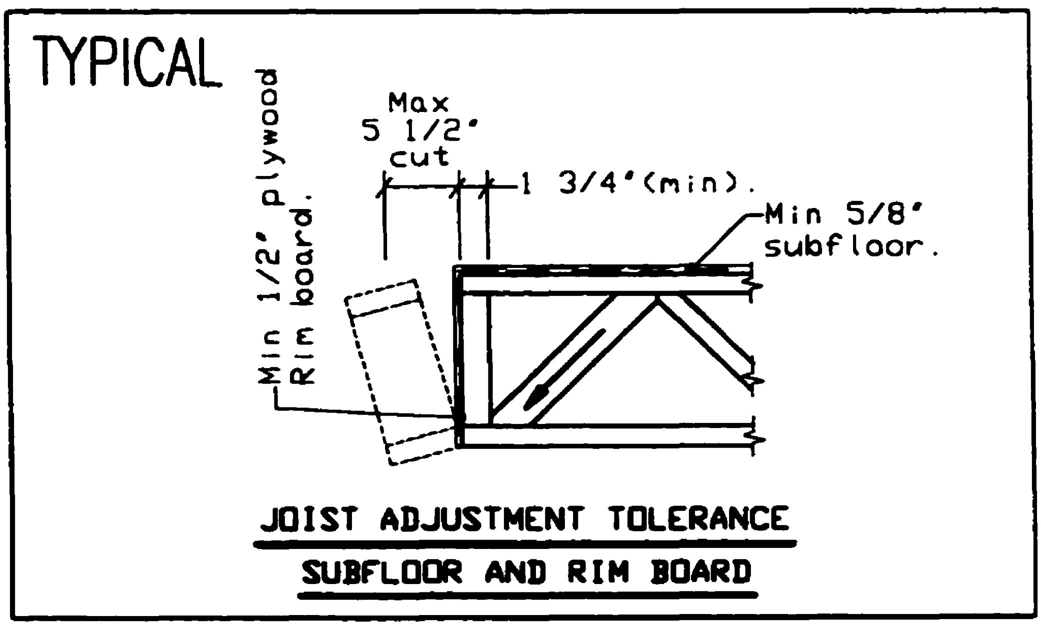


Figure 4.27: Reinforcement framing detail. Because the outermost web bars are designed going downward, Open Joist may not be used as rafters in roof framing. (Source: Ibid. 1996)

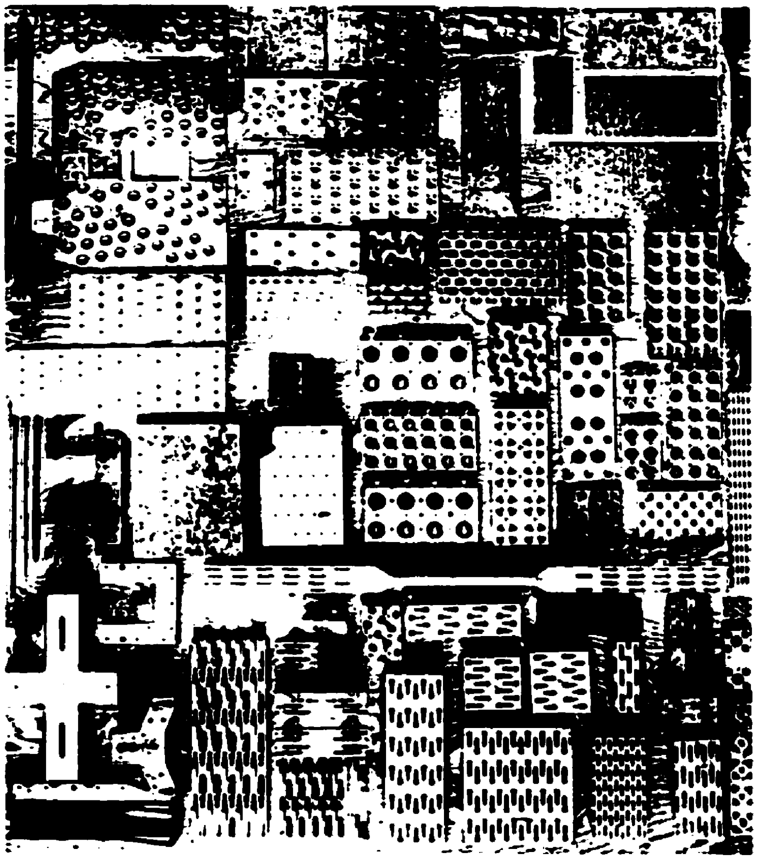


Figure 4.28: Steel plate connectors. (Source: Dietz 1991)

Figure 4.29: Steel plate connectors are gauge metals that have teeth, and were pressed into the wood with a hydraulic press, eliminating the need for nails. (Source: Canadian Wood Council 1999)

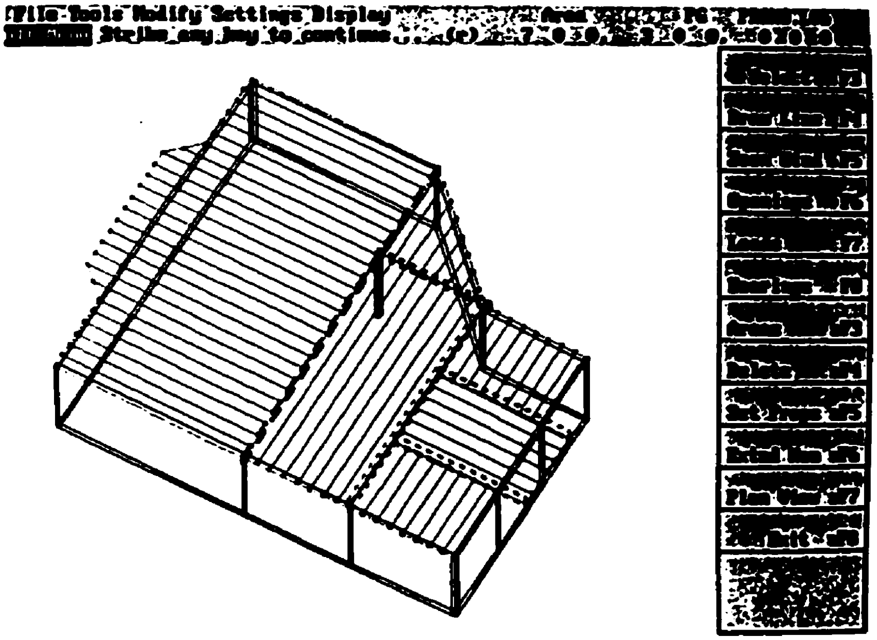


Figure 4.30: An example of a computerized layout for engineered lumber in a floor framing system. (Source: Bianchina 1997)

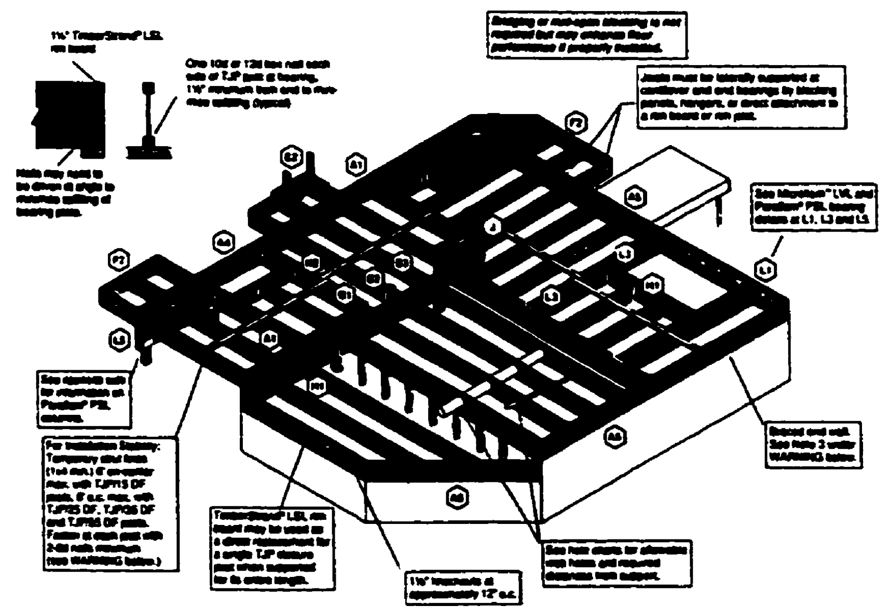
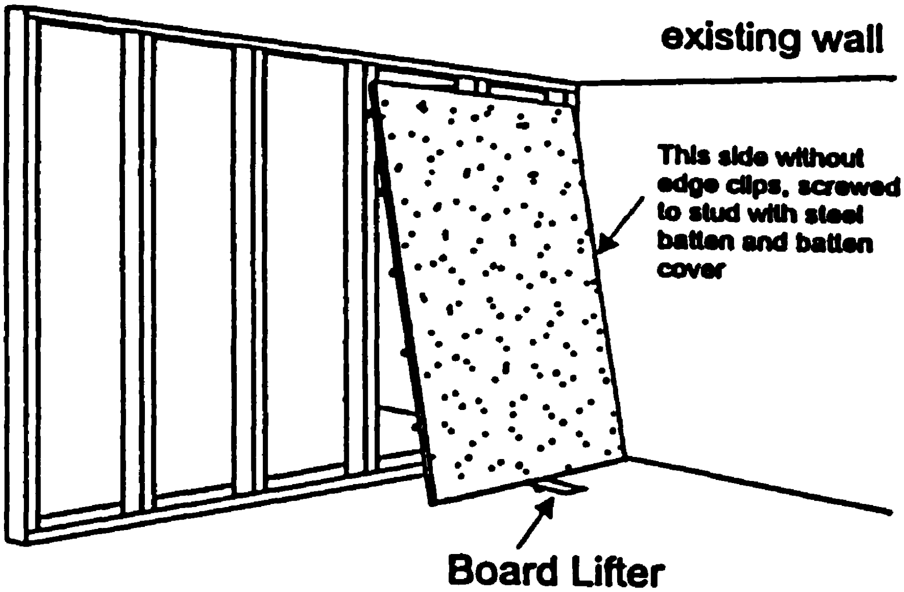


Figure 4.31: This sample layout of a typical floor framing system shows the various components in the system. Letters and numbers relate to printed examples of framing application, and the computer indicates which details are used at which locations. (Source: Ibid. 1997)

4.2 FLEXIBLE PARTITION



4.2 FLEXIBLE PARTITION

4.2.0 INTRODUCTION

The basic idea of user participation is to let occupants choose their interior arrangements. As well, the flexible building can respond more actively to changing life styles. In North America, the development of flexible partition systems was stimulated by constantly changing environments in the commercial sector. Although the flexible partitions are not yet commonly used in houses, in the future, the same principles and technology could be applied to reconfigure internal residential space in a fashion which is less time-consuming and less disruptive to household activities. Flexible partitions are available in numerous technical designs, standard sizes, constituent materials, textures, quality levels and degrees of flexibility. The modular design grants physical flexibility that can help occupants to make their preferred interior arrangements with less difficulty[14]. This section studies four representative flexible partitions; side by side data comparisons are presented as well.

4.2.1 BASICS

Rooms are designed according to their respective functions, and are separated by partitions to gain isolation. The purpose of a dividing wall is not only to define individual space both physically and visually, but also to protect against noise, and fire for at least a specified period of time. At the beginning of the 20th century, internal walls were often built of brick, or sometimes of stone or concrete material in masonry construction. Massive thick walls were acknowledged to have the advantages of strength, increased fire resistance and of deadening sound. The word "partition" was applied exclusively to wood structures, and it consisted of sheathing over a framework of wood posts known as

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[14] It includes mechanized flexibility, flexibility by addition and/or subtraction, locational and/or positional flexibility and sometimes, infrastructure flexibility (Dluhosch 1974).

"studding". Stud partitions are secured to floor-joists or floor-boards, and covered on both sides with laths and plaster (Sutcliffe 19??). Both masonry and stud partitions are permanent. They must be completely demolished before a new one can be built.

The gypsum board drywall partition system came out around 1910 in the United States as a direct substitute for plaster-and-lath wall construction. The shortage in skilled labour after the Second World War and high housing costs increased its demand. By 1970, drywall was used in 95 percent of all interior finishes (CMHC B 1989). Gypsum wallboards are light, fire-resistant, inexpensive, can be quickly installed, and save materials. In addition, they are manufactured in a variety of types for different uses, such as fire rated, foil backed, water-resistant and pre-finished (CMHC 1997). They are applied directly on the framing members by screws, and joints are covered with tape along with a premixed joint compound to give drywall a consistent finish. Gypsum board is flexible because it can be easily cut and patched to fit walls of any size and shape. Wires, pipes and other within-the-wall systems can be serviced if a renovator has the necessary skills to open up the wall. However, fixed gypsum board drywall is not demountable, and any modification or repair can not be done without a certain degree of demolition.

Inflexibility is not only limited to the partition's mobility, but also to its maintainability. This includes repairs, upgrades, as well as within-the-wall system repairs or upgrades that require cutting and opening a wall. As John Gregerson (1989) points out:

> Driving the need for office flexibility is the increased use of computer technology by the general business sector, according to Rick Widmann, director of commercial construction systems for Gold Bond Building Products. "A great deal of flexibility is required to reach the particular point of a wall, ceiling or floor system that requires wiring. Because they can be easily detached from a given point, prefinished or movable walls provide that flexibility."

This situation also applies to the residential domain. Concealing cables and wires within traditional drywall can pose problems given the increasing use of computers, entertainment systems and other data communication electronics in modern households. The masonry and lath-and-plaster partitions are not flexible for renovation because of their monolithic constructions. Neither are the gypsum/plaster boards in drywall partitions since they can not be easily detached from studs once finishing is done. However, low-costs and simple demolition/installation will compensate for this inflexibility in terms of future renovations. Certain manufacturers of flexible partitions modified their designs by making wires (electrical, telephone, cable, data, network) more accessible, thereby increasing their product's practicality. Others use demountable gypsum panels to gain access to the wiring, although this is less practical and time consuming when frequent modifications are required.

4.2.2 TYPES OF FLEXIBLE PARTITION

Syed Muhiuddin Yamin (1990) studied the adaptability of commercial flexible partitions to residences in North America in his research paper. According to him, there are three types of commercial flexible partitions. However, not all of them are suitable for residential applications:

I. **Mobile or Operable Partition System:** This type of prefabricated partition system generally has a sliding mechanism (trolley or slide) that allows wall panels to move along ceiling tracks. There are two kinds of mobile partitions: the sliding type and the folding type. Sliding type panels can be joined together to form a large wall by placing adjacent panels at the stacking end. The folding type partition is composed of a series of panels connected by hinges, which can be folded and stacked at the end. Both types are available in a wide range of finishes, and can be either manually or electrically operated. Mobile or operable partitions are generally used in spaces where a quick transformation is required (e.g., in restaurants, or in gymnasiums). Because instantaneous space transformation is not the main focus of this study, these partition systems are excluded from this research (Figure 4.33).

II. **Demountable Partition System:** The concept of this type of partition system is similar to the traditional drywall construction. It is usually composed of metal studs that are placed at specific intervals and prefinished wallboards that are installed parallel to each side of the metal studs. Ceiling or floor tracks hold studs in place, which are in turn fastened using screws. All parts are reusable and can be relocated easily and economically. Panels are available in a different variety of finishes, colors and fittings. The demountable partition system is commonly used in commercial spaces where short to medium term transformations of space are required (e.g., in office buildings). The demountable partition system tends to be non-progressive or point accessible by nature, so that individual panels can be removed and replaced without disturbing adjacent panels. However, as Gregerson (1988) noted, demountable partitions are less solid by nature and tend to rattle when doors are closed (Figure 4.33).

III. **Portable Partition System:** This type of partition system is generally composed of single prefabricated panels held in position by metal channels at floor and ceiling levels. The panels can be joined together by interlocking mechanisms without the need for studs. The portable partition is used extensively in offices, industrial and institutional buildings where frequent space alterations are required. The portable partition system is a more unitized system because it is more monolithic and solid. This system is simple but tends to be progressive. That is, removing one panel may require the adjacent panels be removed as well. As a result, some have suggested that this limits future flexibility for wire access (Gregerson 1988) (Figure 4.33).

4.2.3 PRODUCTS

4.2.3.1 DEMOUNTABLE WALL SYSTEM

The rising cost of renovations coupled with the need for flexible interior space has created a demand for an easily demountable wall system. One of the most popular products is the demountable partition made by Partition Components Incorporated. The company offers a prefabricated component kit that is ready to install once it is brought to the site. The main panels (that are available in many different colours, finishes and fittings) are easy to install due to the innovative gravity lock system. The gravity lock system not only simplifies the installation process, but also eliminates damage to wood floors or holes in carpets. Pre-punched holes in the studs allow for wiring to pass through these walls creating a very flexible system. A horizontal wiring chase that can be installed at the base of the wall system is also available.

1. PC350 GRAVITY LOCK SYSTEM

Partition Components Inc. (1995) offers a cost efficient system that is quick and easy to install without creating the mess of traditional wall systems. The flexible system can be changed at a moment's notice; therefore, the client gets "more product for their investment." The reusability of this system makes it environmentally friendly as well.

- BENEFITS/COSTS

The cost of installing a demountable wall is relatively equal to the cost of installing a fixed one. This is because labour costs are lower when the demountable system. The cost of dismantling and relocating a fixed wall, however, is much higher when compared to the demountable system's relocating cost. Installing a demountable wall takes considerably less time than installing a permanent wall. Therefore, faster tenant turnaround is expected as well as less down time when renovations are needed. Being a flexible partition system, the PC350 anticipates future modifications of mechanical, electrical or communications components. The more flexibility there is, the more the owner will save in maintenance costs. Rugged construction results in a product that is easy to maintain throughout its life, thus eliminating the need to repaint every few years. The Gravity Lock System allows the panels to be installed and disassembled faster than ever before. There is no need for any special tools such as nails, screws or other fastening devices; all that is required is to clip the panels in place once the wall studs are installed. The panels fit perfectly into the framing creating a monolithic wall.

Installation of the system also creates less waste, as there is no need for sanding, taping or painting. Individual panels can be removed and replaced (for access to wiring) without disturbing the rest of the wall. The system supports are one half and five eighths of an inch gypsum panels. There is also an unlimited amount of new vinyl, fabrics, and colours from which to choose. Installation of their demountable partition system onto an existing wall is also possible with wood or metal strapping. Door frame kits are also available (they are fitted for universal left and right swing).

The system also features a horizontal wiring chase that provides a simple and efficient means of organizing and accessing wiring. Additions and modifications can be made easily by simply removing a section of the base. This system, therefore, provides a continuous cavity that can accommodate standard electrical boxes and all the cables and wiring that are typical of today's interior environment. Wiring is completed more quickly and more easily since there is no need to feed lines through a series of knockouts in the studs (Figure 4.34). The PC350 Horizontal Wiring Chase also has the following advantages:

- a continuous barrier which separates electrical, television, telephone wiring

- it accommodates vertical wiring drops at any time
- it accepts standard electrical boxes
- it has a large cable capacity
- it accommodates future expansion due to easy add-ons
- it replaces the conventional floor track and installs just as easily
- the wires are completely accessible
- it accepts standard electrical boxes
- a cable support is available
- it allows for easy interface with other framing elements (e.g. walls and columns)
- panels are reusable since receptacles penetrate the trim, not the panels
- it reduces time spent installing wiring and, therefore, reduces labour costs

- DETAILS

The PC350 Gravity Lock System offers a unique demountable wall system that uses prefabricated, pre-finished vinyl covered gypsum panels (that are offered in a variety of standard or custom colours and textures), or square edge unfinished panels that are ready for painting on site. It supports ½ inch and, 5/8 inch gypsum panels. This system uses a gravity lock clip that uses the panel's own weight to rigidly anchor it in place. A patented 2 ½ inch stud is designed to accommodate an 11 inch cross channel. The cross channels are easy to assemble as they "twist fit" into place and require no additional fasteners (Figure 4.35). Horizontal wiring is accommodated by a series of pre-punched knockouts found in the studs. An exclusive feature of the PC350 system is the 11-inch stud extension. Each box-stud is delivered to the job ¾ of an inch short of the floor to ceiling height. Installation is simple as the extension fits into the bottom of the stud and extends to the finished floor. This system has a number of advantages. Field cutting of the stud is eliminated; also, the studs can be removed and relocated elsewhere without regard to high or low spots on the floor.

- INSTALLATION

Householders without special expertise can install the PC350 demountable partition system. The installation procedure is described as follow:

I. Install ceiling and floor tracks as per layout plan.

II. Position studs vertically into floor and ceiling tracks as required. Install three rows of horizontal clip retainer channels (in accordance with manufacturer's instructions).

III. After installing the panel clips, the panels are hung on the framework (ensuring to seat all of the panel clips on the cross channels). Electrical or communication cables can be held in the cavity. Insulation can also be put in the cavity if required (Yamin 1990).

IV. Install ceiling trims, base molding, corner and other trims.

2. PS350 WALL SYSTEM

- DETAILS

Another type of demountable partition is made by Partition Systems Limited. Although the design is very similar to the PC350 Gravity Lock Wall System from Partition Components Incorporated, the PS350 Wall System is different in terms of gypsum panel connection. The system also consists of steel framing with individual pre-finished vinyl-faced gypsum panels. To achieve a monolithic appearance, each panel is attached to the framing with a support clip and carrying bracket system (no screws and tools are required). According to Partition Systems Limited (1999), with 1 being the most economical on a Cost Scale of 1 to 10, this wall system would rank a 3.5. In addition, the relocation wastage factor is less than 10% (Figure 4.36).

Gypsum panels can also be supported by the Edge Clip instead of the carrying bracket. The Edge Clip Easy Wall is a monolithic steel stud framed system that is site assembled from components. It is similar in appearance to that of the PS350 series. It differs only in that this system is progressive by design. Being a progressive system, dismantling and assembly must start at a wall end. This may restrain flexibility when wiring modifications are frequently performed. The Edge Clip Wall System ranks 3.4 on the Cost Scale, and the relocation wastage would also be less than 10% (Partition Systems Ltd. 1995).

- INSTALLATION

After the ceiling runner and the base track are installed, the Edge Clips are inserted along the edges of the gypsum board. Because the construction is similar to standard drywall, screws and a screwdriver are needed. Clips are not inserted along the side of the panel where they are against an existing wall; therefore, this edge is screwed to the stud with a steel batten and PVC batten cover. Afterwards, top and bottom of gypsum board are screwed to tracks. Consecutive panels are clipped on both sides. The protruding tabs are fitted between the stud and previous panel. The clips on the free edge are screwed to the stud. This procedure continues until the wall comes to another wall (T-intersection). Then the free edge is screwed in place with a steel batten and cover (Figure 4.37). When two walls intersect at a corner (90 degree L-corner), three corner details are available: Round, Square and Surface corners (Figure 4.38). However, an arbitrary-angle corner kit is not available. It must be custom-built with the necessary skill and tools; therefore, this restricts user-controlled flexibility. Visually, expect to see panel joints after all walls are erected. Because there is no joint cover, the aesthetic appearance may depend greatly on the build quality. It may take some practice for a first time installer to set it up right.

Like many other demountable wall systems, the PS350 series offers door and window kits. There are two door kits: standard height and full height. Before door/window frames are installed, steel stud rough framing must be completed. To an opening in a wall, requires pre-planning as door and window constructions are not flexible. After gypsum panels are erected, aluminum door/window frames can be installed. The frames (header and jambs) are cut on-site to fit the size of the opening, then screwed onto rough frames. The rest of the components are assembled in a fashion very similar to that of standard door/window installation. Because the kits are independent, they can be quickly detached and reused. It is possible that door/window kits may fit other companies' demountable wall systems. This adaptability will increase flexibility in the selection of a wall system (brand, type, model, etc.), particularly when one system becomes obsolete or is no longer produced.

3. ENVIROWALL PARTITION SYSTEM

A. PROGRESSIVE, BATTENLESS

In addition to cost effectiveness, ease of installation and flexibility are emphasized by most manufacturers. The demountable partition system made by Envirowall Partition System Limited (1999) focuses also on "Environmental Friendliness" (i.e. materials that are recyclable). The Envirowall is a non-unitized system, offered in both progressive and non-progressive types. Both consist of pre-finished gypsum panels that are erected with steel stud framing. The only difference between the two is the way in which panels are connected to studs. In the progressive Envirowall, the Enviroclips are inserted into the edges of gypsum board. Clips are screwed onto the stud on one side of the panel, and on the other side clips are locked in place by fitting them in-between the next panel and the stud (Figure 4.39). The design and installation method of the Enviroclip, is almost identical to the previously described PS350 Wall's Edge Clip System. However, the Enviroclip is adjustable because of its groove opening design. The Edge Clip, on the other hand, is non-adjustable and, therefore, demands careful attention during installation.

B. NON PROGRESSIVE, WITH BATTEN

Assembly of the non-progressive Envirowall resembles that of its progressive counterpart. Although there are no clips to be installed, it requires steel battens and covers. The pre-finished gypsum boards are screwed onto studs with steel batten. The batten is a device that holds a batten cover down (in PVC or aluminum); together they help to hide screws. This is similar to traditional drywall construction. But panels are removable because screws are not covered with a joint compound. As a result, batten covers will appear at every panel joint, which may not be visually acceptable to some householders. Another potential problem is that certain furniture, paintings, cabinets, etc. can not be placed close to the surface of the wall. Nevertheless, it has higher flexibility than the progressive system because panels can be detached independently. This system is also more monolithic as each panel is screwed securely onto studs; therefore, it will not shake and rattle as much as the PC350 Gravity Lock System. However, some people may think it is still not very flexible because it takes time to uninstall the progressive Envirowall, and even longer without the use of power tools.

4.2.3.2 MOVABLE WALL

Some demountable partition manufacturers also produce movable wall systems. For instance, the Palliser Series and the World Wall Series from Partition System Limited (1995) provide different alternatives to interior flexibility. Movable wall systems are normally highly engineered and factory finished to reduce the time and technical skill required to install them. Structurally, they are unitized, meaning that gypsum boards may not be detachable. The panel modules can be attached progressively or non-progressively depending on their designs, but non-progressive systems have a higher degree of flexibility as individual panels can be interchanged without disturbing adjacent units. To let users build their own interior arrangements with minimum technical input, there are numerous connectors to attach between wall modules, doors and windows. There is also a wide range of colours and textures from which to choose, and, if needed, finishes can be customized at the factory to meet a user's demands.

1. THE PALLISER SERIES

The Palliser Wall series is a highly engineered and luxurious partition system. It is factory finished and shipped to the project site ready for assembly. Wall modules are all interchangeable. Each unit is fitted with a pair of spring-loaded upper guide pins (at ceiling) to enhance installation positioning. In addition, there is a set of leveling feet on each module to permit quick adjustments to any floor irregularities. To reduce the installation time, panel modules are attached to one another by way of simplistic panel connectors. The wall system is designed to accept either standard or full height doors and can be fitted with either butt or pivot type hardware (Figure 4.40). Doors can also be built to accept conventional hardware or modern pull handles with roller latches. Wall finish selection is from an almost unlimited collection of vinyl colors and textures. Door and window frames are powder-coat finished in the manufacturer's standard colors. Custom powder-coating is also available in an endless range of colors. The frames can also be factory finished to match the selected wall vinyl. According to the manufacturer, the relocation wastage factor is zero, and the Cost Scale rating is 7.8.

Although unitized, movable wall systems have higher mobility than demountable wall systems, and they usually do not have built-in service ducts or cavities for wires and cables. They need to work with external cabling systems to achieve their high level of mobility and still remain practical. Certain movable wall manufacturers tried to compensate for this inflexibility by incorporating a vertical electrical/data chase in panel joints (Figure 4.41), others by producing a wall module that is pre-wired according to a user's specifications. Together with a perimeter cabling raceway and accessible ceiling panel, they will form a flexible wiring system. Outlets, switches, fixtures, appliances and electronics can virtually be placed anywhere within the house. Details on this aspect of flexibility will be studied in a subsequent section on electrical services.

2. THE WORLD WALL SERIES

Unlike the demountable wall, the unitized movable wall can not be trimmed to a desired width and shape on site. This contributes to the system's inflexibility, Because the modular panel lacks physical flexibility, pre-planning is necessary. When modules do not add up to the total dimensions, special size panels must be ordered from the factory. This inflexibility can limit space design or increase costs. The Partition System's World Wall Series (2000) was designed to improve the unitized movable wall's on-site flexibility. It is lightweight, economical, and easy to install. The Wall System is factory fabricated to desired project widths and heights. Door, door-hardware, panel and window modules are all pre-finished. Panel connector trims can be finished to match the selected panel color(s). The end panel (whether at a wall start, "T" or "L" intersection) may be cut down in width. However, door panels can not be cut. The system requires installing ceiling and floor tracks prior to the installation of panels. Both tracks are fastened to the ceiling or floor by screws. The Wall Start Adapter should be used when installing a panel from an existing wall. Panels should be cut 1 inch to 1-1/2 inches less than the floor to ceiling height when installing. Two panels are joined without screws or tools using a special panel connector (which is also a plastic joint cover). If electrical service is needed, a plastic vertical wiring chase (an enlarged panel connector) is used instead of a regular panel connector. Finally, the base and vertical trims are installed (Figure 4.42).

3. V-WALL

The V-Wall system by Herman Miller Inc. (1989) is similar to The Palliser Series by Partition Systems Ltd. It too has a mechanical device for the adjustment of a panel's position. The system consists of unitized gypsum board panels (with or without vinyl or fabric surface finishes), and a series of aluminum extrusions[15] for attaching those panels to the fixed building construction (Figure 4.43). It also includes aluminum framing components, a snap-on-grid, rigid vinyl base and trim, aluminum door frames, and aluminum glazing frame members. These subassemblies provide for the inclusion of doors and glazing areas of various heights. Wall components are interchangeable for a total reusability of all full, uncut modular units. Apart from the aforementioned flexibility, which is common in most demountable or movable wall systems, the V-Wall's Action Office Wall Hanger Strip/Connectors design addresses the issue of storage flexibility. There is a metal hanger installed at each panel joint to receive or support hang-on furniture components. Cabinet, shelf table modules and other wall-hung fixtures can be installed at regular intervals with an array of such hangers; in addition, their heights are adjustable (Figure 4.44).

4.2.4 FUTURE TREND

It is not difficult to find similarities among the above products. This means that some components may be interchanged and, therefore, offer more flexibility. In the author's opinion, commercial flexible partition systems should be standardized for residential use. This is because no modification work should exceed an occupant's abilities when the goal is user flexibility. Demountable wall systems can easily be standardized since their principles are nearly the same. Unitized movable wall systems

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[15] These include track components such as Ceiling Runner and Floor Runner; modular and compound intersections; concealed connectors; modular intersections; concealed connectors; glazing components; door frames; Action Office accessories; and fixed trim components.

can be standardized if a universal panel module connector is invented. Also, attention should be focused on increasing the durability of these systems for home use. Most flexible partitions do not resist moisture well. Moreover, their "tightness" (fire and sound rating) is often compromised due to their increased mobility. Therefore, in the future, special bathroom and kitchen kits should be developed. Fire safety and sound isolation should be improved as well.

Many residents of experimental sheet-metal frame homes report that they find these houses noisy. Some report that plumbing noises are particularly bothersome, the floors squeak, and odd noises occur with temperature changes. The reason is that sheet metal reverberates sound. Moreover, tests conducted by the National Research Council in Ottawa discovered that in a fire, a sheet metal framed wall will lose its drywall covering faster than a wood framed wall, because the attachment between the drywall and the steel fails as heat builds up. If wood studs are used in place of steel studs, the noise and fire safety problems may be corrected.

4.2.5 CONCLUSION

Although most flexible partitions are designed for commercial use, their designs seem applicable in residential construction. However, because of their appearances (especially the joint between panel modules), and their lack of sturdiness, some people may not accept them as a substitute for tradition drywall. Despite wall systems being movable and demountable, their flexibility is still limited by other building components. For example, their intended level of flexibility will not be attained when wiring is not properly managed. More specifically, without the cooperative use of other flexible building systems in residential construction, such as the Drop-Ceiling or Accessible-Floor, some flexible partitions will not be as flexible as they should be. Another issue that emerges is that when the flexible wall is displaced, elements, which define a room (flooring, wall covering and fixtures), should be displaced as well. So far there is no demountable floor for residential use. The question then becomes whether the entire flooring should be uniform, or whether it should be rebuilt where necessary. The first choice will limit variety, while the second is a more sophisticated alternative over which the users themselves may not have control. The same idea applies also to wall/ceiling finishes and fixtures. This illustrates why making adaptable space is so complicated. The house interior will not become flexible simply by introducing flexible partitions. If the house is not under constant change in interior arrangement, then it may not cost more renovate using traditional fixed drywall, than it would to use demountable or movable wall systems. The author believes that the opposite is also true: if it is just as expensive and troublesome to renovate an interior using flexible partitions, people will be unwilling to make constant changes[16]. In the following sections, building components that can enhance the flexibility of traditional drywall or flexible partitions will be examined.

[16] Assuming that uniform flooring is not used in residential construction.

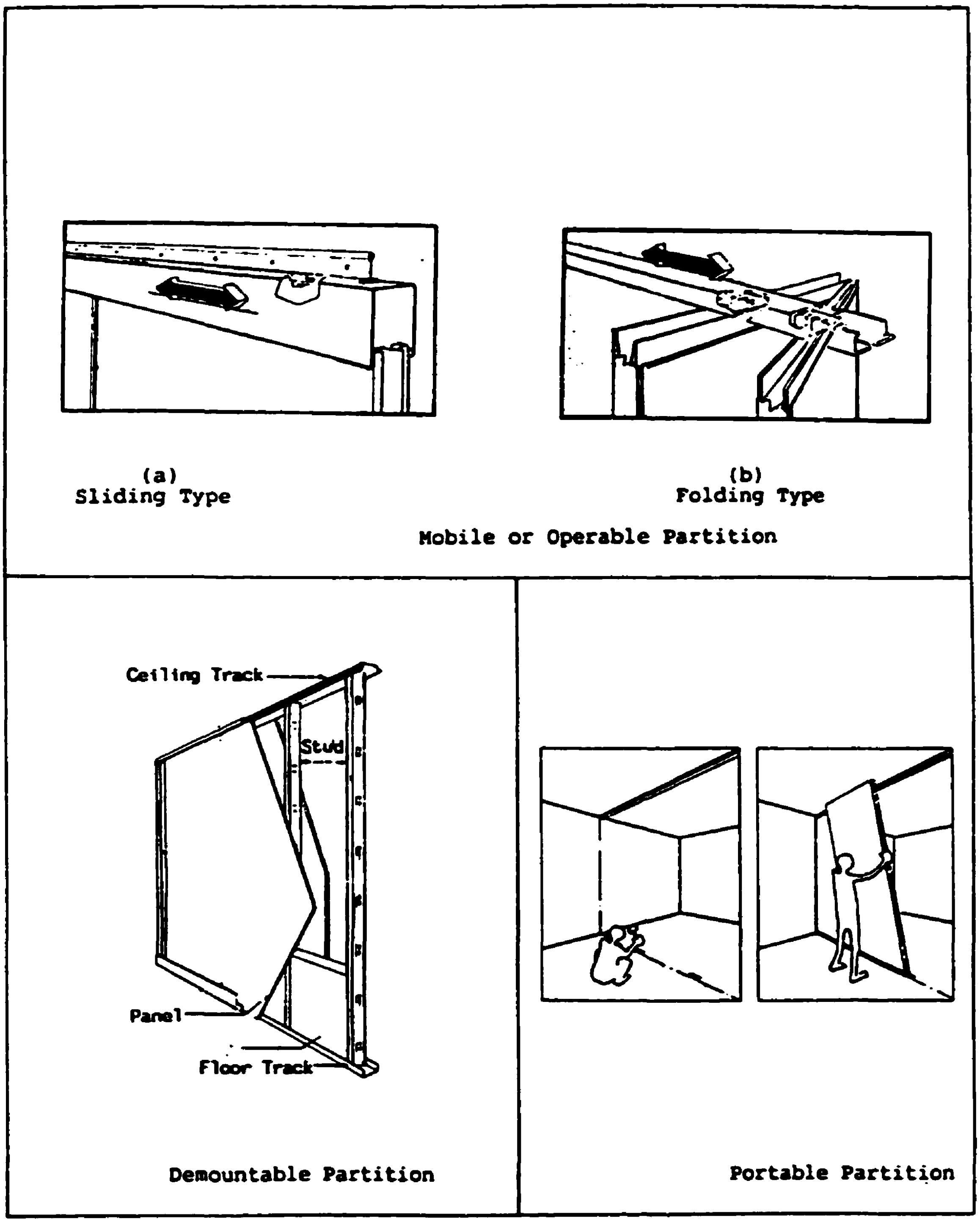


Figure 4.33: Three types of flexible partition. (Source: Yamin 1990)

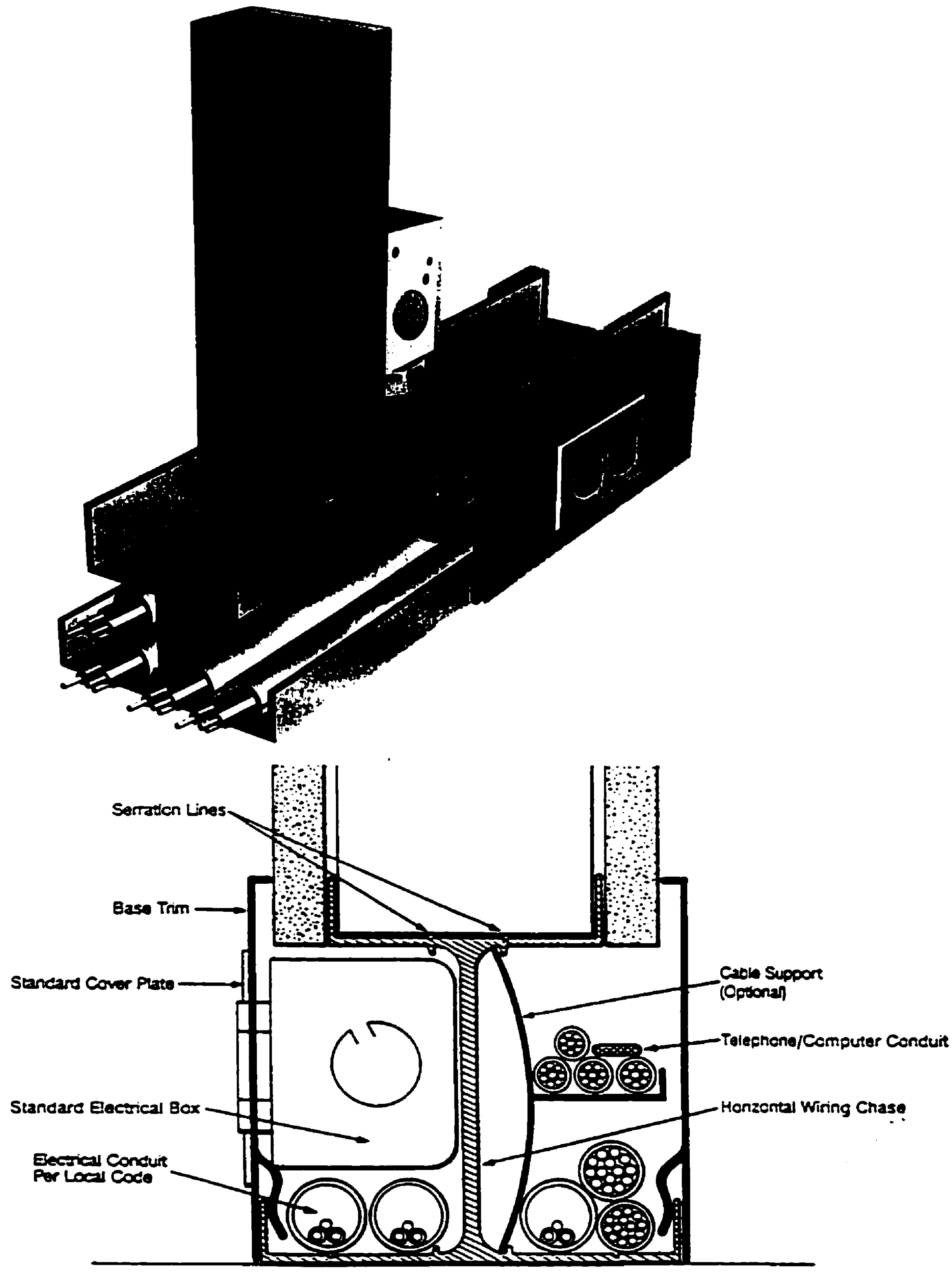


Figure 4.34: The system provides a continuous cavity that can accommodate standard electrical boxes and all the cables and wiring that are typical of today's interior environment. (Source: Partition Components Incorporated 1999)

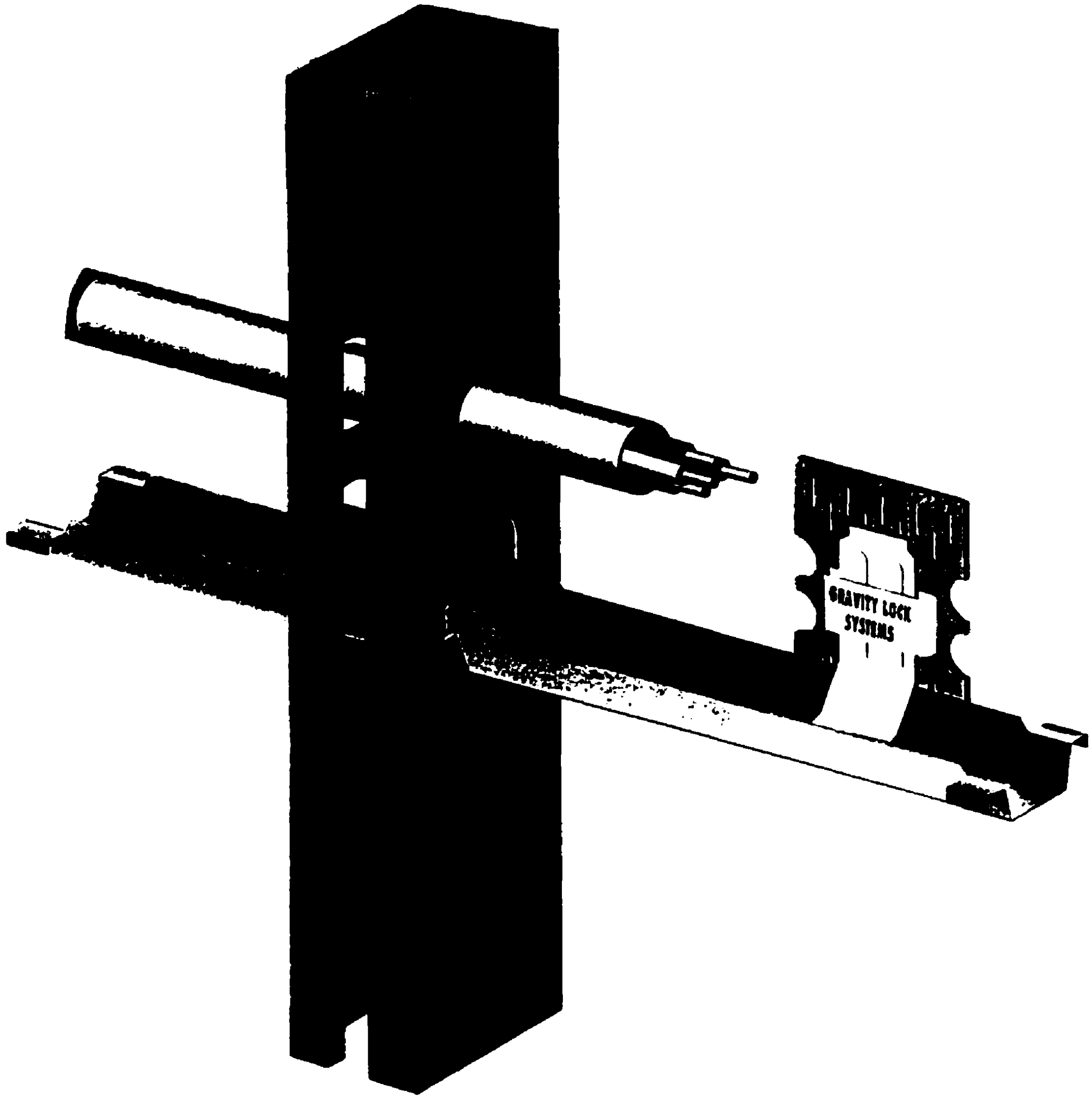


Figure 4.35: The PC350 Gravity Lock System uses a gravity lock clip that utilizes the panel's own weight to rigidly anchor in place. A patented 2 ½ inch stud is designed to accommodate an 11 inch cross channel. The cross channels are easy to assemble as they "twist fit" into place and require no additional fasteners. Horizontal wiring is accommodated by a series of pre-punched knockouts found in the studs. (Source: Partition Components Incorporated 1999)

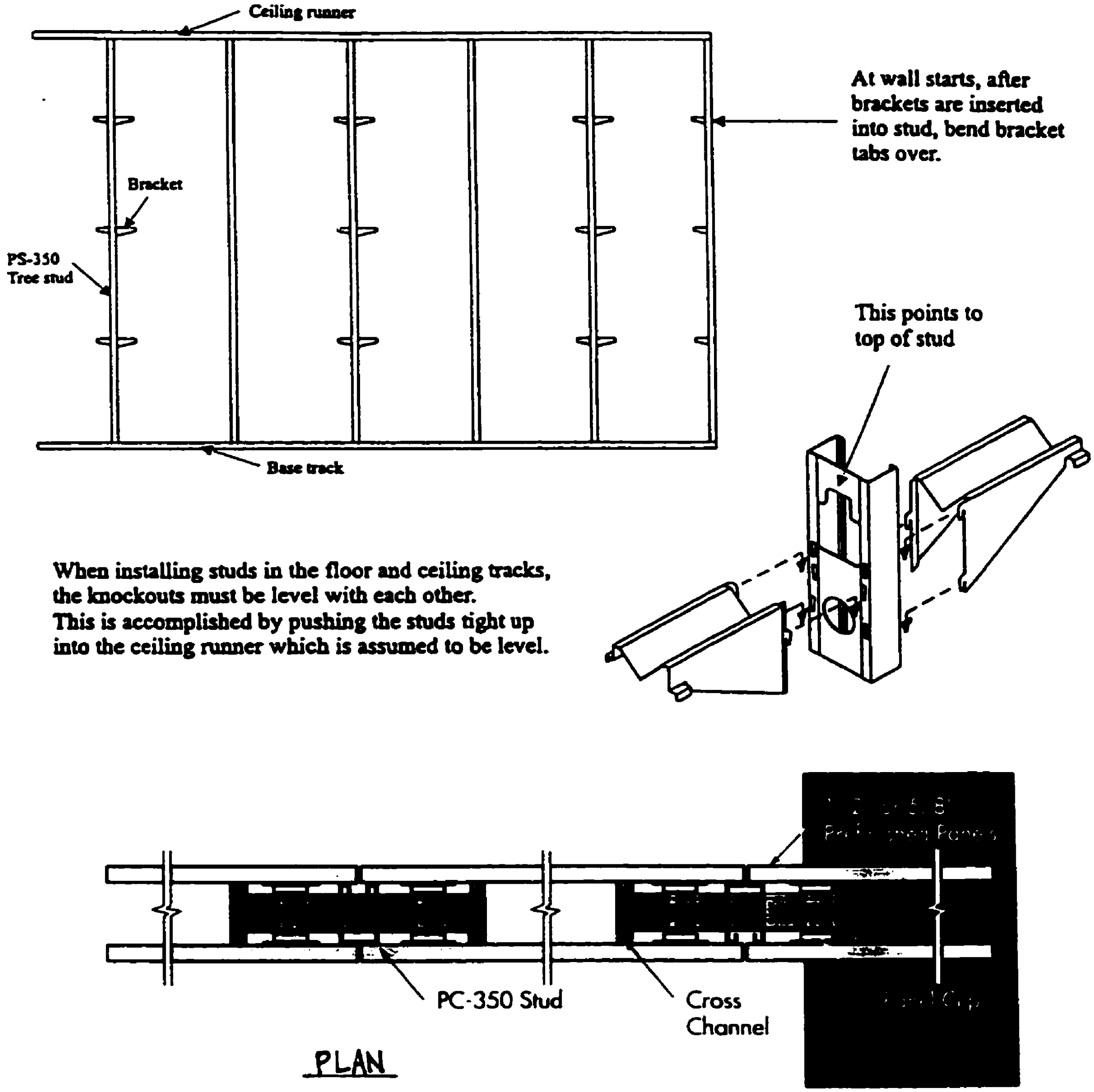
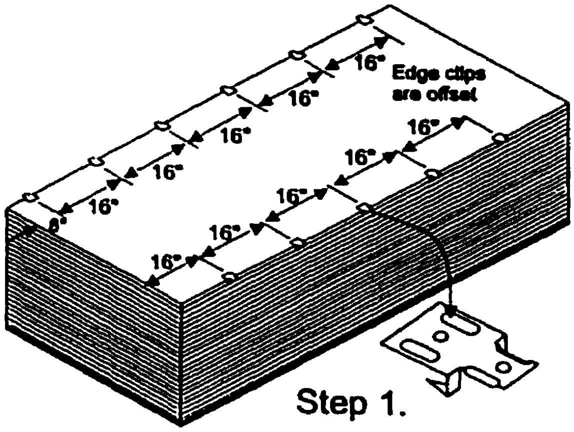
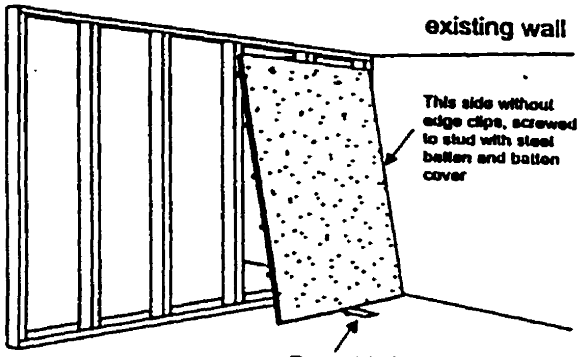


Figure 4.36: The PS350 Wall System. Each panel is attached to the framing with a support clip and carrying bracket system. (Source: Partition Systems Ltd. 2000)

EDGE CLIP - Installation Instructions





Step 1.

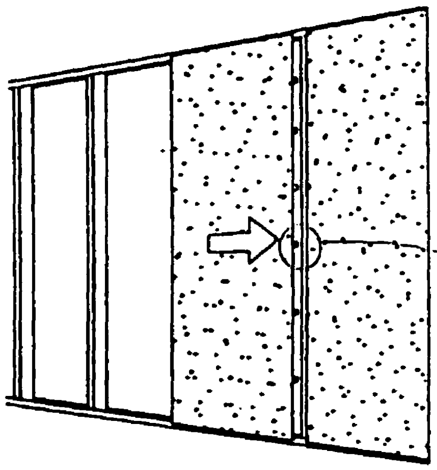
Cut the sheet to slightly less than the floor to ceiling height.
Install edge clips along the edges of the panel 16" O.C..
Offset the spacing as shown.

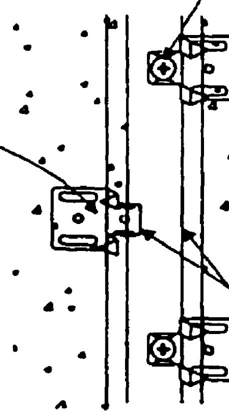
Step 2.

Panels against an existing wall are not cliped on the side against the wall. This edge is screwed to the stud with a steel batten and PVC batten cover.

Step 3.

Consecutive panels are cliped on both sides. The protruding tabs are fit between the stud and previous panel as shown. The clips on the free edge are screwed to the stud.



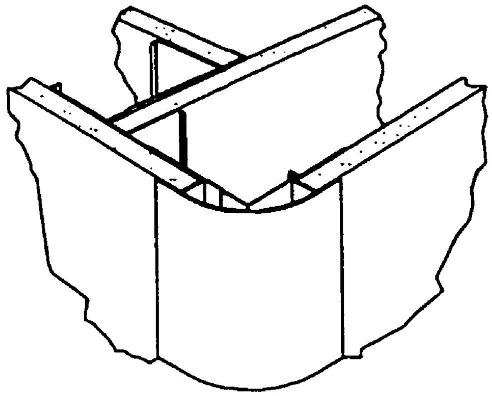


Step 4.

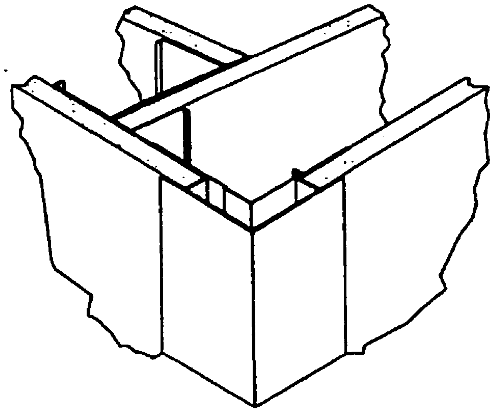
When the wall comes to another wall.
The free edge is not cliped and again screwed in place with a steel batten and cover.

Note: For increased sound control install PS-350 sound attenuation blanket between the studs after the board is installed on one side of the wall.

Figure 4.37: The PS350 Edge Clip System. Gypsum panels can also be supported by the Edge Clip instead of the carrying bracket. This system is progressive by design, dismantling and assembly must start at a wall end. (Source: Partition Systems Ltd. 2000)

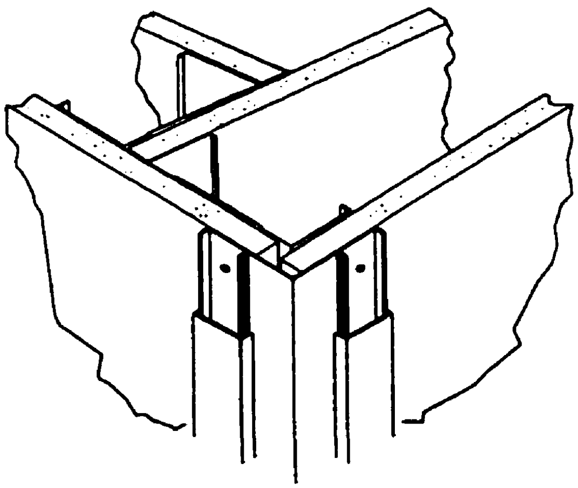


Round corner



Square corner

After installing the studs, the corner pieces are put in. Screw corner pieces into corner studs.



Surface corner

Note:
Surface mounted corners are installed AFTER wall panels are put in.

Figure 4.38: Corner details of the PS350 Edge Clip System. Plastic corner pieces or batten are needed. (Source: Partition Systems Ltd. 2000)

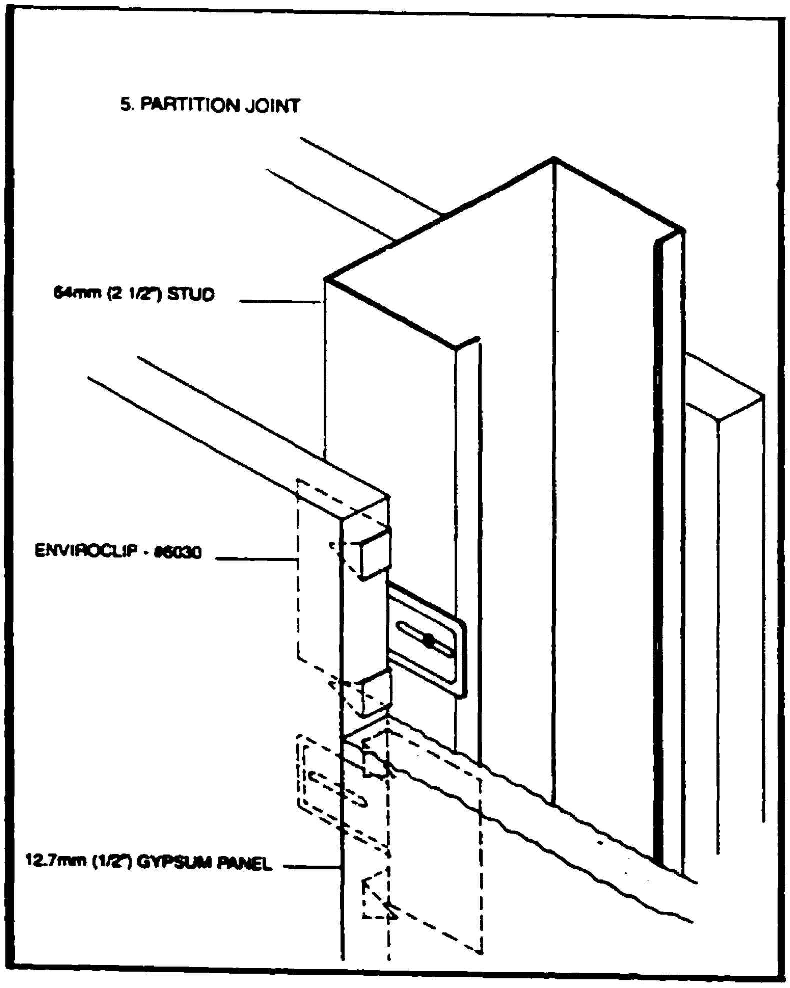


Figure 4.39: Enviroclip installation instruction. The Enviroclips are inserted into the edges of gypsum board. Clips are screwed onto the stud on one side of the panel, and on the other side clips are locked in place by fitting them in-between the next panel and the stud. (Source: Partition Systems Ltd. 2000)

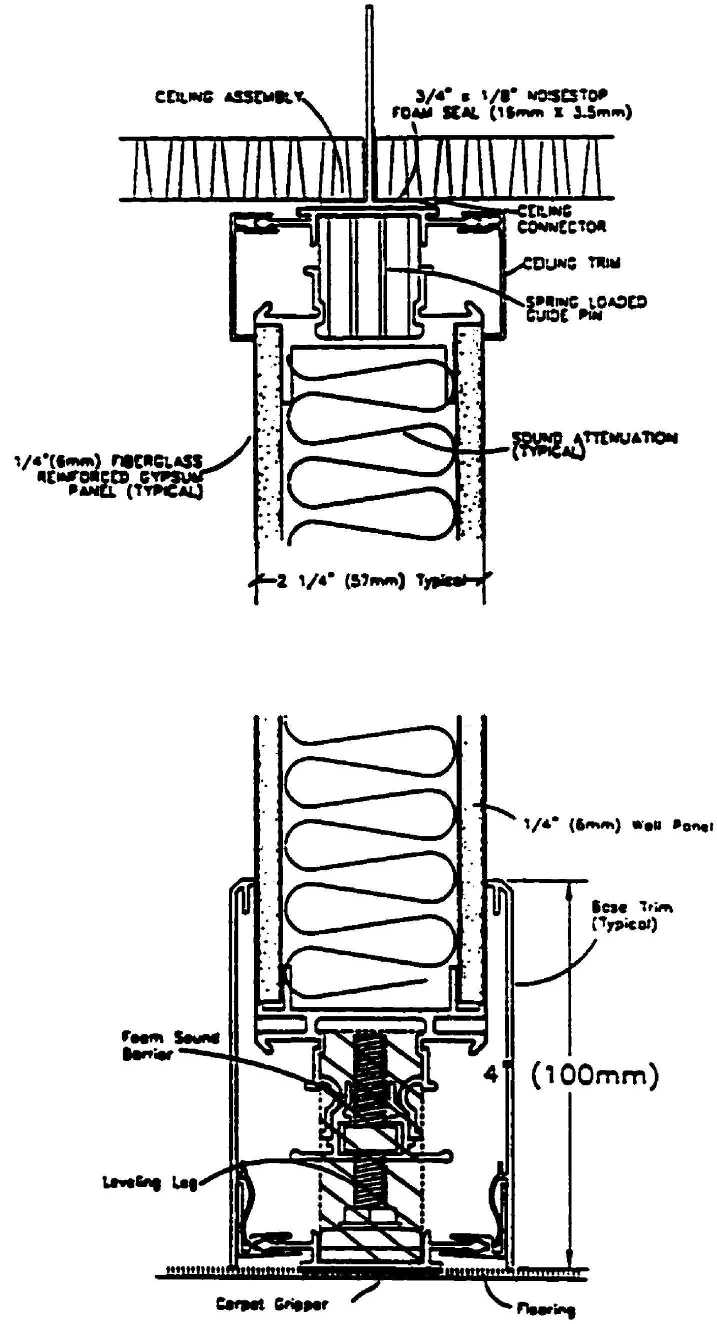


Figure 4.40: Details of the Palliser Wall Series. Each wall module is fitted with a pair of spring-loaded upper guide pins (at ceiling) to enhance installation. In addition, there is a set of leveling feet on each module to permit quick adjustments to any floor irregularities. (Source: Partition Systems Ltd. 2000)

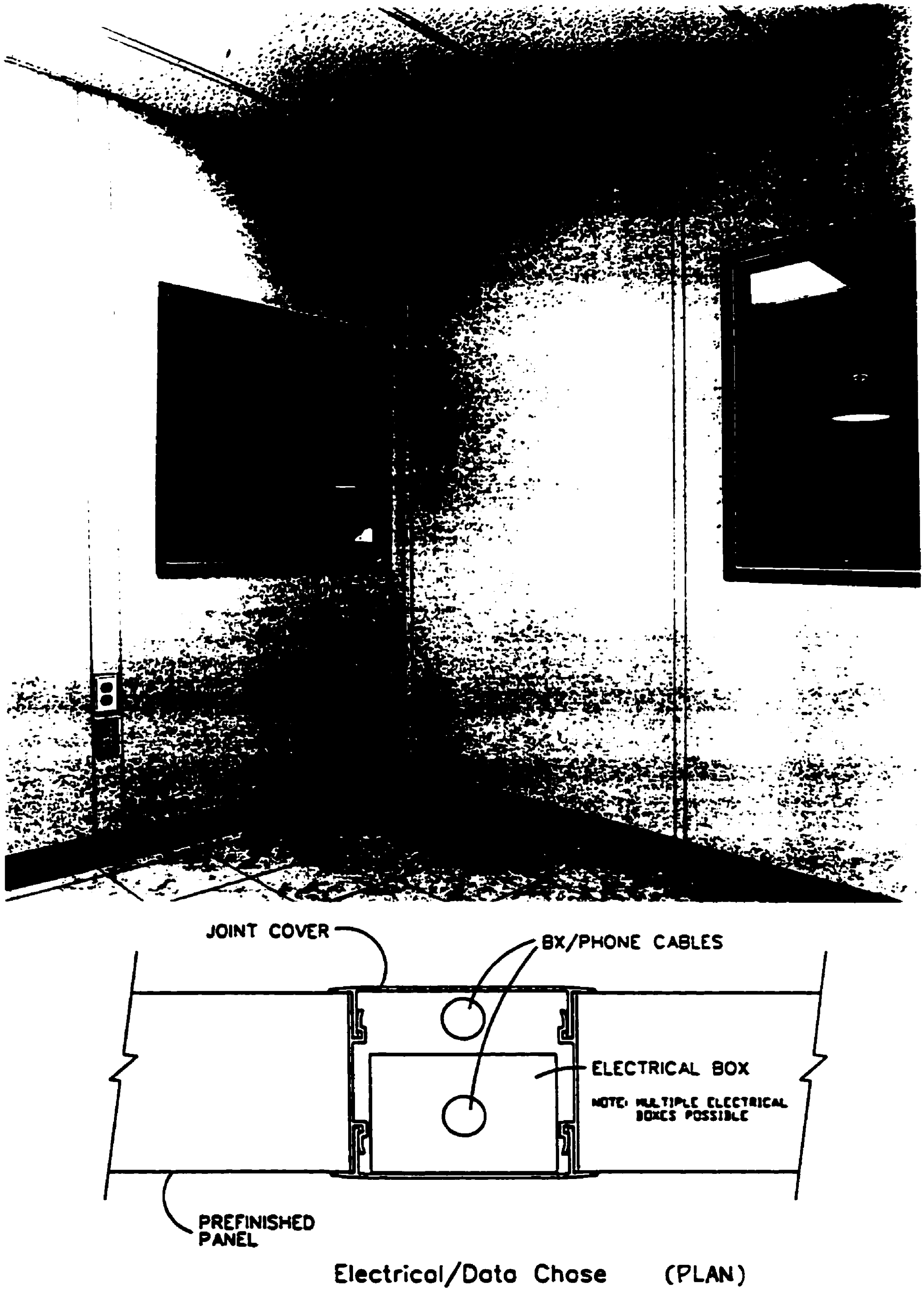


Figure 4.41: Vertical electrical/data chase. A plastic vertical wiring chase can be used instead of a regular panel connector. (Source: Partition Systems Ltd. 2000)

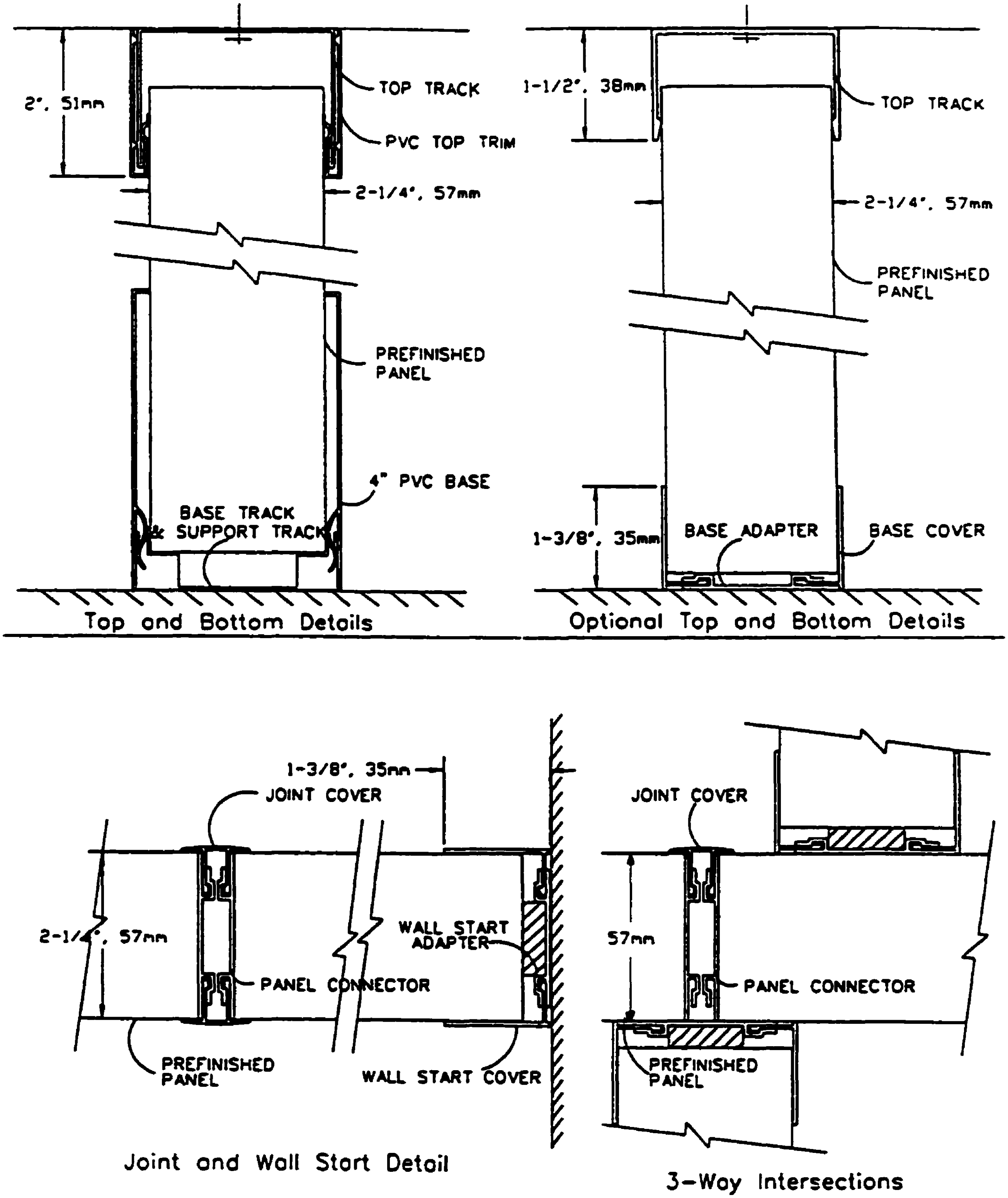


Figure 4.42: Details of the Partition System's World Wall Series. (Source: Partition Systems Ltd. 2000)

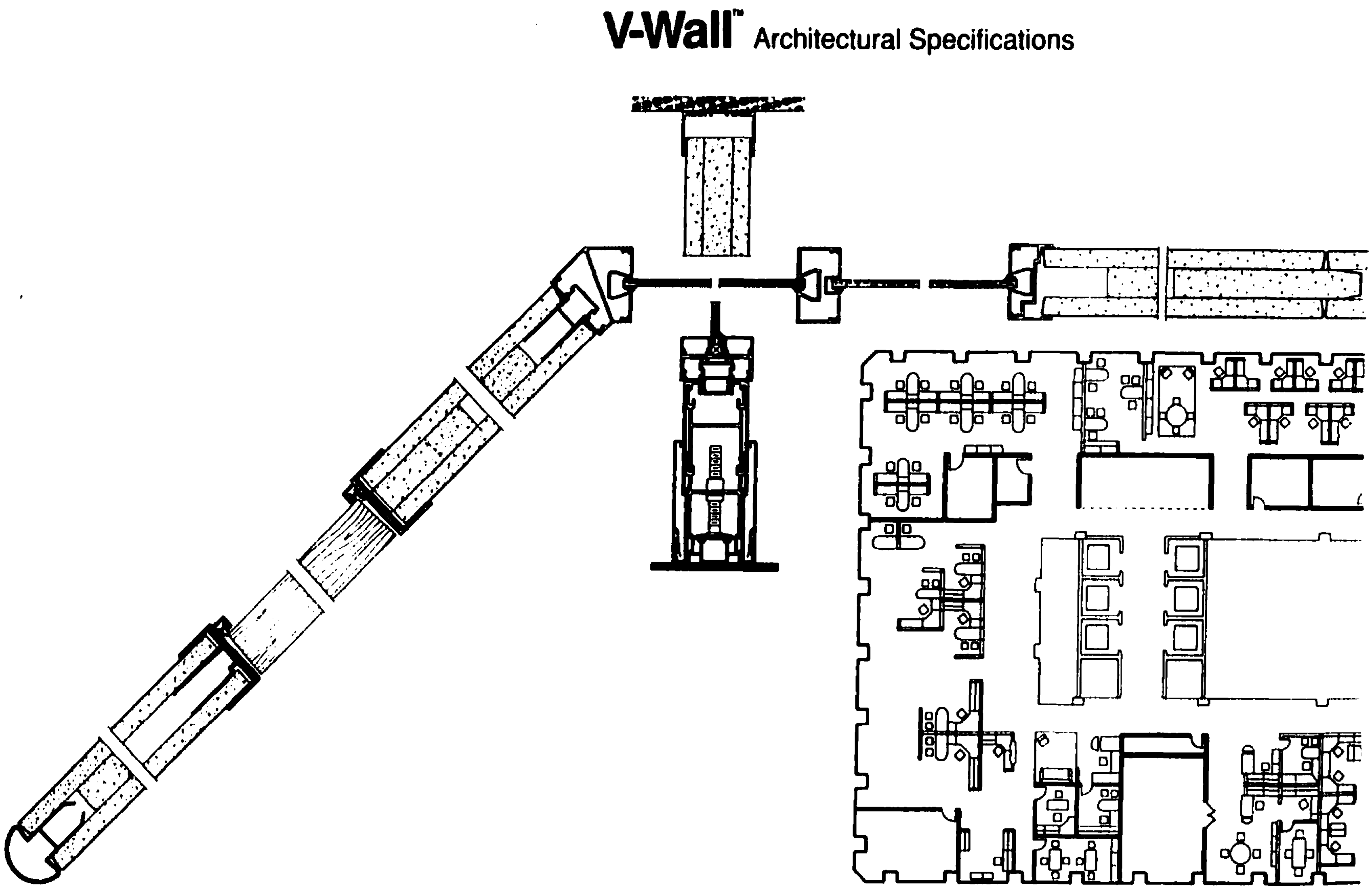


Figure 4.43: Details of the V-wall system. It consists of unitized gypsum board panels, and a series of aluminum extrusions for connection. Wall components are interchangeable for a total reusability of all full, uncut modular units. (Source: Herman Miller Inc. 1989)

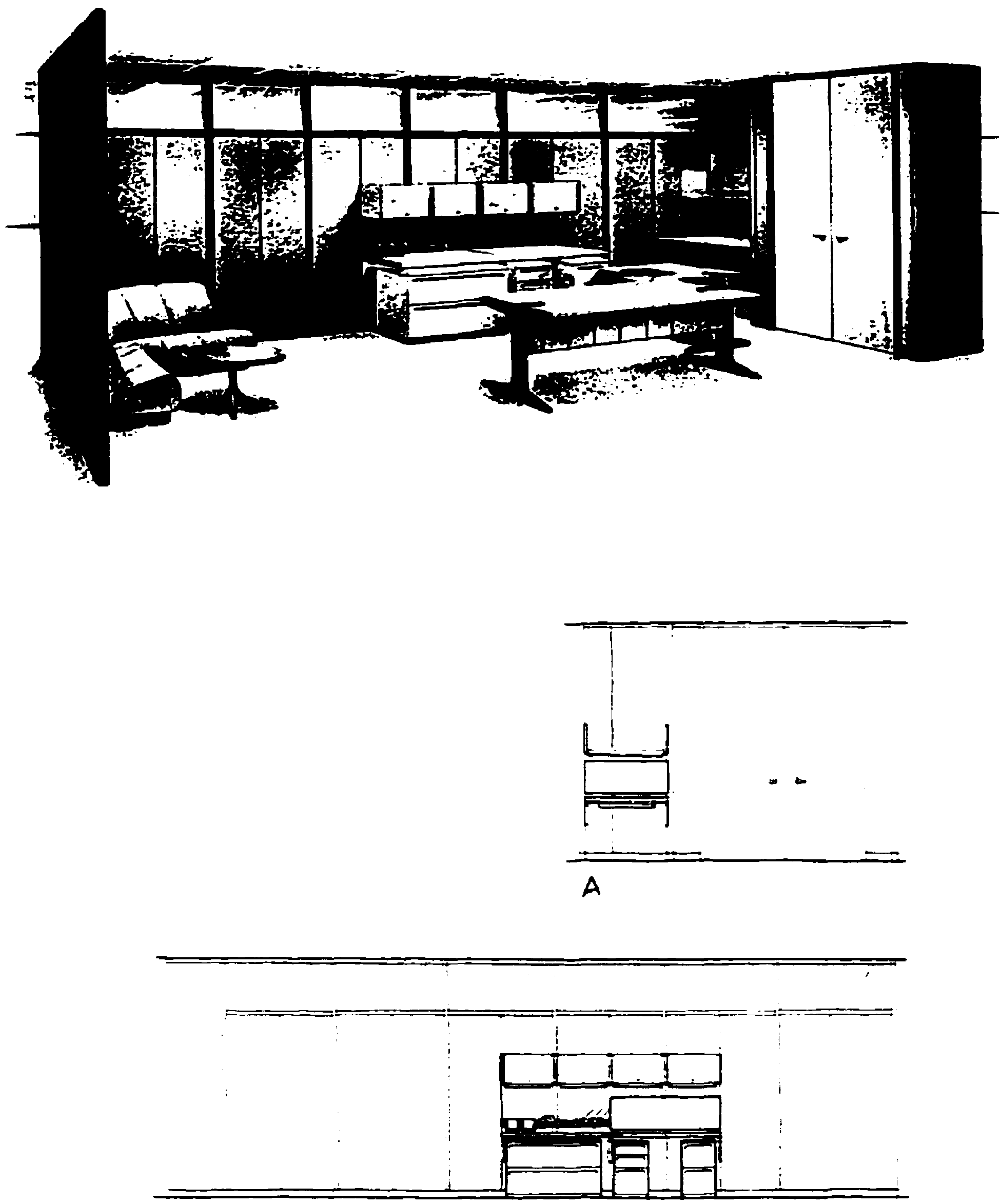
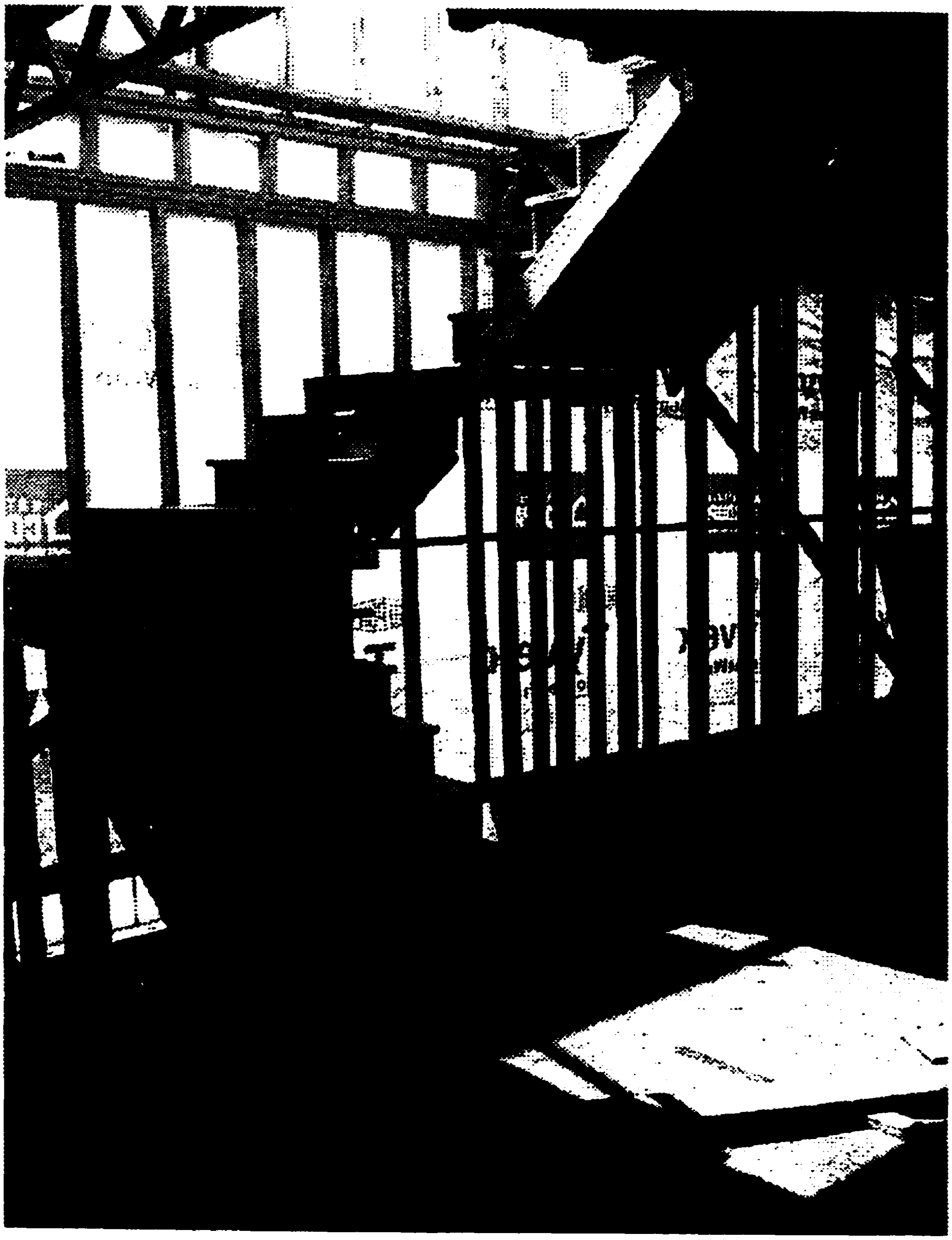


Figure 4.44: The V-Wall's Action Office components are hung directly on the V-Wall connectors to provide storage. (Source: Herman Miller Inc. 1989)

4.3 STAIRS



4.3 STAIRS

4.3.0 INTRODUCTION

Flexible partitions obtain flexibility through relocation from an open space created by the Support structure. This type of flexibility does not apply to stairs because the floor does not easily accommodate large openings. Instead, flexible stairs rely on the mechanized flexibility of combining a number of possible arrangements in one design[1]. This section studies the use of new materials and assembling techniques in stairs design.

4.3.1 BASICS

Stairs are constructed following the completion of the floor and walls. They may be built in place or built as a unit in a shop and set in place. When stairs are built in place, stringers are carefully cut to exact size and set in place. Closed-riser stair construction demands more attention because stringers, treads and risers are joined together by tongues and grooves: rear edges of treads are grooved to fit tongues in the lower portions of risers, and tops of risers are tongued to fit grooves in the bottom of treads (Dietz 1991) (Figure 4.46). In the case of prefabricated stairs, ploughed stringers are installed first on site. Afterwards, treads and risers are fitted in place (Figure 4.47). There are rules pertaining to stairway design: the common dimensions used for main stairs are a rise 7 to 7 ½ inches with a run of about 9 ¾ to 10 ¼ inches, which combines both comfort and safety (CMHC 1997). However, this common rise-to-run ratio does not apply to all stairs. The dimensions will vary depending on the total rise and the space allocated.

4.3.2 DETAILS AND INSTALLATION

Different stair designs occupy different space. There are six types of stair designs according to CMHC (1997): straight stairways with or without an intermediate landing,

[1] According to Eric Dluhosch (1974), this mechanized flexibility refers to components or sub-assemblies joined by means of hinges and slides.

long L, wide L, narrow U, double L with winders and landing, or wide U (Figure 4.48). A recent stair innovation puts all variations and their respective constructions into one universal "format". Let us recall that custom-made stairs are labour intensive, but fit nicely in any given space. Mass-produced stair packages are inexpensive, but may not be adjusted to fit (length, width, and height) due to their modular designs. The STARIFRAME system by Structures Monocoques inc. (1999) finds the balance between custom-made and mass-produced stairs. The modular steel frames can be set up to form eight types of stairway (Figure 4.49 & 4.50). It can also be quickly installed and adjusted on site. The construction begins by installing wall stringer(s), open stringer, landing module, pivoting mechanism, steel bearing plates, treads and risers. The pivoting mechanism, which is bolted to lower end of the upper open stringer and upper end of the lower open stringer, allows stairs to turn left or right with winders. Steel bearing plates are bolted to stringers. Finished modular treads and risers are screwed to bearing plates from the underside.

4.3.3 CONCLUSION

The STAIRFRAME system gives contractors higher flexibility because of its variation in stair design; in addition, width and height are adjustable on-site. Quick installation and minimum material wastage means substantial savings to users. Temporary steps are installed during house construction. This gives users the flexibility to wait until the last moment to choose finishing material for treads and risers. Moreover, since no cutting and demolishing are necessary, the occupant can renovate the stairs by using simple tools. However, the disadvantage of STAIFRAME is its appearance. The metal frames do not have the aesthetics of wood; therefore, it may not be suitable for use as exposed stairs.

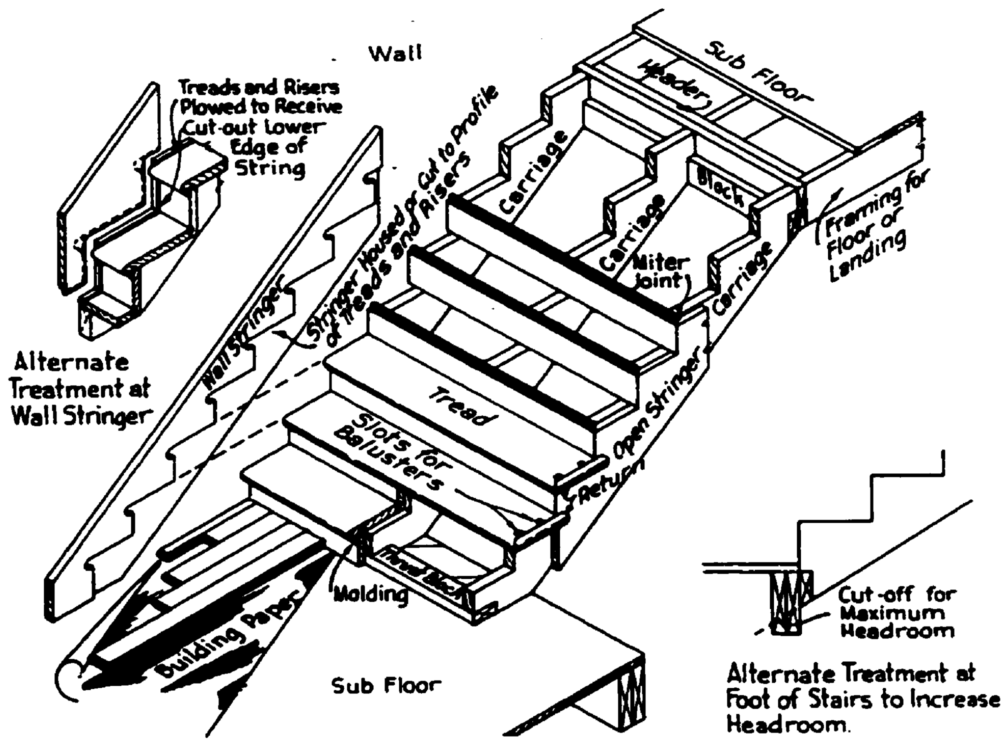


Figure 4.46: Detail of built-in-place stairs. Closed-riser stair construction demands more attention because stringers, treads and risers are joined together by tongues and grooves. (Source: Dietz 1991)

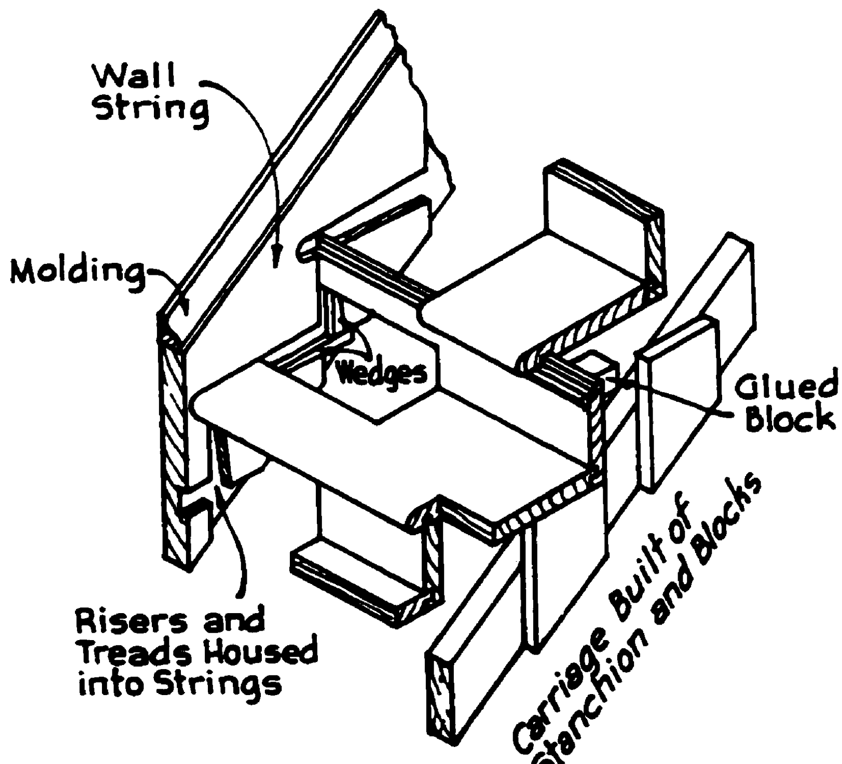


Figure 4.47: Detail of shop-built stair. Ploughed stringers are installed first on site. Afterwards, treads and risers are fitted in place. (Source: Dietz 1991)

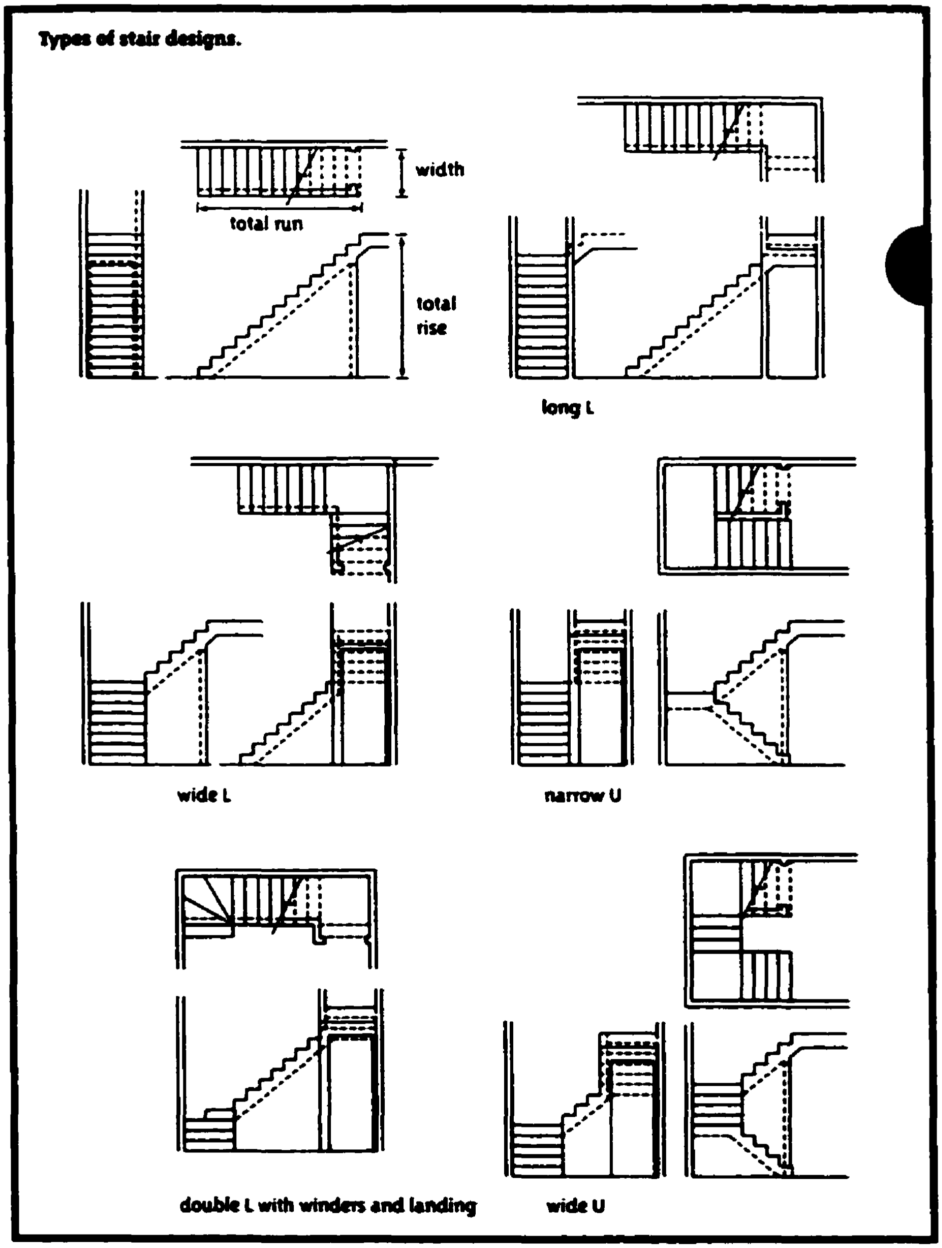


Figure 4.48: Six types of stair designs. (Source: CMHC 1997)

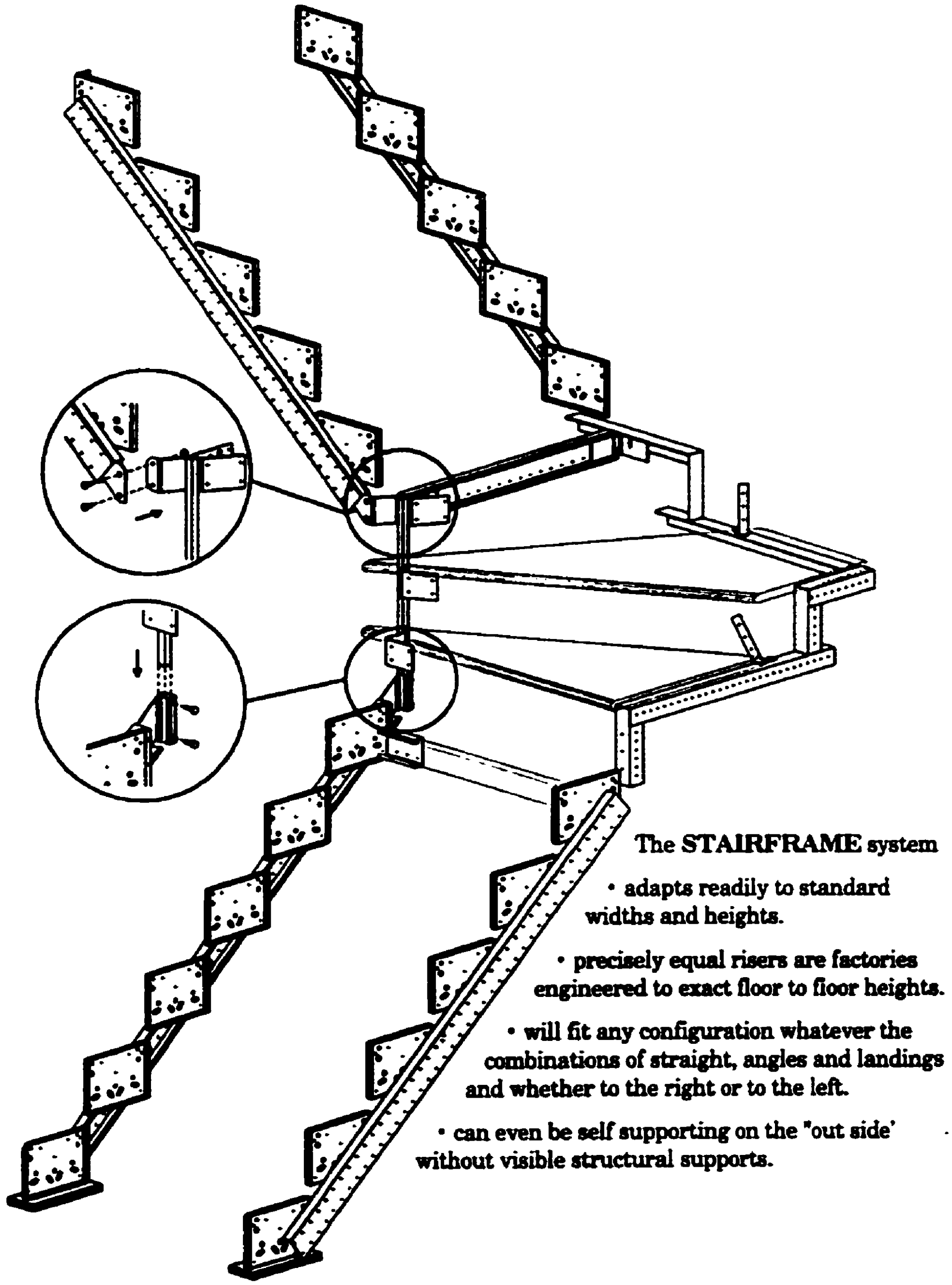


Figure 4.49: The STAIRFRAME system combines the economy of prefabricated stairs and the quality of custom-made stairs. (Source: Systèmes STAIRFRAME 2000)

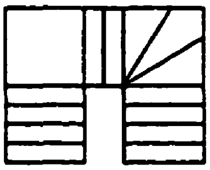
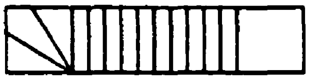
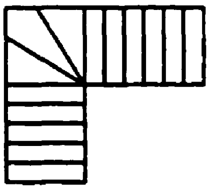
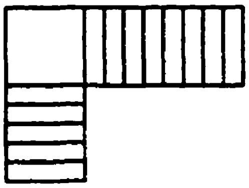
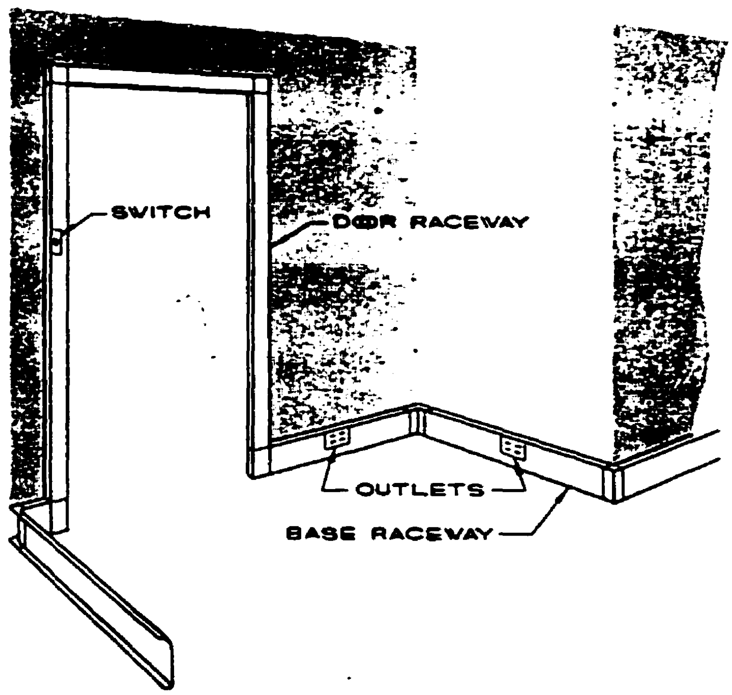
1		Modèle 180° en « U » 14 marches (avec palier et marches d'angle) Prix régulier **Constructeurs [2] : -10 %**
2		Modèle 180° droit 14 marches (avec marches d'angle et palier) Prix régulier **Constructeurs [2]: -10 %**
3		Modèle 90° en « L » 14 marches (avec marches d'angles) Prix régulier **Constructeurs [2] : -10 %**
4		Modèle 90° en « L » 14 marches (avec palier) Prix régulier **Constructeurs [2]: -10 %**
5		Modèle 90° droit 14 marches (avec marches d'angle) Prix régulier **Constructeurs [2]: -10 %**
6		Modèle 90° droit 14 marches (avec palier) Prix régulier **Constructeurs [2]: -10 %**
7		Modèle droit 14 marches Prix régulier **Constructeurs [2]: -10 %**
8		Modèle droit « split » 7 marches Prix régulier **Constructeurs [2]: -10 %**

Figure 4.50: The STAIRFRAME system offers eight types of stairs. Numerous variations are possible within each model. (Source: Systèmes STAIRFRAME 2000)

4.4 ELECTRICAL SYSTEMS



4.4 ELECTRICAL SYSTEMS

4.4.0 INTRODUCTION

The entangled building service systems indicate that the house as a whole does not become flexible simply by providing flexible partitions (Kendall 1994). Certain building systems must also be flexible enough to be moved around in the house in order to bring in the necessary services for the remodeled space. The electrical, data, and mechanical systems deliver electricity, communication, heating, venting and air conditioning throughout the house. Their conduits are normally hidden in the ceiling or wall, which prevents flexibility. Innovative flexible electrical and mechanical systems resolve systems' entanglement by becoming more independent. This encourages the development of prefabricated components (as a kit-of-parts). The mechanized flexibility or the flexibility by addition and/or subtraction will allow users to manipulate them in a pre-designed way. Improving the nature of the service systems by changing conduit size and material is another direct method of controlling their flexibility (i.e. material flexibility). In addition, flexibility of the service systems can also be passively achieved by making the walls and ceilings more amenable to these systems (i.e. infrastructure flexibility) (Dluhosch 1974).

4.4.1 FLEXIBLE ELECTRICAL AND DATA/COMMUNICATION CONDUIT

The electrical and data/communication components, which are low in the entire building system's hierarchy, can attain a higher degree of flexibility than plumbing and HVAC regardless of whether the building structure is flexible or not because of their material nature. These systems are frequently updated, yet more difficult and expensive to modify because of the entanglement of the parts and the parties involved; therefore, they need to be organized (Kendall 1994). Flexible cabling systems work with both permanent walls and movable walls. The principle is to place traditional within-the-wall electrical systems outside so that they can be easily managed. This subsection studies electrical raceways that allow for the free placement of electrical and data/ communication fixtures and equipment.

4.4.1.1 BASIC

Typical electrical equipment includes service/distribution panels, boxes for fixtures, junction outlets, switches and outlets in the house, receptacles, switches, wires and conduits (CMHC 1997). Data and audio/visual equipment includes wiring for the telephone, fax, computer, TV and stereo. Roughing-in is done before applying the insulation and gypsum boards. Lighting fixtures, switches, outlets and cover plates are installed after the interior finishing and painting (CMHC 1997). The service line is brought to the main circuit breaker and distribution panel from outside. Branch circuits traveling through walls, ceiling and floors are connected to a distribution panel. Installation is usually done by a licensed electrician, and is regulated by provincial electrical codes. This work includes drilling, laying wires, connecting and securing electrical equipment. The electrical boxes of outlets and fans on insulated ceilings and exterior walls must be properly sealed to prevent air leakage. The installation of TV cables and telephone lines is similar to electric wiring except the task is smaller and no special skill is required (Figure 4.52).

With a wall construction of fixed gypsum board, the locations of switches and outlets are carefully predetermined because additions and alterations are expensive after the house is finished. The traditional approach offers a certain degree of flexibility by anticipating future needs for power consumption, and the number of circuits and outlets. Nevertheless, future demands may still exceed this built-in level of flexibility. In addition, some flexible partitions need to work with movable electrical systems in order to stay flexible. Baseboard raceways are electrical/communicational distribution systems that have the flexibility to expand and to move around. Originally conceived for use in the commercial sector, electrical raceways are now available for residential applications.

They are mounted on interior walls and encase electrical and communication wires. Raceways permit wires to be run along the surface of interior walls instead of through wall cavities. Electrical raceways can simplify the task of wiring and reduce the number of wall penetrations, which can compromise a building's thermal performance. Residential electrical raceways may become more common as home wiring increases in complexity (Figure 4.53).

4.4.1.2 DETAILS

The WIREMOLD Company (1999) is a leading manufacturer of electrical raceways in North America. Their perimeter systems are made of steel, aluminum or PVC, whether mounted on wall surfaces or in baseboards. The steel raceway systems are vulnerable to wet conditions, and, therefore, are not suitable for residential applications. The PVC electrical baseboard raceways for residential use come in several colours and wood veneer finishes to blend into the décor. The raceway and fittings are CSA (Canadian Standard Association) certified for up to 300 volts. The baseboard system has a dual channel (two-compartment) design that separates electric wiring and low-voltage cables such as phone, data and coaxial (Figure 4.54). The modular device brackets and faceplates, which can be installed anywhere along the raceways, accommodate standard electrical devices, telephones and cable connectors (Figure 4.55). The base comes in a standard 8 feet length, and can be easily cut to desired length. A wide selection of fittings makes connections between raceways and device brackets possible in most situations (see also Figure 4.53). Because the electrical raceways are located on the interior wall, there is no need to run electrical wires through the framing. The location of outlets can also be changed easily and retrofit wiring does not require cutting holes in walls. They also make houses more energy efficient because there is no penetration to the building's envelope (i.e. no plugs on the exterior wall).

4.4.1.3 INSTALLATION

No special tools are needed to install electrical raceways. Installation requires mounting the base, running the wires, and snapping on the cover. Raceways can be installed in new constructions and in retrofits. The whole installation process begins by placing the base at the bottom of a wall, then fixing it in place using screws. The elbow is inserted into the ends of two adjacent bases where the raceway encounters a 90-degree turn. The trim cover (quarter-round profile) is inserted at the top of the base to improve the product's appearance (Figure 4.56). The second phase of installation is roughing-in and wiring. Wires are fed from either the back of the base (Figure 4.57), or at both ends of the raceway system (Figure 4.58). No carpentry work is involved once wires are brought to the system. To install electrical receptacles, a device bracket is inserted in the top compartment. Telephone wire and coaxial cable are installed in the lower compartment (see also Figure 4.55). A locking mechanism will hold the wire clips and device bracket in place (Figure 4.59 & 4.60). The device plate is snapped in place after all wires/cables are connected and the receptacle is mounted onto the device bracket using screws. Installing the receptacle's faceplate completes the installation of the outlet (Figure 4.61). Finally, the cover is fixed after all modular device brackets and faceplates are installed (see also Figure 4.54). The installation of the raceway system is relatively simple and wiring is accessible for future changes. The location of outlets and jacks can be changed. However, possible drawbacks include the appearance, and the issue of safety when installed by users who have limited knowledge of electrical systems.

4.4.1.4 OTHER CONSIDERATIONS

There is a switch for every ceiling or wall fixture. The baseboard raceway systems do not accommodate wall switches and ceiling fixtures, nor their wiring. In fact, these electrical components are often hidden behind wall and ceiling panels; therefore, they are not flexible. Although there are surface raceway systems for connecting wall switches and ceiling fixtures, their "looks" may be even less acceptable to most householders (Figure 4.62). Non-progressive demountable partitions are a better flexible alternative for mounting wall switches without compromising appearances.

4.4.2 SUSPENSION CEILING SYSTEMS

4.4.2.1 INTRODUCTION

The traditional fixed ceiling prevents the installation and maintenance of fixtures, plumbing and mechanical systems with flexibility after construction. This is because work such as cutting the ceiling panels and the framing members, redistributing the conduits, as well as finishing can not be quickly or easily accomplished by most users. Commercial suspended ceiling systems permit easy access to electrical, mechanical and plumbing systems by making the ceiling easily removable. However, some suspended ceiling systems may not yet be ready for use in low-rise wood frame houses because they do not meet fire and humidity resistance requirements. They may also not be suitable because extra clearance is needed for removing ceiling panels. Moreover, some people may reject this ceiling system due to the commercial look of the supporting grid.

4.4.2.2 PRODUCT DETAILS

1. CGC SUSPENSION CEILING SYSTEMS

CGC Inc. offers a wide variety of suspended ceiling systems in terms of ceiling panel designs, textures, finishes, options, and features that will satisfy most occupants (CGC 1998). Their "ClimaPlus" ceiling panels generally have good humidity resistance and sound absorbency. Among the ClimaPlus product lines, the CERAMIC model is made of ceramic-bonded mineral fibers that can withstand high heat, high humidity, and corrosive chemical fumes (Figure 4.63). It can also be cleaned with a damp sponge and, therefore, is qualified for residential use. The CLEAN ROOM model is made of vinyl covered gypsum board that is as durable and as easily maintained as the CERAMIC model (Figure 4.64). The CELEBRATION metal ceiling panels offer the easiest and quickest plenum access: the panels are snapped in place onto the supporting grid from below. It also requires minimal ceiling clearance. The panels may be field cut at walls to counteract the inflexibility caused by its modular design. Air diffusers and light fixtures may be laid into the grid in place of CELEBRATION panels, or, instead, hardware-compatible ceiling panels may be installed to increase the flexibility of their placements (Figure 4.65).

2. CONCEALED ACCESSIBLE CEILING SYSTEMS

The supporting grid of the Concealed Accessible Systems is completely concealed, creating a monolithic, uninterrupted ceiling plane. Concealed systems are available to accommodate a variety of upward or downward access requirements by side or end pivoting ceiling panels (Chicago Metallic 1999) (Figure 4.66). Light fixtures, air diffusers, and plenum access points can be arranged with great flexibility when installed in conjunction with the hardware-compatible ceiling panels (CGC 1998) (Figure 4.67).

4.4.3 CONCLUSION

Technically, the suspension ceiling systems would be ready for use in low-rise wood frame houses if the industry had developed an effective connection between the joist and the supporting grid. The author thinks that the supporting grid should be connected directly to the joist to make the ceiling more monolithic and to save space. In addition, because houses do not have the extra ceiling clearance of most office buildings, ceiling panels should be installed from below the grid. The side/end pivot panel from Chicago Metallic's concealed accessible systems or the CGC's CELEBRATION system are good examples of providing quick and easy plenum access. However, the trade-off for switching to accessible ceiling systems, is lower quality in certain areas, such as reduced fire ratings and durability. There are many specialized ceiling systems presently available for designed environments (e.g. laboratory, restaurant and swimming pool). The author believes that by combining selected characteristics from the existing systems, a special package could be developed strictly for residential application.

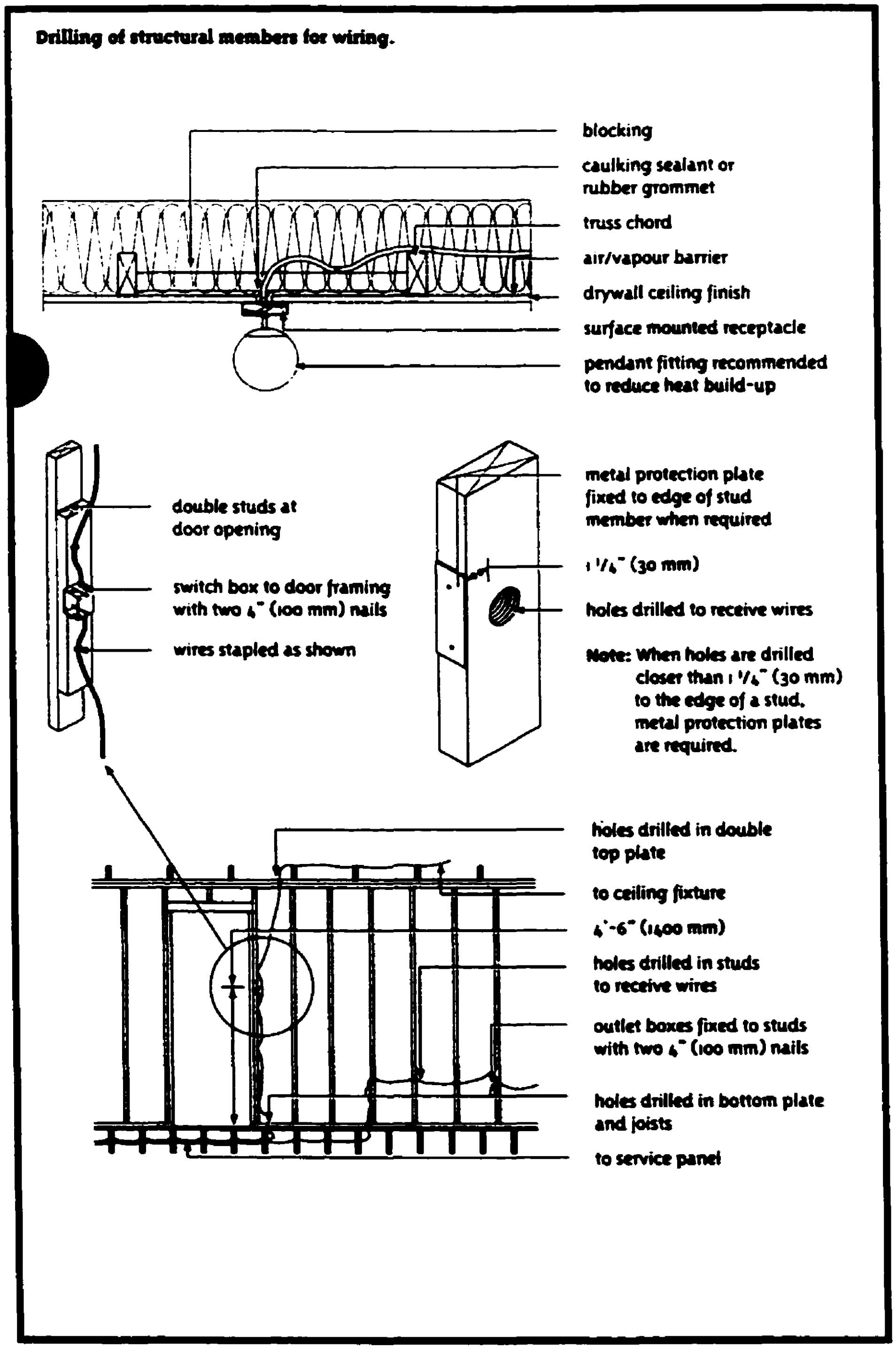


Figure 4.52: Drilling of structural members for wiring. (Source: CMHC 1997)

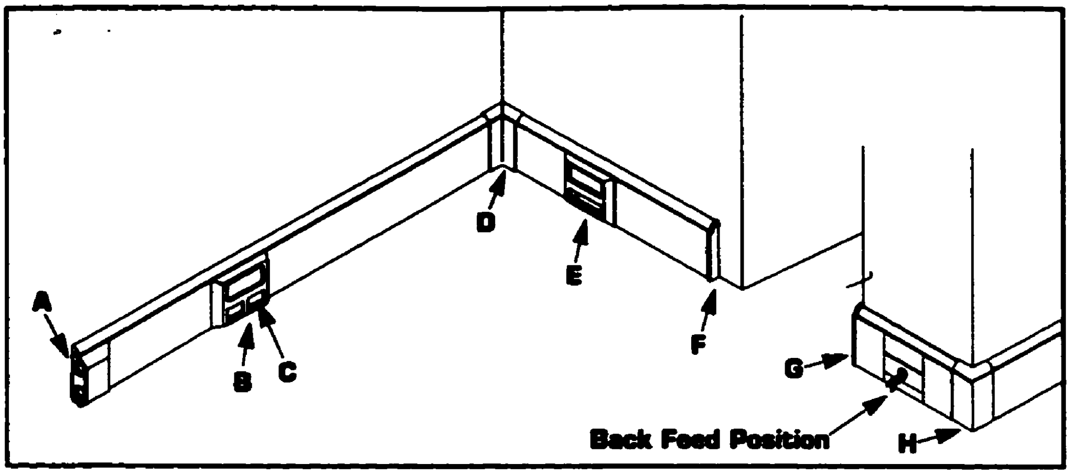


Figure 4.53: The baseboard raceway system. It is an electrical/communicational distribution system that has the flexibility to expand and to move around. Raceways permit wires to be run along the surface of interior walls instead of through wall cavities. (Source: The Wiremold Company 1999)

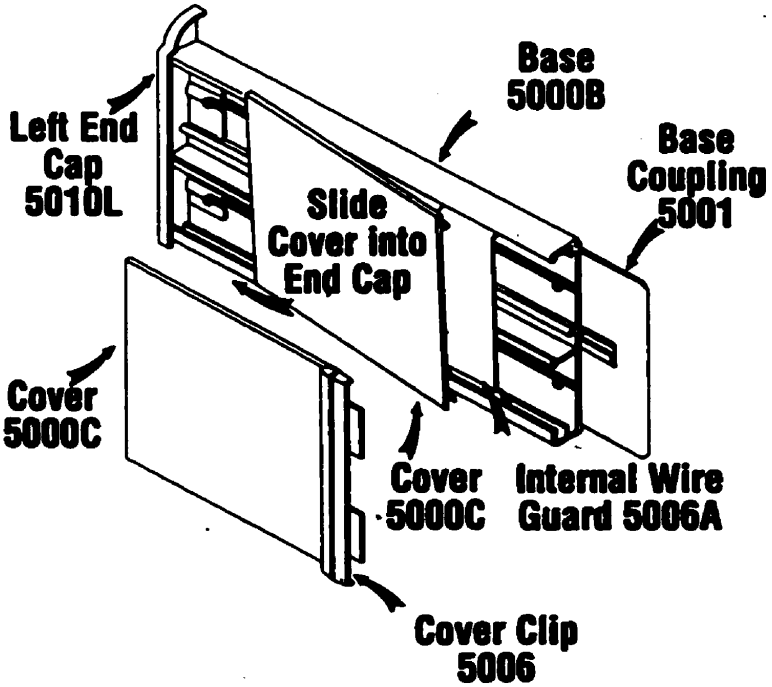


Figure 4.54: Detail of baseboard raceway. The system has a dual compartment design that separates electric wiring and low-voltage cables such as phone, data and coaxial. (Source: The Wiremold Company 1999)

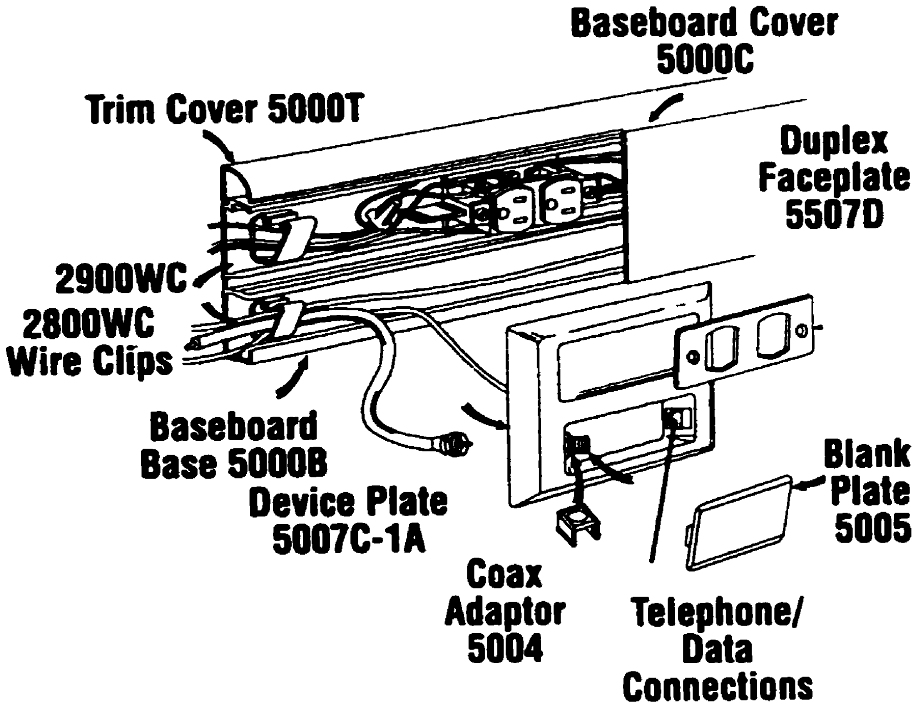


Figure 4.55: The modular device brackets and faceplates, which can be installed anywhere along the raceways, accommodate standard electrical devices, telephone and cable connectors. (Source: The Wiremold Company 1999)

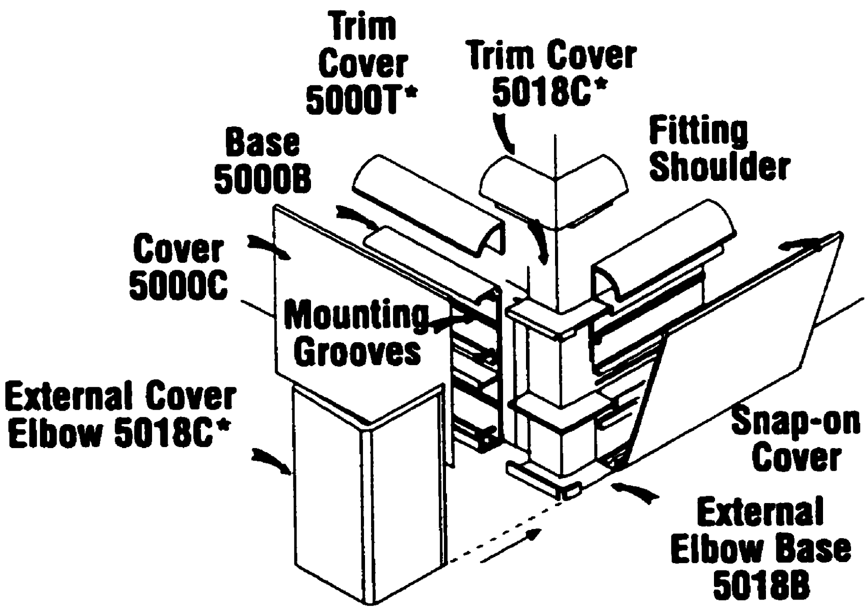
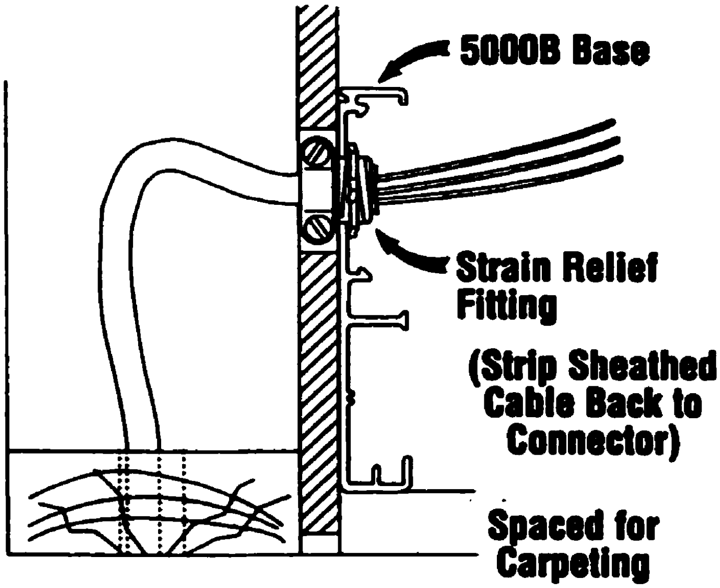


Figure 4.56: The elbow is inserted into the ends of two adjacent bases where the raceway encounters a 90-degree turn. (Source: The Wiremold Company 1999)



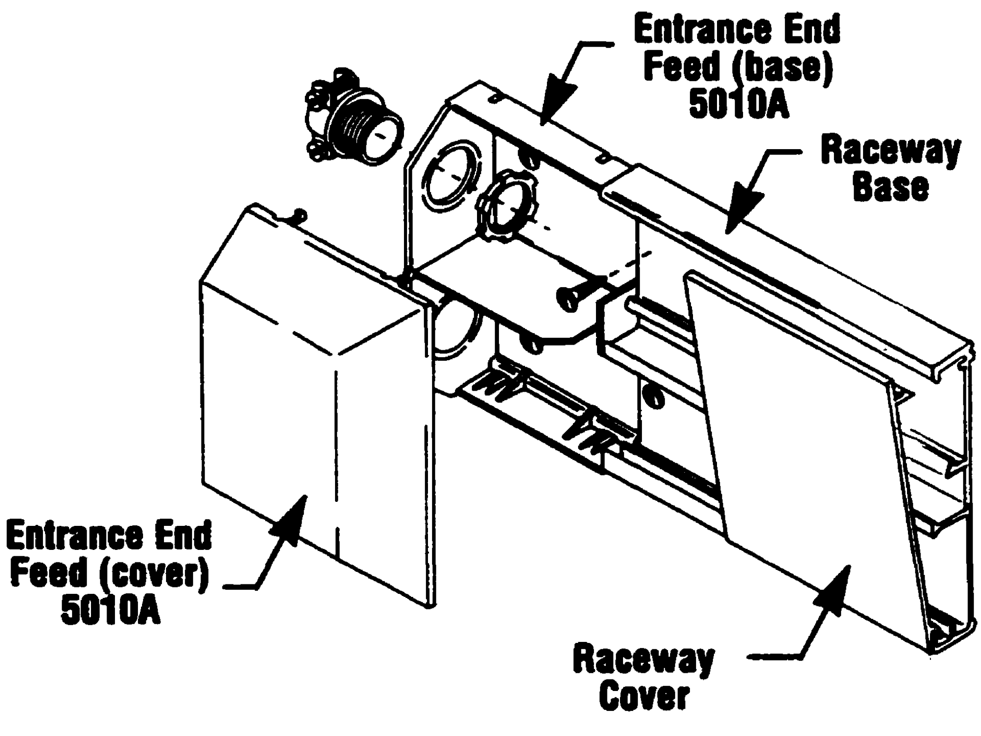
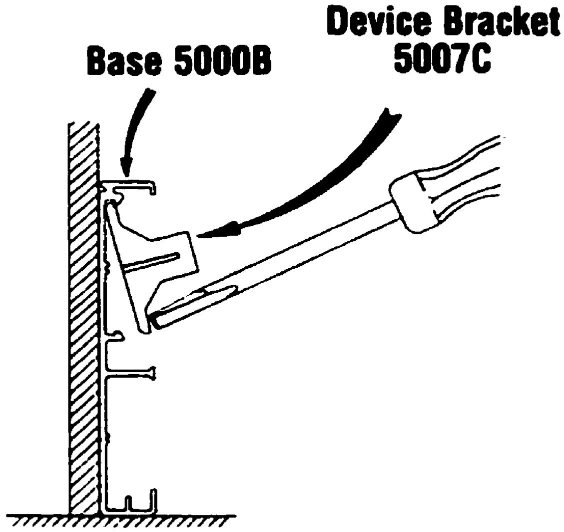


Figure 4.57, 4.58: Wires are fed either from the back of the base, or at both ends of the raceway system. (Source: The Wiremold Company 1999)



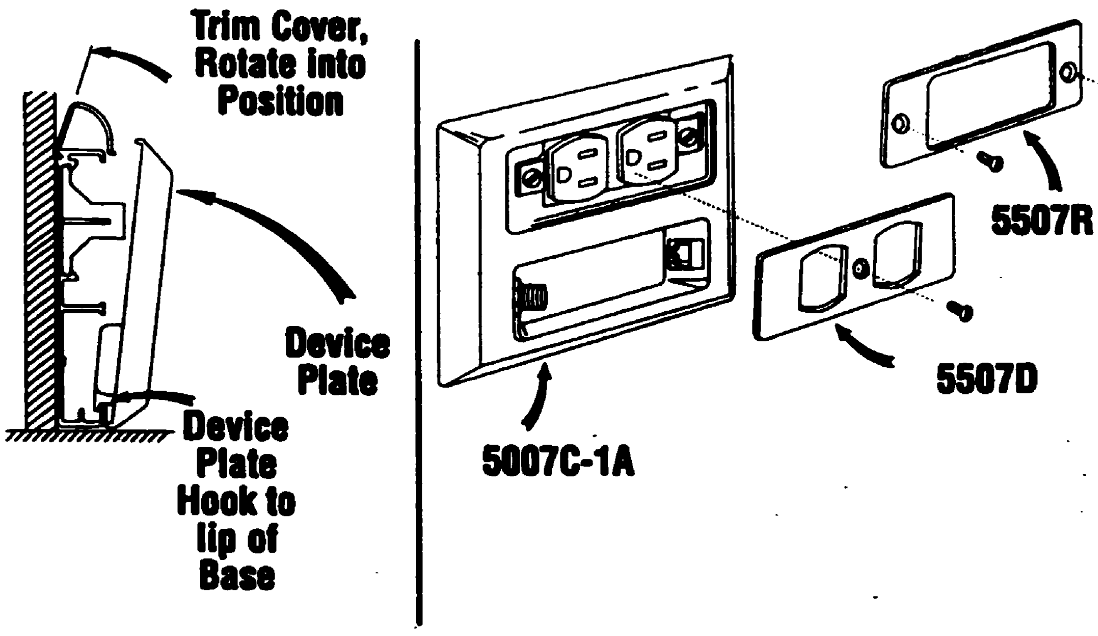


Figure 4.59, 4.60: To install electrical receptacles, a device bracket is inserted in the top compartment. Telephone wire and coaxial cable are installed in the lower compartment. A locking mechanism will hold the wire clips and device bracket in place (Source: The Wiremold Company 1999)

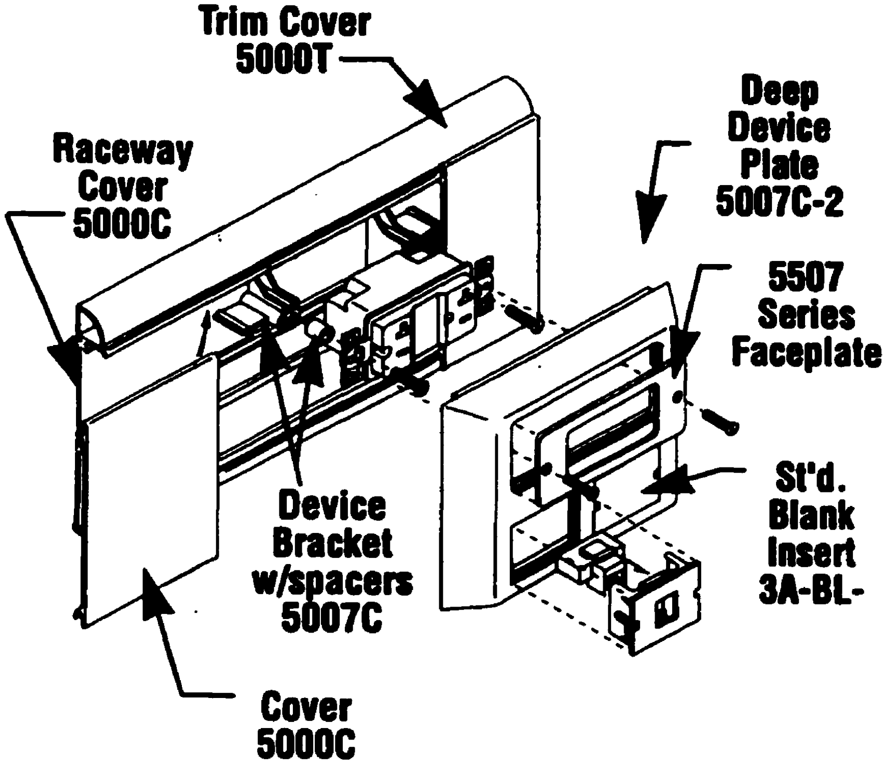


Figure 4.61: Installation of electrical/communication outlet. (Source: The Wiremold Company 1999)

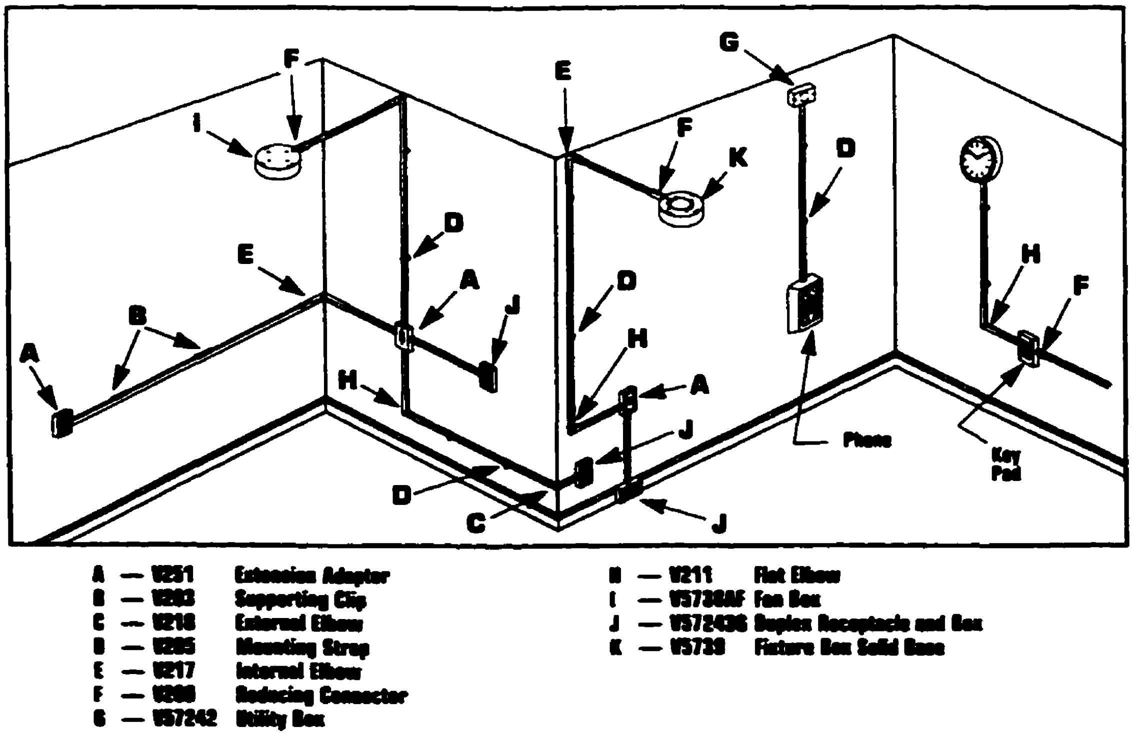
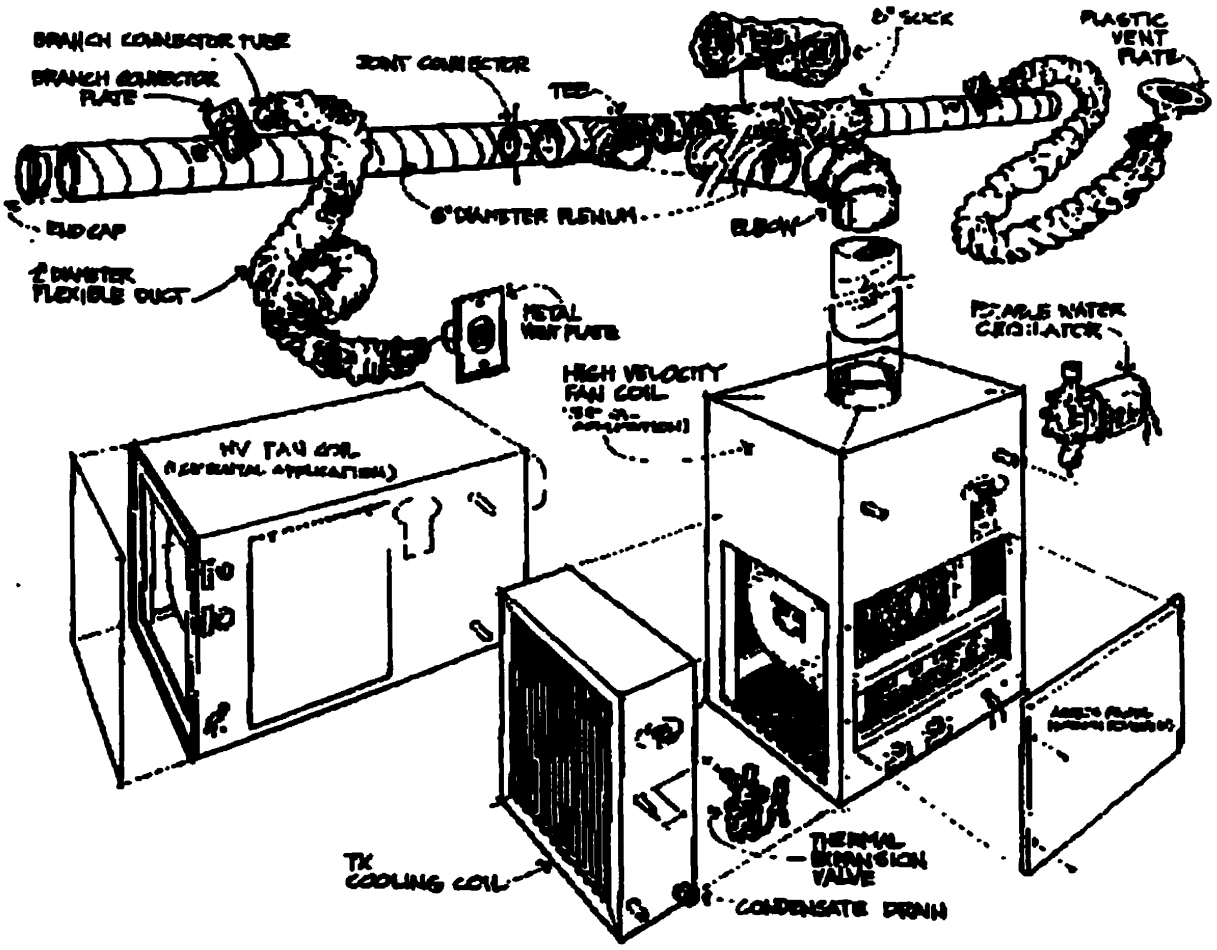


Figure 4.62: Other surface raceway system for connecting wall switches and ceiling fixtures. Note that their "looks" may be less acceptable to some householders. (Source: The Wiremold Company 1999)

4.5 HEATING, VENTING & AIR CONDITIONING SYSTEMS



4.5 HEATING, VENTING & AIR CONDITIONING SYSTEMS

4.5.1 MINI-DUCT AIR DISTRIBUTION SYSTEM

4.5.1.1 SUMMARY

Traditional HVAC systems are less flexible than electrical and plumbing systems because they lack material flexibility. The system requires ductwork; therefore, interior walls, ceilings, and floors may need to be modified to accommodate standard-sized air ducts in post construction renovation (Figure 4.68). The high velocity heating and cooling systems are mini-duct air distribution systems that can be mounted in floor, ceiling, and wall cavities. According to the manufacturers, high velocity systems operate more quietly and offer better dehumidification, room air mixing, and energy efficiency than do standard air-delivery systems (National Association of Home Builders 2000).

4.5.1.2 DETAILS AND INSTALLATION

High velocity heating and cooling systems use high-pressure air handling units. The main supply trunk is either a 6 ½ inch rectangular duct or a 7 inch to 9 inch round duct that supplies air to flexible, insulated, plastic feeder ducts with 2 inch diameters. Instead of installing a diffuser, air passes through sound-suppressing tubing at the end of a duct run before entering the room through a plastic collar fitting. Unlike systems with standard-sized ducts, the number of structural alterations to accommodate duct runs for retrofit installations are minimized, and the need for dropped ceilings in new construction is largely eliminated. Because of reduced duct size and the use of plastic material, the location of air outlets can be changed more easily and quickly. Also, the connection to feeder ducts can be made with PEX pipes. However, high velocity systems may cost more than standard air distribution systems in new construction. In existing homes, the labour cost savings of high velocity systems can result in an installed cost that is lower than standard heating and cooling systems (NAHB 2000) (Figure 4.69).

4.5.2 DUCTLESS (MINI-SPLIT) HEAT PUMPS

4.5.2.1 DETAILS

If only central cooling is needed, then ductless electric heat pumps are better alternatives than the mini-duct air distribution system. Most central air conditioning systems rely on ductwork to distribute cool air to rooms throughout the house. Ductless systems combine the flexibility of room air conditioners with the whole-house cooling of central systems. In ductless systems, there is usually one outdoor unit (condenser) serving multiple indoor units (evaporators). Refrigerant is piped from the outdoor unit through small-diameter insulated refrigerant lines directly to individual evaporator units. This type of setup saves about 20 to 24 percent more energy than conventional systems (NAHB 2000) (Figure 4.70).

4.5.2.2 INSTALLATION

Ductless systems are relatively easy to install. It takes two professional installers about a day to install a system with up to three zones. Wiring for power and controls is easier than with a conventional unit since wires can be run along with the refrigerant lines. Lines from outdoor units can span up to one hundred feet to indoor units. Indoor units are about six to eight inches deep and are mounted flush on a wall, ceiling, or recess in a drop ceiling. A three-inch hole is cut through the wall. Wiring, refrigerant lines, control cables, and the condensate drain all pass through this hole. The mini-split system piping can often be routed through walls and joists. Furthermore, split systems allow separate zone control for increased comfort and efficiency (NAHB 1999). Similar to high velocity systems, ductless mini-split HVAC systems are not more cost effective than conventional systems for most new home installations. They are generally cost effective in retrofit situations.

4.5.2.3 CONCLUSION

In summary, changing a conduit's size and material seems to be the manufacturers' approach to achieving flexibility. However, the "real" degree of flexibility may depend on the users' ability and level of participation in the installation work themselves (Warshaw 1974). The use of plastic piping for the high-velocity mini duct air distribution system suggests that typical users may be able to install it themselves; therefore, it is more flexible. The pipes in ductless (mini-split) heat pump systems contain refrigerant and are made of metal; therefore, they are less flexible. Cost is another factor that determines the flexibility of these systems. The new "mobile" HVAC unit delivers heating and cooling where it is needed the most; therefore, it has a high degree of flexibility and reduces installation and operation costs (Figure 4.71). The author believes that, along with developing new materials and technologies for traditional mechanical systems, improving the performance of the mobile HVAC unit would be a worthwhile research goal.

Figure 4.63: The CGC's ClimaPlus ceiling panels have good humidity resistance and sound absorbency. (Source: CGC Inc. 1999)

Figure 4.64: The CGC's CERAMIC model is made of ceramic-bonded mineral fibers that can withstand high heat, high humidity, and corrosive chemical fumes. (Source: CGC Inc. 1999)

Figure 4.65: The CGC's CELEBRATION metal ceiling panels are snapped in place onto the supporting grid from below. The panels may be field cut at walls to counteract the inflexibility caused by its modular design. (Source: CGC Inc. 1999)

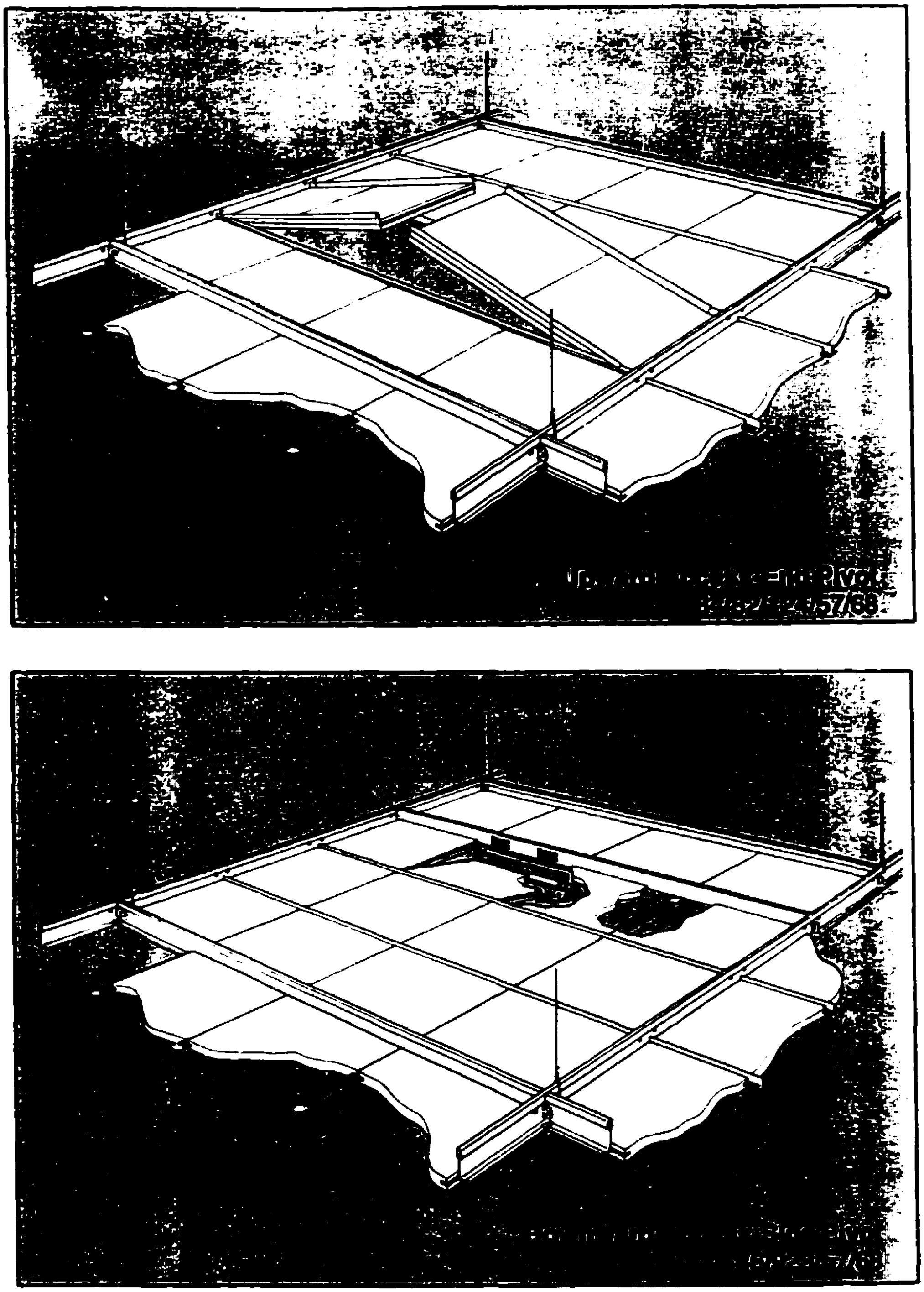
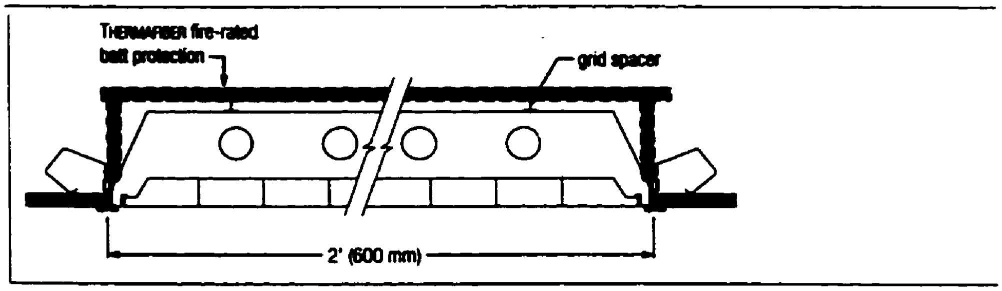


Figure 4.66: The Chicago Metallic's Concealed Accessible Ceiling System is completely concealed, creating a monolithic, uninterrupted ceiling plane. Concealed systems are available to accommodate a variety of upward or downward access requirements by side or end pivoting panels. (Source: Chicago Metallic 1997)

When installing the panel and clip next to a fluorescent fixture (or other obstruction), cut half of the clip assembly and install as illustrated in Fig. 2.



When installing the panel and clip next to a HID fixture, the clip assembly will fit over the fixture face (Fig. 3) when the ballast is positioned parallel to the clip. A field-fabricated, 2-1/2"x6" (64x150 mm) piece of ROCK FACE impaction panel must be positioned under the impaction clips on each side of the fixture (Fig. 4).

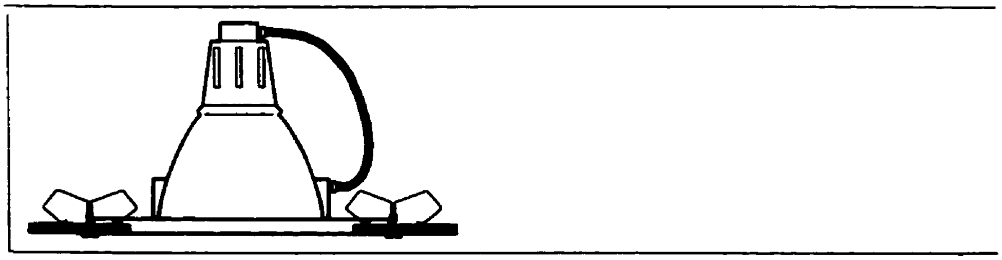


Figure 4.67: Light fixtures, air diffusers, and plenum access points can be arranged with flexibility when installed in conjunction with the hardware-compatible ceiling panels. (Source: CGC Inc. 1998)

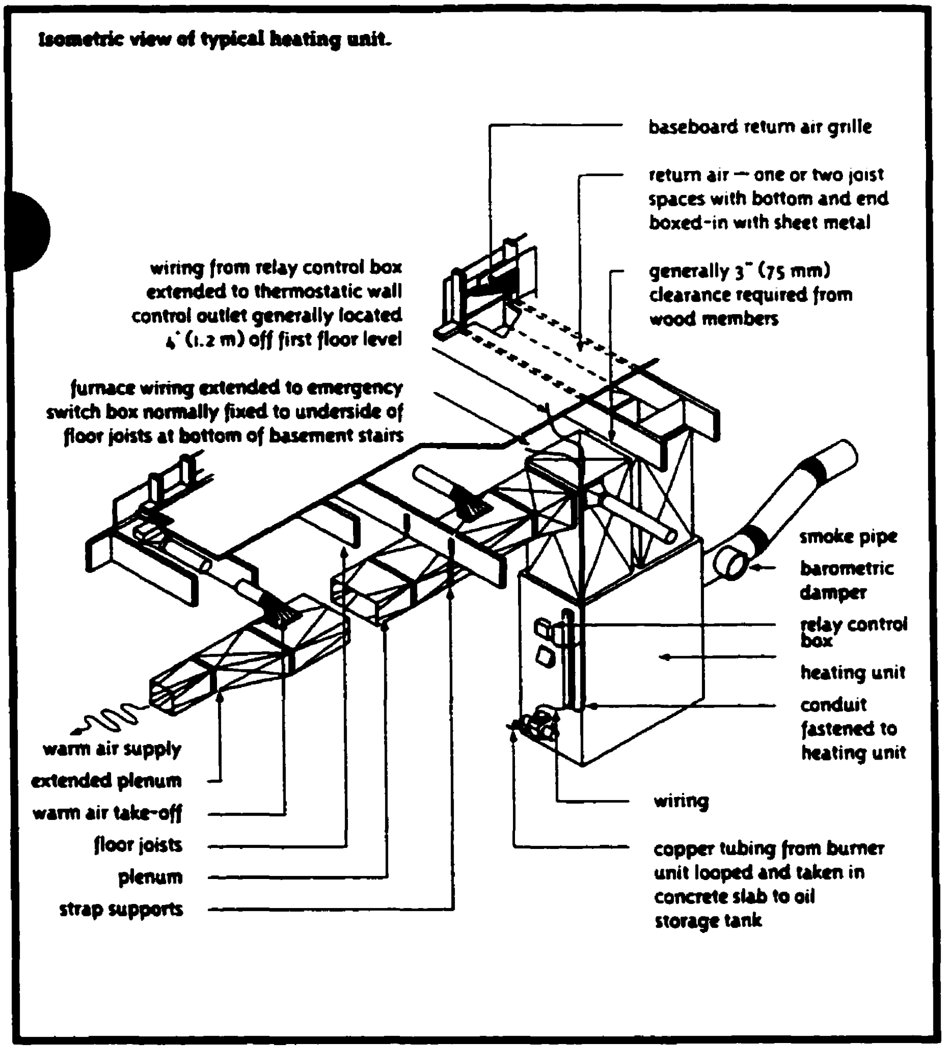


Figure 4.68: The ductwork of traditional centralized HVAC systems. It is less flexible than electrical and plumbing systems because they lack material flexibility. (Source: CMHC 1997)

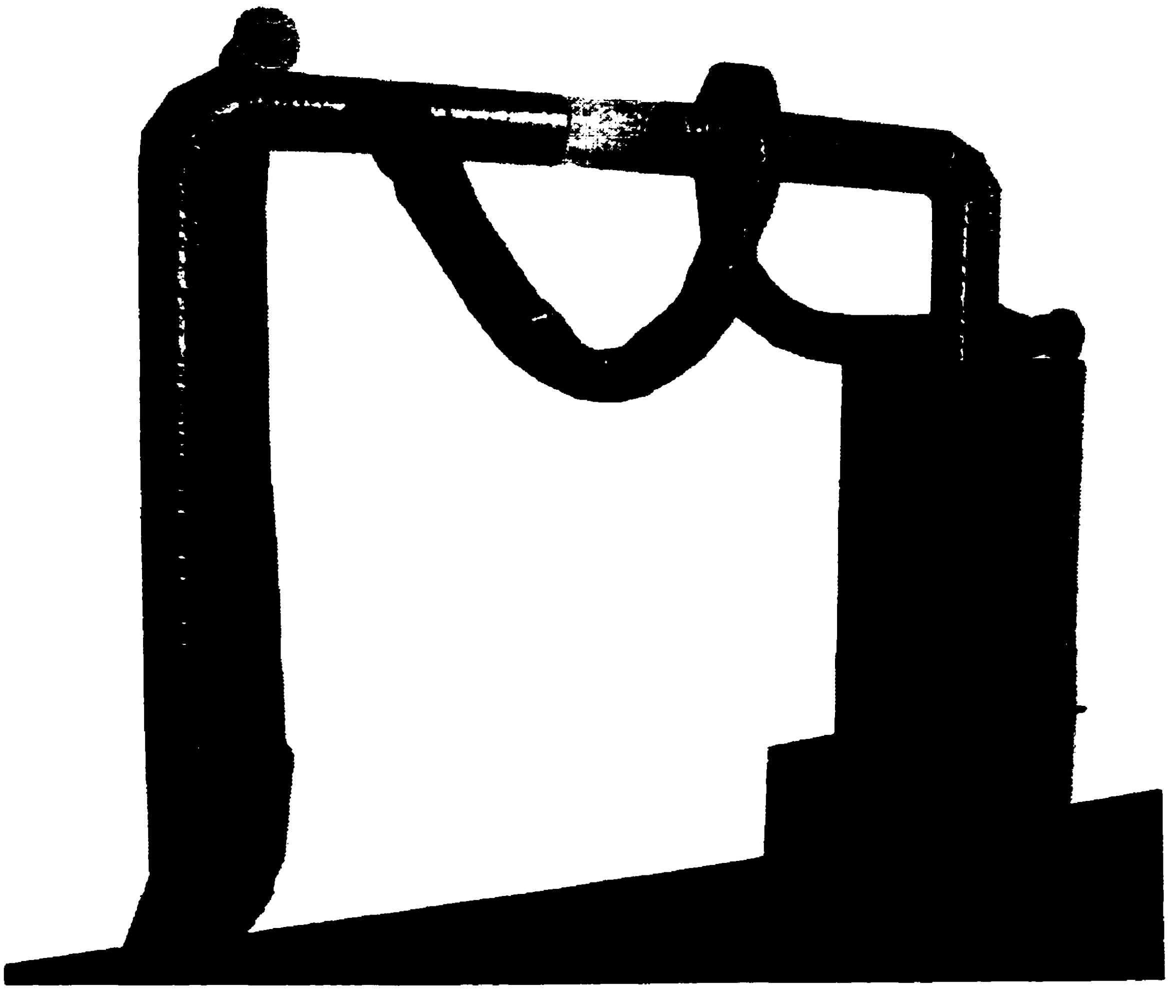


Figure 4.69: High velocity heating and cooling systems use high-pressure air handling units. The main supply trunk supplies air to flexible, insulated, plastic feeder ducts with 2-inch diameters. Because of reduced duct size and the use of plastic material, the location of air outlets can be changed more easily and quickly. (Source: www.hi-velocity.com 2000)

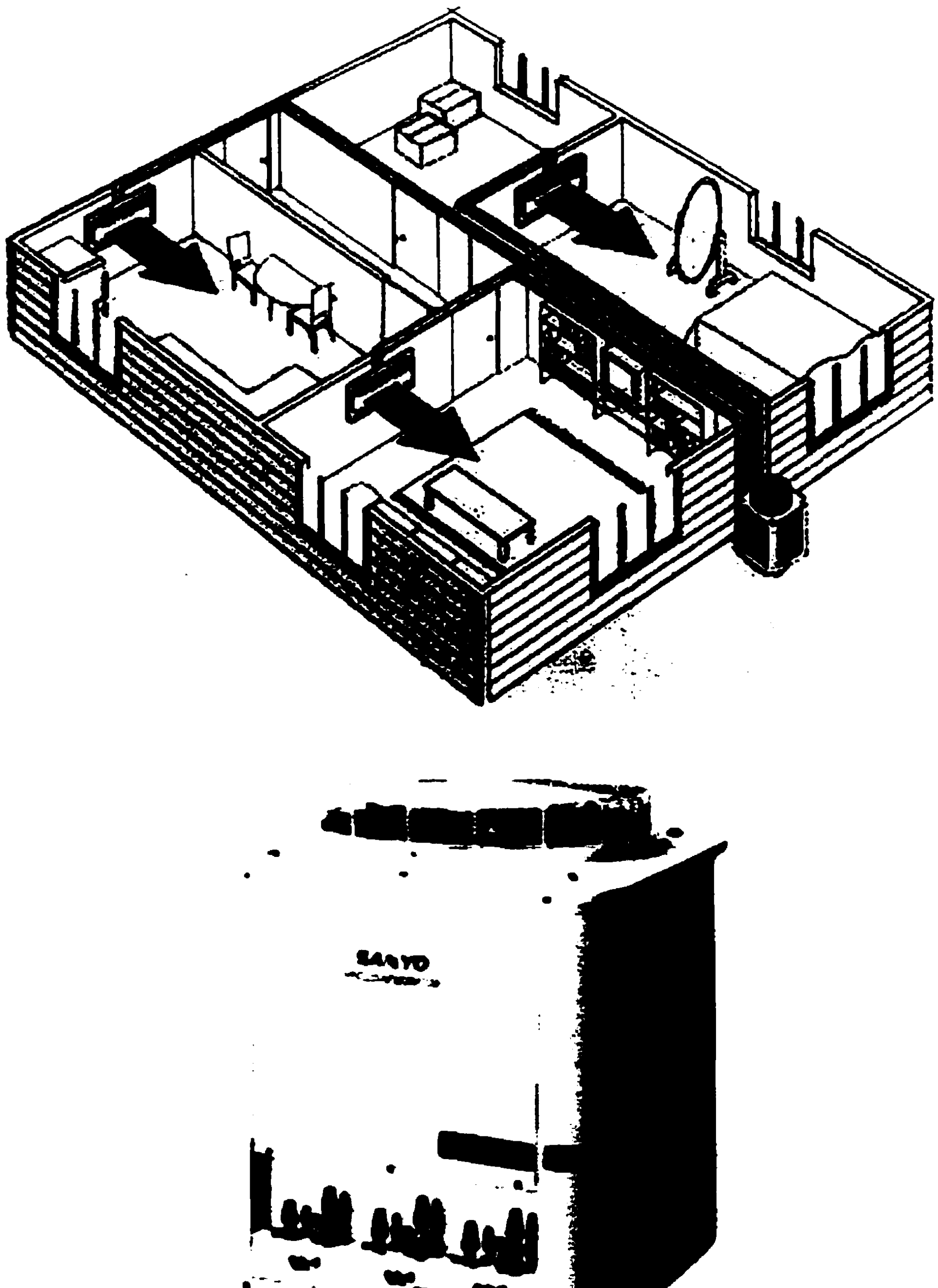


Figure 4.70: Ductless (Mini-Split) heat pump system. There is usually one outdoor unit (condenser) serving multiple indoor units (evaporators). Refrigerant is piped from the outdoor unit through small-diameter insulated refrigerant lines directly to individual evaporator units. (Source: www.sanyohvac.com 2000)

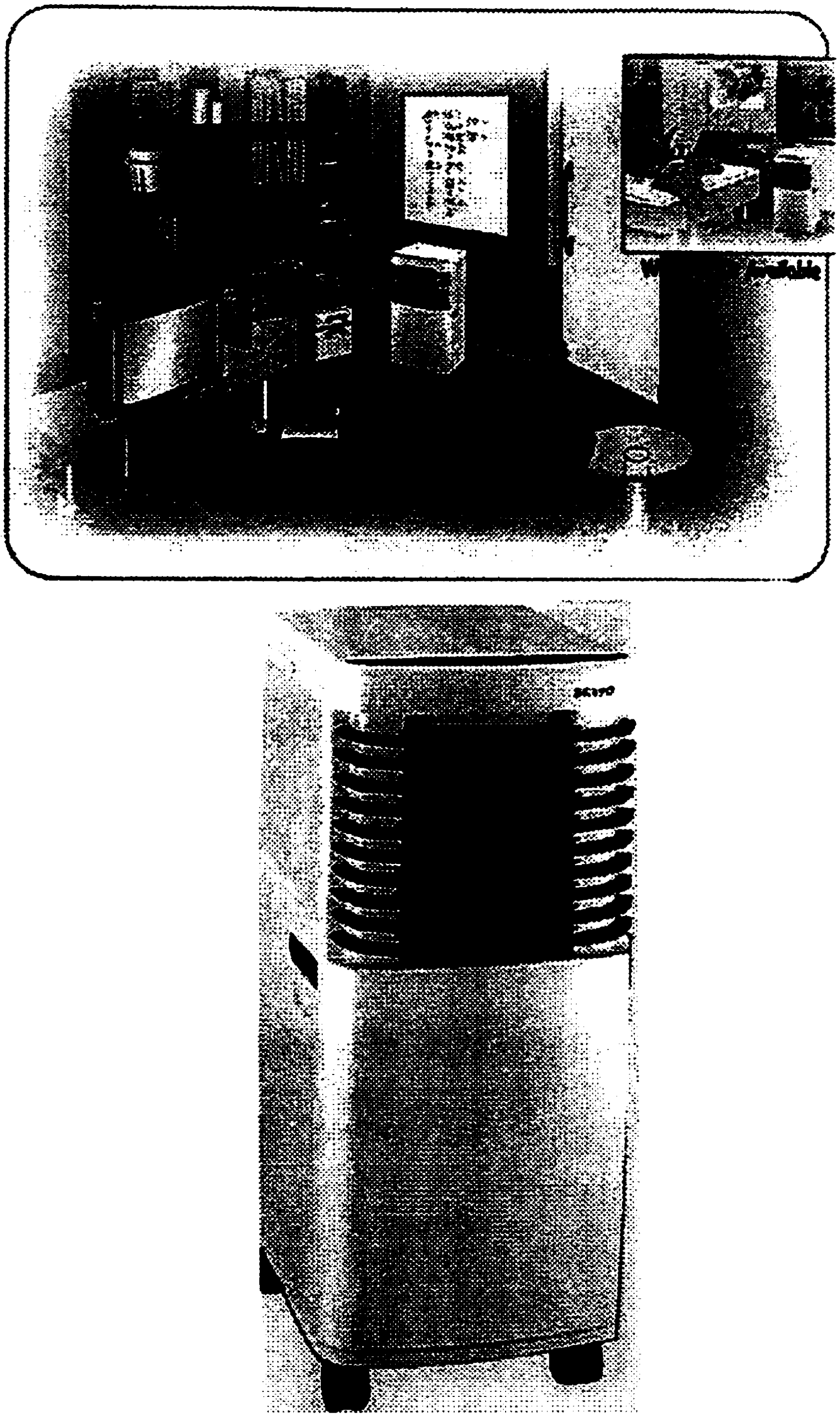
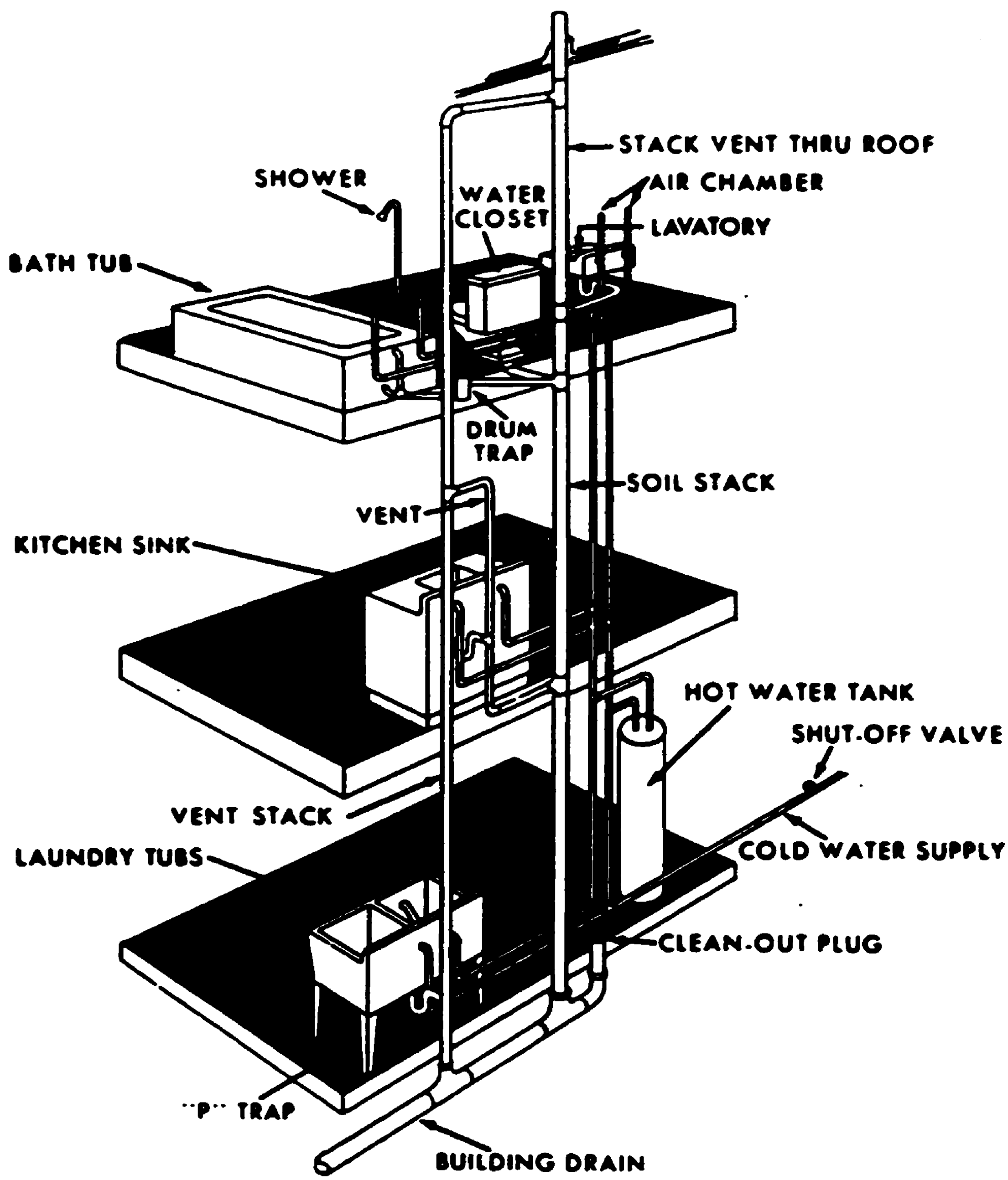


Figure 4.71: Mobile HVAC unit delivers heating and cooling where it is needed the most; therefore, it has a high degree of flexibility and reduces installation and operation costs. (Source: www.sanyohvac.com 2000)

4.6 PLUMBING


STACK VENT THRU ROOF
SHOWER
WATER CLOSET
AIR CHAMBER
LAVATORY
BATH TUB
DRUM TRAP
SOIL STACK
VENT
KITCHEN SINK
HOT WATER TANK
SHUT-OFF VALVE
VENT STACK
LAUNDRY TUBS
COLD WATER SUPPLY
CLEAN-OUT PLUG
"P" TRAP
BUILDING DRAIN

4.6 PLUMBING

4.6.0 INTRODUCTION

The flexibility of plumbing, electrical and mechanical systems depends greatly on their physical properties. Pipes that transport drinking water or waste run through the floor and walls. Innovative plumbing systems use new materials to simplify installation, which increases flexibility. Minimizing penetration to the Support structure, such as the floor and building shell, is another means of increasing flexibility. Improvements in material flexibility have produced pipes which bend more easily and are more easily worked. This section reviews plumbing basics to establish the rules for flexible plumbing systems. Past and present materials are compared to highlight improvements in flexibility. New products and product installations are assessed, and, finally, the section concludes with an overview of future trends.

4.6.1 BASICS

The plumbing system of a house is composed of two subsystems: the drain, waste, and vent system (DWV system); and the domestic water system (potable water system). Unlike water supply systems that work by pressure, the DWV system typically relies on gravity to pull the waste along a piping system, and must be installed with a slope or grade. The greater the slope of the pipe, the greater the carrying capacity and the higher the velocity of the fluid within the pipe. Most experts believe that a fluid velocity that is too high or too low will cause high maintenance expenses due to the constant clogging of the system. Therefore, the slope of a plumbing system is often regulated by a code. This raises several issues: the clearance between the floor and ceiling; the location of fixtures or drainage pipes; and the freedom of DWV systems travel through floor and wall structures. This may also suggest that in terms of installation choices, the most ideal location for the soil stack and the vent stack is near the center of building (Wentz 1997).

"Every plumbing fixture must have a trap, and every trap must have a vent" (Wentz 1997). The venting system removes dangerous odors and gases from the plumbing system, and prevents "trap blowout" and "trap siphonage" which are caused by positive and negative pressures within the system (Figure 4.73). The plumbing code restricts the distance between the trap and trap vent in relation to the fixture drain diameter, which is often referred to as the "trap arm". This is because the longer the distance, the greater the air resistance, and the increased likelihood that positive/negative pressures will build up. Since fixtures' drain pipes are usually 2 inches in diameter, the fixtures in most residential plumbing systems are less than five feet away from the vent (Figure 4.74).

The primary objective of the plumbing code is to protect consumers' health, safety and financial investment. As far as plumbing fundamentals, plumbing codes, and costs are concerned, the flexibility of moving around plumbing fixtures is limited by the location of the soil and vent stacks, the clearance between floor and ceiling, and the extent to which the DWV system allows travel within floor and/or wall structures. Another major factor controlling the level of flexibility is the installation. The degree of installation has a lot to do with the materials being used, and the installing techniques they require.

4.6.2 MATERIALS

At the turn of the century pipes were exposed as much as possible. It was believed that this would ensure cleanliness and accessibility. Water supply pipes were made of lead and galvanized iron. These were later replaced by galvanized steel pipe and copper tubing. Although this was relatively inexpensive, it was not very successful as pressure drops occurred due to rust at joints (i.e. phenomenon of electrolysis: corrosion occurs where two dissimilar materials meet). The stiffness of these materials also restricted plumbing layout, and, therefore, made renovation work very difficult.

Between 1940 and 1990 plumbing was hidden in order to allow for more usable space. Hot and cold water pipes were improved by using softer cast iron and copper. These joints were less susceptible to rusting. Although improvements were made with respect to rust prevention, little flexibility in the arrangements of pipes was achieved: the rigid nature of the pipes made most residential plumbing work very difficult. In addition, existing pipelines in the house further contributed to inflexibility by restricting the placement of fixtures. Drain and water supply lines were very dependent on the floor and wall frame: hot and cold water pipes were usually placed parallel to joists, while hot and cold branches were located near the water main, and soil branches near the soil stack. Although this arrangement was economical, it was very restrictive with respect to kitchen and bathroom arrangements. The use of plastic in recent plumbing applications has many advantages over the traditional metal or clay pipes. They are durable, lightweight, rigid but flexible, easier to work with, and cost effective. In fact, plastics are gradually replacing other plumbing materials as more technologies are found which improve their production, strength, durability, and installation.

According to Plumbing Systems by Tim Wentz (1997), most design engineers have the following criteria when selecting material for plumbing systems. Only the materials meeting all these standards are considered flexible:

1. Corrosive nature of the fluid being conveyed: Some wastes are very corrosive. The waste and vent piping must be made of special materials that resist corrosion.

2. Temperature and pressure of fluid being conveyed: Special consideration must be given to the pressure rating of the piping for certain tasks.

3. Piping materials that are allowable by code: Some local plumbing codes are very restrictive and others are very lax concerning what types of materials are allowed.

4. Availability of piping material: Some piping material is not available in certain sizes.

5. Cost of piping material: Cost is an important criterion when selecting a plumbing material. Considerable savings can be achieved by switching from an expensive piping material, such as copper, to a less expensive material, such as plastic.

6. Cost of installation of piping material: Similar to the cost of piping material. For example, a glued joint, as used in most plastic systems, will be quicker and less expensive to install than the soldered joint used in most copper systems. The number and type of piping supports required by the code is also an important economic consideration.

7. Miscellaneous criteria, such as noise considerations: Some materials, such as some thinner wall plastics, do not do a good job of absorbing the sounds generated within a plumbing system.

4.6.3 MATERIAL TYPES

4.6.3.1 PLASTICS

Plastics and copper are the most commonly used materials in today's residential plumbing systems. Although plastics have been widely used for drain, waste, and vent piping, they are starting to gain acceptance for domestic hot and cold water piping as well. Most plastic systems use a glued type of joint. Most glued joints depend on the application of a primer, then an application of adhesive. Plastics are usually quite inexpensive to buy and install. Typically, they have good to excellent corrosion properties and are available in a wide range of sizes. Plastics also have acceptable thermal resistance; however, they do not respond well to heat. The maximum service temperature is 180° F (82.2° C) which means that plastics cannot always be used in hot water systems. When compared to copper, plastic tubing is cheaper, lighter, more flexible, it needs fewer joints, and is much faster to install (Wentz 1997).

- ACRYLONITRILE BUTADIENE STYRENE (ABS)

ABS is generally used in above ground DWV systems. It has been used since the early 1960s in piping systems. It is known for its chemical resistance ability to withstand a wide range of temperatures. ABS is less expensive, lighter and easier to assemble during installation than copper, cast iron, steel and clay piping. ABS has the following advantages: it is chemical and corrosion resistant; it has joint integrity which enables it to withstand heavy earth loads; it is easily fabricated and installed, and easily repaired; it is light weight; and it has excellent electrical insulating properties making it useful for handling communication and electrical wires and cables.

- CHLORINATED POLYVINYL CHLORIDE (CPVC)

CPVC is generally used in domestic hot and cold water systems. It has a maximum operating temperature of 180° F (82.2° C) and pressure of up to 100 PSI (689KPA). It is able to withstand a water temperature of 200° F (93.3° C) for limited periods of time. It is similar in strength and overall chemical resistance to the PVC. CPVC is softer than ABS or PVC, and it can be easily cut with a knife. Pipes and fittings must be solvent welded to make a permanent bond.

- POLYBUTYLENE (PB)

It is generally used for domestic hot and cold water piping. There is no method yet that can chemically bond PB; therefore, a solvent weld joint cannot be used. Instead, compression type joints are used. However, due to some recent performance failures that were highly publicized, its use is currently being scrutinized by the industry.

- CROSS-LINKED POLYTHYLENE (PEX) AND CROSS-LINKED POLYTHYLENE/ALUMINUM/CROSS-LINKED POLYTHYLENE (PEX-AL-PEX)

PEX and PEX-AL-PEX are new developments in domestic water piping that are gaining some acceptance. They can be used in both hot and cold potable water distribution systems and hydronic radiant heating systems. Design temperature and pressure ratings are 160 psi at 73 ° F and 100 psi at 180° F.

- POLYVINYL CHLORIDE (PVC)

PVC is the most popular material in plastic plumbing systems. It is widely used in DWV systems. It is strong, rigid, and economical. It resists most acids and bases but can be damaged by some solvents and chlorinated hydrocarbons. Since the maximum service temperature is 140° F (60 C), it cannot be used for hot water systems.

4.6.3.2 METAL

- COPPER

Copper is the most popular material for use in present domestic plumbing systems. Copper pipe and fittings are used for potable water piping, DWV (Drain Waste Vent) piping, and medical gas piping. It comes in four different grades or wall thicknesses. Type "M", "L", "K" are used for water piping and in pressure situations, while type "DWV" is used only on drain, waste, and vent piping and is classified as a non-pressurized pipe. Copper pipe is joined either by soldered joints, brazed joints, or a type of mechanical joint, such as a slip joint or a flared joint. Soldered joints are the most common in domestic water piping, and they must be made with lead-free solder. Soldered joints are made at temperatures below 900° F, and a flux compound on the joint must be applied to enable the solder to penetrate the joint completely. Copper piping is used extensively in plumbing systems primarily due to ease of installation, which means lower total system costs. Copper piping is quite durable and will take quite a bit of abuse. However, copper pipe and fittings, although easy to install, are more expensive than comparable plastic materials. Another problem that using copper piping poses is electrolysis: the transfer of electrons between dissimilar metals. As the electron transfer increases (i.e. as the water temperature increases), the metal pipe losing the electrons corrodes (Wentz 1997).

4.6.4 ROUGH-IN

Much of the average plumbing job is hiding pipes in walls, ceilings, and floors. The degree of flexibility is determined by how easily pipes can run through joists, studs, and other framing members without weakening the structures in any way. There is little flexibility in traditional residential plumbing, since the pipeline is very dependent on the structural layout of the building. In addition, the solid wood members used in most traditional wood frame house constructions make it harder to create space for piping. Installation tasks become more difficult when pipes have to run across framing members in certain locations. Sometimes, for aesthetic reasons, a wall may even have to be built just to hide pipes (Figure 4.75). Concern is also centered on cutting through frame members, supporting pipes, protecting plastic and copper tubing from nails, and making connections while pipes are within walls: cutting must be done correctly so that structural integrity is not compromised. Pipes must be fastened into place so that they can function properly. Pipes should be protected against penetration by nails or hammers. Making connections when pipes are up in the walls requires special maneuvers due to tight working space. The quick solution to this inflexibility is to use framing members that have a cavity in them, which provides unobstructed clearance and working space. Open-web joist and commercial metal studs, for example, facilitate installation well.

4.6.5 INNOVATIONS

The most recent innovation in domestic plumbing is the use of cross-linked polyethylene (PEX) as water supply piping material for North America's low-rise wood frame homes. PEX plumbing systems are not new. They have been used extensively in Europe for over 20 years. PEX pipe has several advantages over copper and other plastic pipes. It can be used in cold and hot potable water distribution systems, and it is four times lighter than copper. It is also more durable and flexible; it requires fewer joints; and it is more resistant to corrosion, easier to handle, and two times faster to install. Although plastic pipes are similar in performance, the PEX system outperformed CPVC and PB pipes because its durable, efficient and trouble free mechanical joints outperformed those which require welding with solvents.

Plastic pipes have higher ductility than copper pipes. Particularly pipes made out of PEX or CPVC can be bent at a radius 8 times to 24 times the outside diameter (Vanguard Industries 1999) (Figure 4.76). This gives pipes the flexibility in plumbing layout, also it reduces labor and materials needed for joints. This often results in savings on labor and material costs, quicker installation, and an increase in maneuverability in tight spaces. PEX pipes offer superior chemical resistance to copper, thus there is less water contamination due to scale and other hard-water deposits. They are also quieter, more energy efficient, and more resistant to water freeze (Vanguard Industries 1999).

Flexibility depends on compatibility with existing building systems. There is only one grade for PEX pipes, and their wall thickness is proportional to the tubes' outside diameters. PEX pipes are manufactured to the same dimensions as copper pipes in outside diameter. Most PEX manufactures offer pipes from ¼ inch to 1 inch in diameter. These include 3/8 inch, 1/2 inch, 5/8 inch, 3/4 inch, and 1-inch pipes. Copper to PEX adapters and fittings are also offered. Various sizes are available to provide the flexibility required for switching from a copper plumbing system to a PEX system (Figure 4.77). All pipes are available in standard straight lengths or tubing coils. For new construction or large plumbing projects, PEX tubing coils are more flexible because the tubes can be cut at any length. Moreover, they can help to reduce waste, are cheaper in unit price, monolithic, and more efficient. For smaller projects or renovations, standard straight length pipes are more flexible in terms of size selection and cost control (Figure 4.78).

Because of the flexible nature of plastic pipes, PEX requires about one half the amount of copper fittings. Fewer fittings mean an increased water flow, less pressure drop, less maintenance, and less installation work. However, different companies have different methods of pipe connection. Many manufacturers use mechanical joints standardized by ASTM[17]; others used PEX fittings (hand-tightened nut and bolt) that need no tool at all for connection. Most types of mechanical joints are similar in design; they require no glues, solders, torches or lubricants and can be quickly installed (Figure 4.79). A typical mechanical joint consists of a copper compression ring and a brass/copper fitting. A ratchet is needed to set the compression ring onto the fitting (Figure 4.80). Different companies provide different methods and tools for tightening rings. Some companies offer a universal ratchet that can crimp different size rings. Others chose specialized ratchets that can crimp one size only, which means one ring size per ratchet. Flexibility can be restricted because ratchets from different companies may not be interchangeable. There is another potential drawback: PEX connections designed by some companies cannot be reused. This means that if mistakes are made, or modifications required, pipes, fittings, and compression rings must be scrapped.

However, the application of PEX pipes and fittings is very convenient for post-construction home renovation. Copper pipes and joints cannot be soldered with water in them. The quality of a soldered joint depends on how pipes and fittings were prepared. Also, the strength of the copper pipe connection depends on the solder; the joint will

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[17] ASTM (American Society for Testing and Materials) is a non-profit organization that provides a forum for the development and publication of voluntary consensus standards for materials, products, systems and services (ASTM 2000).

eventually fail due to solder corrosion. Working with a torch and solder in a tight space can be very difficult, and sometimes even dangerous. Flexibility is limited when making space for service or modification, since the amount of work for rough in can be more extensive in some hard to reach areas. Installing PEX fittings is easy enough because it just needs enough space to pass a ratchet in order to make the connection. Therefore, it is possible to make a modification or repair in almost any place. However, plastic pipes are softer than metals and may be damaged by abrasion or by objects with a cutting edge. Use of PEX or CPVC materials in hot and cold water distribution systems must be in accordance with good plumbing practices, applicable code requirements, and current installation practices available from any manufacturers.

4.6.6 PRICE

Plastic pipes are often one-half the price of copper or lower. In addition, the price of plastic is more stable than copper which fluctuates. Below is a price comparison list between PEX and copper pipes quoted from RÉNO DÉPÔT in Montreal on November 1st 1999 (Table 5):

PEX TUBE SIZES (diameter, length)	PRICE	COPPER TUBE SIZES (diameter, length)	PRICE (M-grade)	PRICE (L-grade)
1/4", 10'	$2.38	N/A	N/A	N/A
1/2", 10'	$3.18	1/2", 12'	$5.48	$9.14
3/4", 10'	$5.71	3/4", 12'	$10.38	$14.36
1/2", 100' COIL	$0.6/ft	1/2", 66' COIL	$0.93/ft	N/A

Table 5: Price of PEX and copper tubes.

Many PEX plumbing suppliers use copper fittings in the PEX plumbing system. They cost about the same as fittings for copper pipes. Perhaps the manufacturers' strategy was to save on production costs while establishing a standard based on what is already on the market. These two types of fittings are similar in design, shape and size. The prices of copper fittings for PEX tubes range from $0.64 to $3.58 per fitting. However, PEX to copper adapters or transition fittings are quite expensive. They cost from $3.18 to $7.10. PEX or CPVC plastic fittings are relatively inexpensive; the price range is between $0.06 to $0.10 per fitting. Depending on manufacturers' designs, some PEX copper fittings may be reused. PEX plastic fittings (hand-tightened nut and bolt) are also reusable (Figure 4.81). However, some PEX to copper or PEX to CPVC transition fittings may not be reused. Most CPVC fittings are for one-time use only and not reusable. In general, although copper fittings are more expensive than those made of plastic, copper has less flexibility in terms of reusability, and, therefore, can be more expensive. PEX plastic fittings have the highest flexibility because they are reusable, require no tools for installation, and their unit price is cheaper.

What has the invention of plastic contributed to flexibility in plumbing? The flexible nature of plastic allows pipes to go around obstacles more easily. The methods for joining plastic pipes have simplified installation work, rendering it more accessible to a broader public. Although the result of plastic piping may not be revolutionary when compared to copper, it encourages dweller participation in home building or renovation. Moreover, it reduces their dependence on skilled labour, and it eliminates the inconvenience of personnel coordination. Even though, in certain circumstances, the same level of plumbing flexibility may be attained using copper pipes, plastic piping provides another plumbing option and added flexibility to builders, contractors, designers, and users who are in a position to chose the options that best suit their needs. To builders, the plastic-piping system may mean a reduction in costs since the material and installation are cheaper. To contractors, it means increased control over plumbing layout during and after construction. The use of the plastic-piping system will enable architects, engineers and interior designers to allow for minor design modifications without completely changing the plan. To users, the selection of the plastic-piping system means lower costs and a greater opportunity for "do-it-yourself" activities. This is important since the goal of flexibility is to let occupants modify their own layouts without the intervention of secondary parties.

4.6.7 AIR ADMITTANCE VENTS

4.6.7.1 SUMMARY

Every plumbing fixture needs a vent (Wentz 1997). Conventional plumbing vents allow gases to escape and must extend above the roof to minimize odors. The air admittance vents are pressure activated, one-way valves for plumbing drainage, and vent systems allow air in but prevent the plumbing system's sewer gases from escaping. The vents come in two sizes: one for fixture venting and a larger size for system venting. Air admittance vents can eliminate the need for floor and roof penetrations, which provide architects and engineers greater freedom of layout and design. Lengths of vent piping can also be drastically reduced, which decrease labour and material costs for complex open pipe venting systems. The vents (or valves) work by allowing air to enter the plumbing drainage system through a one-way air valve when water flows through the pipes. When the flow stops, the valve closes by gravity and prevents the escape of sewer gas from the plumbing system. Screening protects the valve and keeps out foreign objects and vermin (Studor 2000) (Figure 4.82).

4.6.7.2 INSTALLATION

The smaller vent comes with tapered threaded connectors that allow welding to 1-½ inch to 2-inch pipe. The larger vent fits onto 2-inch to 4-inch pipe. Floor penetrations are generally not necessary, unsightly and costly. Devices compatible with PVC drainage and vent piping and are modularly sized with standard vent pipe diameters for easy installation.

4.6.8 OVERVIEWS AND FUTURE TREND

In order to achieve higher flexibility, new plumbing layouts must be used. Kitchens and bathrooms are most likely to be renovated during the life cycle of a house. Due to limited flexibility and budget, many renovations are done without relocating these rooms to other places. In order for an occupant to upgrade cabinets, appliances, fixtures and finishes, and mechanical and electrical systems, service lines have to be installed in a flexible manner. A utility trench could be located in the floor, and accessed through an open-close floor cover. This would house trunks of numerous mechanical and electrical systems to which branches could connect. Nevertheless, the utility trench must work in conjunction with open-web joists in order to allow unobstructed passage from one end of the building to another.

In the author's opinion, the present rigid PVC drainage pipe should be more flexible. The more rigid a plumbing system, the more fittings and installation are required, and the less user control. This may not mean much in new house construction, but it does have an impact on flexibility in home renovation, repair, replacement, alteration, and demolition. When the piping material is softer, it can be routed around obstacles more easily, which renders the plumbing system more independent. Let us recall that DWV system is working by gravity. If pressurized systems are used in conjunction with flexible drainage pipes, a drainage network could be organized in the same way as the water supply system is. Nonetheless, most plumbing codes prevent the use of motorized systems in domestic plumbing because they have a higher chance of failure. Therefore, until new technologies are invented to solve this reliability problem, flexibility in plumbing systems can not be achieved without interfering with other building systems.

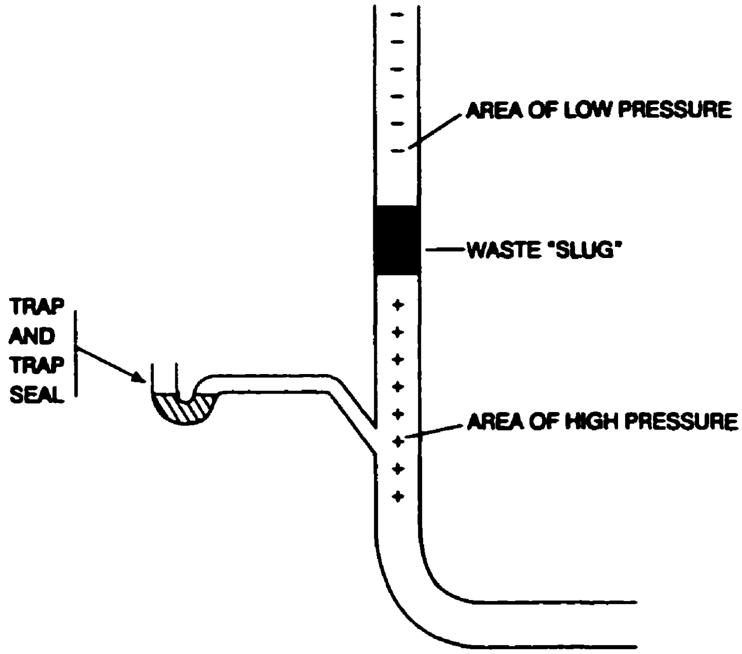


Figure 4.73: Positive and negative pressures in a stack. The venting system prevents "trap blowout" or "trap siphonage" which is caused by positive and negative pressures within the system. (Source: Wentz 1997)

Size of Fixture Drain, in.	Distance–Trap to Vent, ft
1¼	2.5
1½	3.5
2	5
3	6
4	10

Table 19, ANSI A40-1993 Standard, *Safety Requirements for Plumbing.*

Figure 4.74: Maximum length of trap arm. The plumbing code restricts the distance between the trap and trap vent in relation to the fixture drain diameter, which is often referred to as "trap arm". (Source: Wentz 1997)

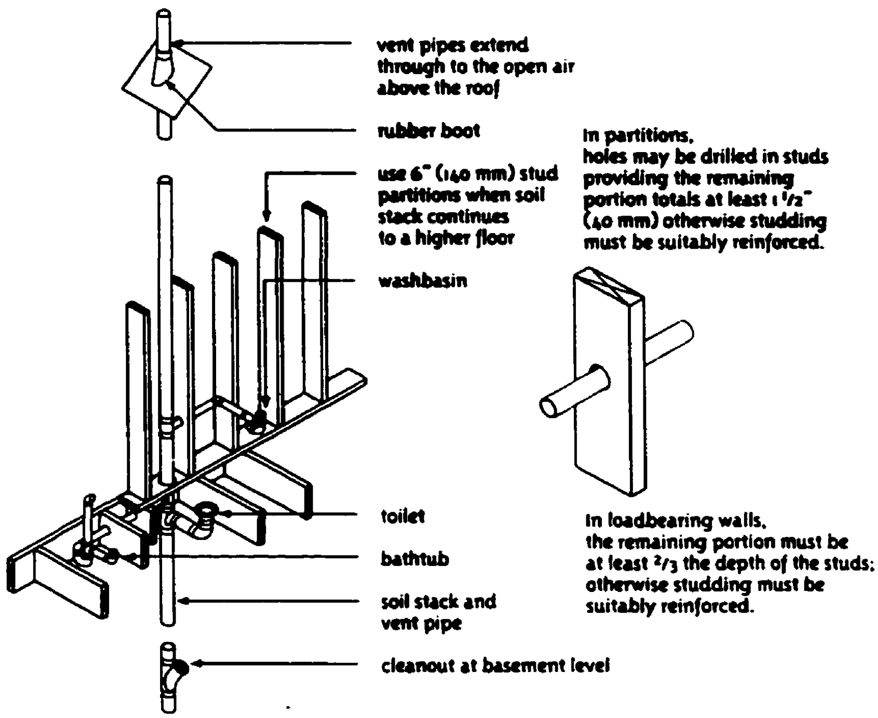
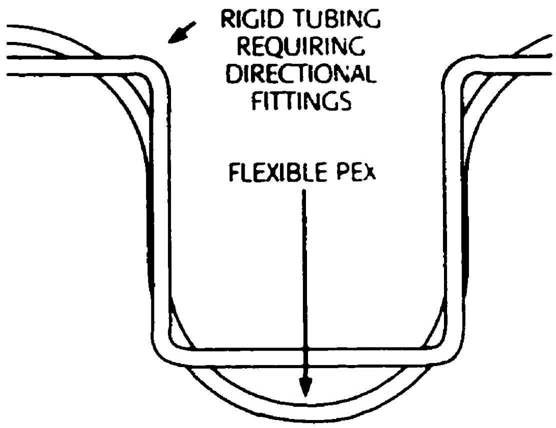
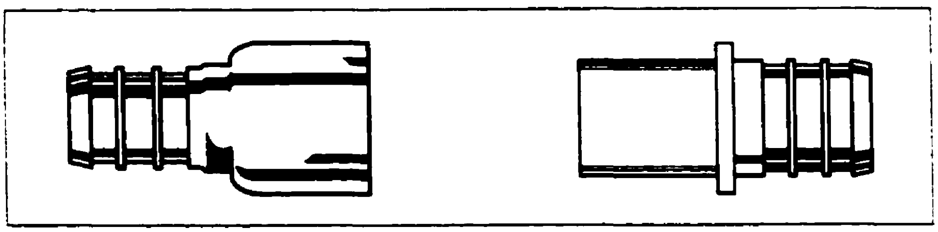


Figure 4.75: The degree of plumbing flexibility relies on how pipes can run through joists, studs, and other framing members without weakening the structures in any way. (Source: CMHC 1997)

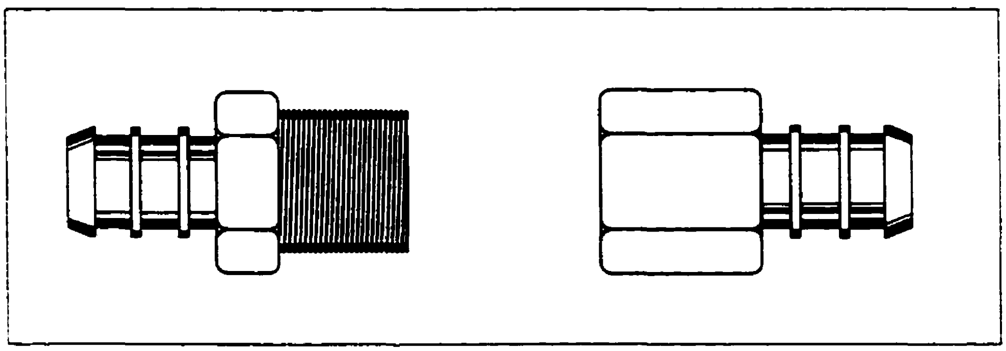


Minimum Bend Radius		
3/8"	Plumb-Pex®	3"
1/2"	Plumb-Pex®	3.75"
3/4"	Plumb-Pex®	5.25"
1"	Plumb-Pex®	6.75"

Figure 4.76: Bending Pex pipe. Plastic pipes have higher ductility than copper pipes. Particularly pipes made out of PEX can be bent at a radius 8 times to 24 times the outside diameter. This gives pipes the flexibility in plumbing layout, also it reduces labour and materials needed for joints. (Source: Radiant Technology 1999)



Roth PEX inserts to sweat adapter



Roth PEX inserts to IP thread transitions

Figure 4.77: PEX transitions. Copper to PEX adapters and fittings are offered. (Source: Radiant Technology 1999)

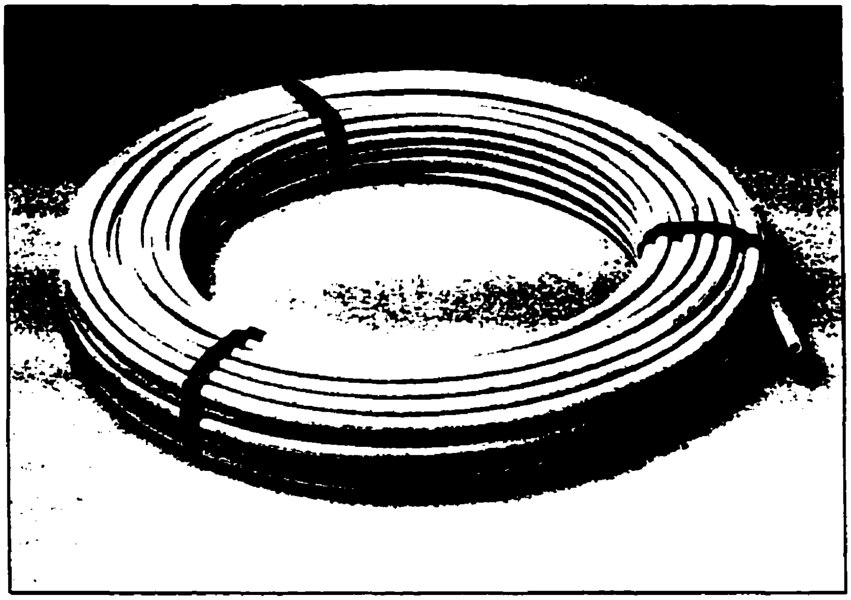
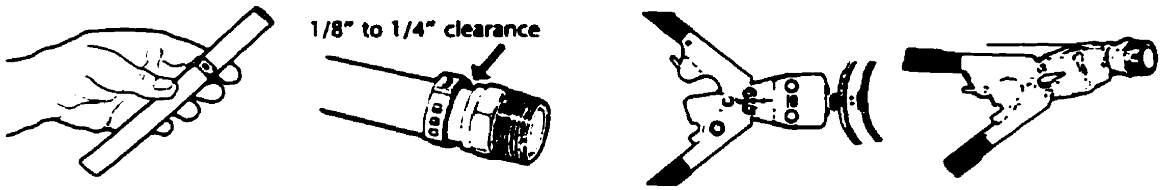


Figure 4.78: PEX coils. For new construction or large plumbing projects, PEX tubing coils are more flexible because the tubes can be cut at any length. (Source: REHAU Incorporated 1999)

Connections are made in 3 easy steps.



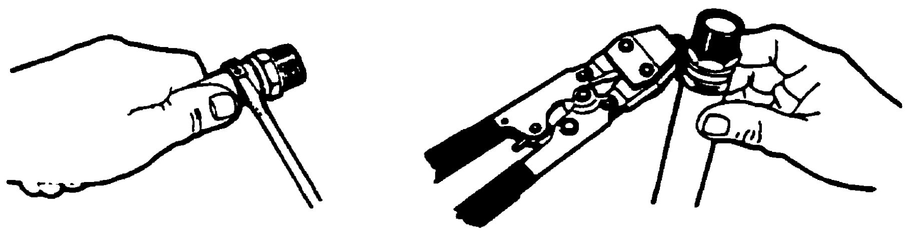
1) Slide the clamp over the tubing.

2) Slide the tubing onto the insert fitting.

3) Close the clamp with the Ratchet tool.

Note: The Ratchet tool will not release until the clamp is properly closed. This insures the installer that the connection is complete.

Removal of a Completed Connection



1) Place a flathead screwdriver under the clamp tab and push up to unlock.

2) Using the Plumb-Pex® tool, grab onto the tab and pull. The clamp should now snap free.

Figure 4.79: PEX installation. Most PEX mechanical joints are similar in design; they require no glues, solders, torches or lubricants and can be quickly installed. (Source: Radiant Technology 1999)

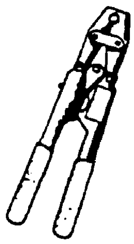
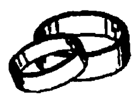
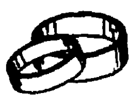
Item	Description	Quantity	List Price
	**Roth PEX Crimp Tool**		
	For 3/8" PEX		$ 240.00
	For 1/2" PEX		$ 240.00
	For 3/4" PEX		$ 240.00
	For 1" PEX		$ 380.00
	**Roth Crimp Rings**		
	3/8" PEX; bag of 100		$ 17.00
	1/2" PEX; bag of 100		$ 16.00
	3/4" PEX; bag of 100		$ 21.00
	1" PEX; bag of 25		$ 7.50
	1/2" PB; bag of 100 NOTE: For PB, only		$ 17.00
	3/4" PB; bag of 100 NOTE: For PB, only		$ 21.00

Figure 4.80: A typical PEX pipe mechanical joint consists of a copper compression ring and brass/copper fitting. Ratchet is needed to set the compression ring onto the fitting. (Source: Radiant Technology 1999)

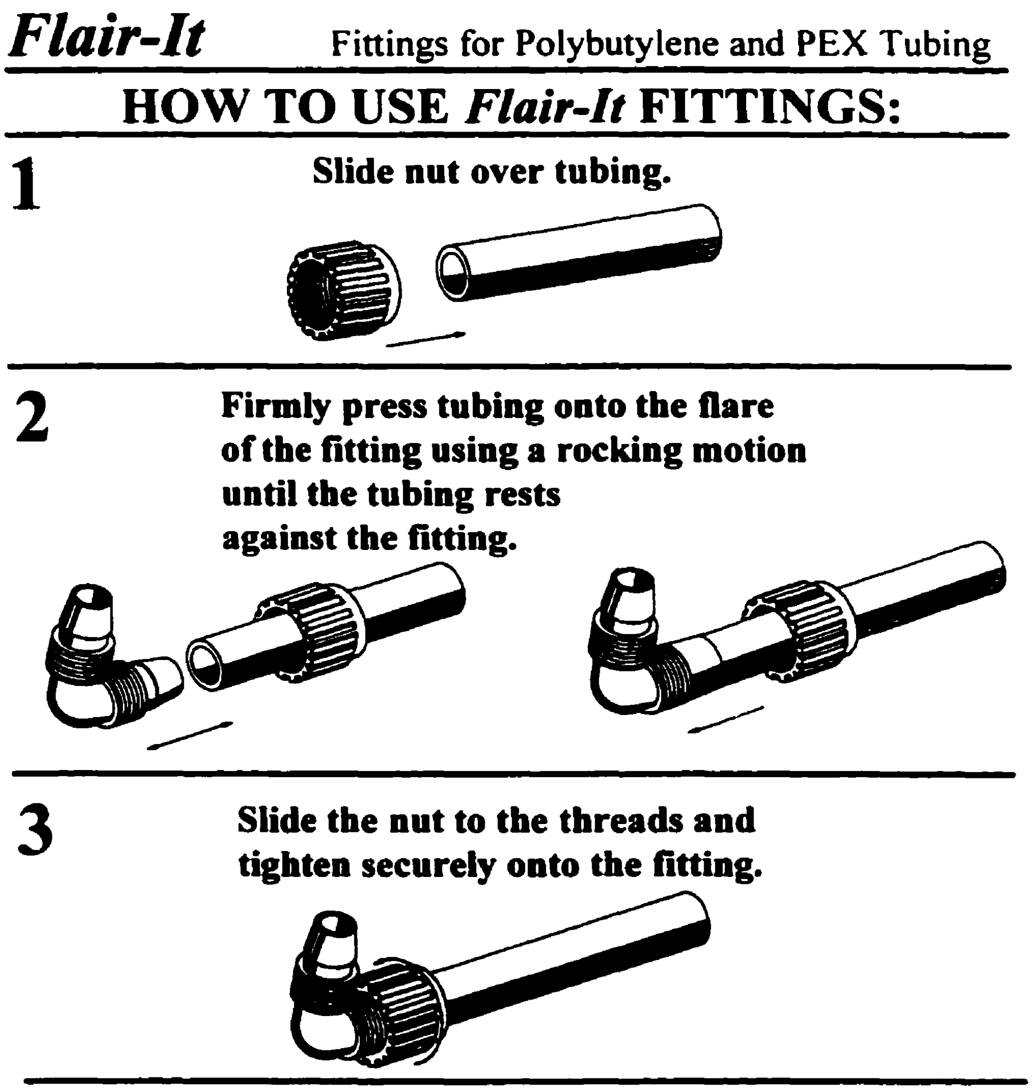


Figure 4.81: PEX plastic fittings are inexpensive and reusable. (Source: Flair-It 1999)

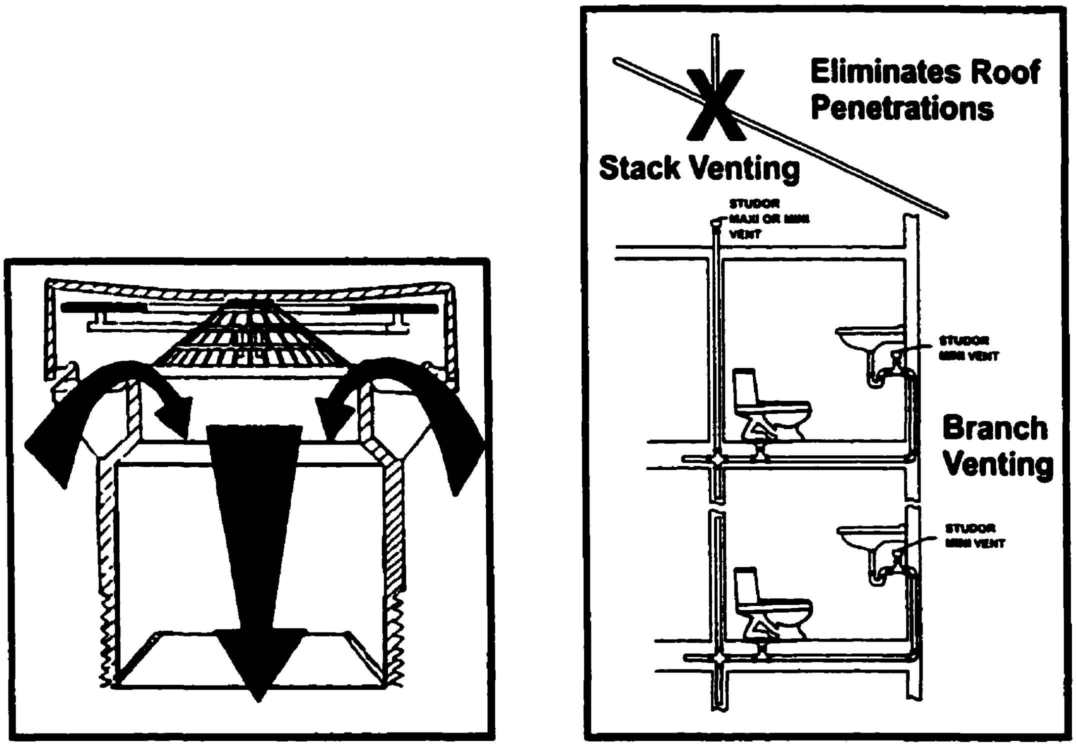


Figure 4.82: Air admittance vent. It can eliminate the need for floor and roof penetrations. (Source: Studor Inc. 2000)

CHAPTER FIVE
CONCLUSIONS

5.0 INTRODUCTION

This chapter presents a general overview of the study and is divided into three sections. The first section reviews the flexible products discussed in this thesis as a whole and whether they increase overall building flexibility. In the second, cost and quality issues are discussed. Finally, the author makes recommendations for the future of flexibility with respect to the user, the economy and the construction industry.

5.1 INTEGRATION OF FLEXIBLE PRODUCTS

When building systems are entangled, a house can not become completely flexible due to the inflexibility of certain components. However, this inflexibility can be a result of a lack of coordination between the flexible systems. Therefore, the author examines the flexibility between products.

The author believes that one should specify the desired level of overall building flexibility before selecting products in order to avoid conflicts between flexible systems. A different mix of flexible systems will offer a different degree of flexibility. For example, if moderate flexibility is desired, flexible partitions do not necessarily have to work with a long-span open web joist and, the flexible electrical, HVAC and plumbing systems may be excluded. This section will study all possible combinations of the flexible systems, which are shown on the table below (Table 6):

Combination of two systems:	Combination of three systems:	Combination of four systems:	Combination of five systems	Combination of six systems:
Ab, ac, ad, ae, af, Bc, bd, be, bf, Cd, ce, cf, De, df, Ef	abc, abd, abe, abf, acd, ace, acf, ade, adf, aef, bcd, bce, bcf, bde, bdf, bef, cde, cdf, cef, def	abcd, abce, abcf, abde, abdf, abef, acde, acdf, acef, adef, bcde, bcdf, bcef, bdef, cdef	abcde, abcdf, abcfe, abdef, acdef, bcdef	Abcdef
15 combinations are available	20 combinations are available	15 combinations are available	6 combinations are available	1 combination is available
Support category a: Long-span Joists		Infill category b: Flexible Partitions c: Flexible Stairs d: Flexible Electrical Systems e: Flexible HVAC Systems f: Flexible Plumbing Systems		

Table 6: Combinations of flexible building systems.

In total there are 57 possible combinations between the six building systems. An evaluation is also given to indicate how flexible these products could be when used simultaneously. The criteria are described below:

I. One point for each independent flexible system (cumulative).

II. Add another point if each independent flexible system favors the flexibility of others.

5.1.1 COMBINATIONS OF TWO COMPONENTS

- (ab) Long-span joists and flexible partitions:

Long-span joists reduce the need for making intermediate supports therefore, augment the flexibility of the flexible partitions.

Combined-flexibility rating: 3

- (ac) Long-span joists and flexible stairs:

  The STAIRFRAME seems to work with both floor systems using the dimension lumber and the engineered wood joists. Thus, the long-span joists would add little flexibility to the stairs. In addition, special details may be required for connecting the stairs to these engineered wood joists. The extra details would make the construction of stairs more complex and their installation more difficult, which could cause inflexibility.

  Combined-flexibility rating: 2

- (ad) Long-span joists and flexible electrical systems:

  Whereas electrical raceway systems are mounted on wall surfaces, the open-web joists allow wiring to be placed in the floor. Cutting the framing members for passing electrical wires can be avoided in the open-web joists. Also, wires can be quickly and easily relocated thanks to the open space in the web areas of these joists. Therefore, long-span joists could help to increase the flexibility of the flexible electrical and data/communication systems by making their installations more manageable.

  The accessible ceiling systems may also work with long-span joists. However, possible drawbacks include reduced fire resistance and sound rating as well as a lack of sturdiness in ceiling structures.

  Combined-flexibility rating: 3

- (ae) Long-span joists and flexible HVAC systems:

The engineered wood joists could increase the flexibility of traditional HVAC systems by fitting the ducts in the web areas. The ductless and mini-duct air distribution systems increase flexibility because their conduits are smaller and more flexible and can travel through floors more easily. The open-web joists could provide more free space for installing, servicing and relocating the conduits.

Combined-flexibility rating: 3

- (af) Long-span joists and flexible plumbing systems:

  The material characteristics and sizes of the present copper water supply systems and PVC drainage systems allow a certain degree of plumbing flexibility in traditional wood frame (dimension lumber) house construction. Engineered wood joists, especially those with open-web designs, permit freer passage of pipes. Therefore, a higher degree of flexibility is expected.

  Combined-flexibility rating: 3

- (bc) Flexible partitions and flexible stairs:

  In the author's opinion, the flexibility of these two components neither complement nor impede each other. They are independent systems.

  Combined-flexibility rating: 2

- (bd) Flexible partitions and flexible electrical systems:

  Although electric outlets and wires could be inserted in the cavities of the demountable partitions, the surface raceway systems still offer the highest degree of flexibility by placing the electrical systems outside. Surface raceway systems must be used in some movable wall systems due to their monolithic constructions. Switches may have to be moved to accommodate wall and ceiling fixtures. The demountable partitions permit electrical boxes to be installed in their cavities.

Therefore, the flexibility of accessible ceiling systems is best put to use when working in conjunction with demountable wall systems.

Combined-flexibility rating: 3

- (be) Flexible partitions and flexible HVAC systems:

  The conduits of the mini-duct air distribution systems are normally set within the floors or ceilings. Therefore, the flexibility of the demountable and/or movable wall systems would not increase the flexibility of the HVAC systems very much. The mini-duct air distribution systems and the ductless heat pumps may be able to increase the flexibility of partitions because they can be moved more easily when the rooms have been relocated.

  Combined-flexibility rating: 3

- (bf) Flexible partitions and flexible plumbing systems:

  Parts of plumbing systems are hidden in the walls. The cavities in the metal studs of the demountable partitions help to run pipes more easlyy and quickly. When the wall finishes are completed, the maintenance and alteration of plumbing can be done without damaging the wall panels. However, the movable partitions are unlikely to accommodate this type of flexibility because of their monolithic constructions.

  Combined-flexibility rating: 3

- (cd, ce, cf) Flexible stairs and flexible electrical, HVAC and plumbing systems:

  The electrical, HVAC and plumbing systems normally do not penetrate the staircase; therefore, flexibility in the stairs would have no effect on the flexibility of these systems, and vice-versa.

  Combined-flexibility rating: 2

- (de, df) Flexible electrical systems and flexible HVAC and plumbing systems:

  Because the electrical raceway systems are mounted on the wall surfaces and most of the HVAC and plumbing lines are placed in the floor/ceiling spaces, the flexibility of the raceways, mini-duct or ductless air distribution systems or plastic plumbing would not be affected.

  Combined-flexibility rating: 2

- (ef) Flexible HVAC systems and flexible plumbing systems:

  The reduced plenum sizes of the mini-duct or ductless air distribution systems may help to increase flexibility in terms of running the pipes for the plumbing fixtures in the floor/ceiling spaces. However, the plastic plumbing systems may have a limited effect on the flexibility of HVAC systems because they usually do not hinder the passage of ducts or conduits.

  Combined-flexibility rating: 2

5.1.2 COMBINATIONS OF THREE COMPONENTS

- (abc, abd, abe, abf): Long-span joists plus flexible partitions and flexible stairs, electrical, HVAC or plumbing systems

  Except the STAIRFRAME systems, which do not contribute much to the flexibility of interior spaces, flexible partitions must work with long-span engineered wood joists, surface electrical raceways, mini-duct or ductless air distribution systems, and plastic plumbing systems in order to stay flexible. Because these building systems are entangled, when the partitions move, the service systems must also move with them.

  Combined-flexibility rating: 4 to 5

- (acd, ace, acf): Long-span joists plus flexible stairs and electrical, HVAC and plumbing systems

  Since the STAIRFRAME systems are independent, they do not affect the flexibility between the engineered wood joists and the surface raceways, mini-duct or ductless air distribution and plastic plumbing systems. The flexibility of these three components combined could be seen as one without the flexible stairs. Nevertheless, the use of open-web joists could always improve the flexibility of installing the electrical, HVAC and plumbing systems.

  Combined-flexibility rating: 3 to 4

- (ade, adf): Long-span joists plus flexible electrical systems and flexible HVAC or plumbing systems

  The open-web joists may accommodate the conduits of the flexible electrical, HVAC and plumbing systems more easily than the engineered wood I-joists and V-joists. It appears that there is no system conflict within this combination. However, it may be less economical to use the engineered wood joists just for passing the wires and pipes.

  Combined-flexibility rating: 4

- (aef): Long-span joists plus flexible HVAC systems and flexible plumbing systems

  Despite the fact that flexible HVAC and plumbing systems could work with dimension lumber joists due to their reduced sizes and improved material flexibility, both the mini-duct/ductless air distribution systems and the plastic plumbing systems work with engineered wood joists just as well.

  Combined-flexibility rating: 5

- (bcd, bce, bcf): Flexible partitions plus flexible stairs and flexible electrical, HVAC or plumbing systems

  The STAIRFRAME systems are independent and, therefore, would not affect the flexibility of the other components. However, the flexibility of the HVAC and plumbing systems would not increase with the use of flexible partitions, except for the demountable type, which allow open access. The contrary is also true. Thus, it is futile to combine these systems in order to achieve a higher flexibility.

  Combined-flexibility rating: 3 to 4

- (bde, bdf, bef): Flexible partitions and the combinations of flexible electrical and HVAC systems, flexible electrical systems and plumbing systems or, flexible HVAC and plumbing systems

  The surface raceways could make wiring more flexible for flexible partitions. A higher mobility of the demontable and movable partitions could be achieved by using the flexible electrical, HVAC and plumbing systems. This is because they are manageable (i.e. easy to cut or make extensions and additions). Because they are small and flexible, installing them in floors, ceilings and walls is less difficult.

  Combined-flexibility rating: 4 to 5

- (cde, cdf, cef): Flexible stairs and the combinations of flexible electrical and HVAC systems, flexible electrical and plumbing systems or, flexible HVAC systems and plumbing systems

  Flexible stairs do not contribute to the flexibility of other building systems. Moreover, because the electrical, HVAC and plumbing systems are independent, no increase in flexibility could be achieved by putting them together.

  Combined-flexibility rating: 3

- (def): Flexible electrical systems plus flexible HVAC systems and flexible plumbing systems

  The surface raceways attain their flexibility by moving the wiring outside the walls and floors. This method would not help the flexibility of the mini-duct/ ductless air distribution systems or the plastic plumbing systems because of their low level of entanglement.

  Combined-flexibility rating: 3

5.1.3 COMBINATIONS OF FOUR COMPONENTS

- (abcd, abce, abcf): Combinations of the long-span joists, flexible partitions and flexible stairs and the flexible electrical, HVAC or plumbing systems

  The independent STAIRFRAME systems do not contribute to the flexibility of other flexible building systems. However, the flexible partitions work best with long-span engineered wood joists, surface raceways, mini-duct/ductless air distribution systems and plastic plumbing systems.

  Combined-flexibility rating: 6

- (abde, abdf): Combinations of the long-span joists, flexible partitions and flexible electrical systems and the flexible HVAC or plumbing systems

  The use of long-span joists with the flexible partitions, and surface raceway systems could increase flexibility when relocating interior spaces with more flexibility. The additional use of flexible HVAC and plastic plumbing systems as well as flexible partitions could push this flexibility higher by making the service systems more mobile.

  Combined-flexibility rating: 7

- (abef): Long-span joists plus flexible partitions plus flexible HVAC and plumbing systems

  The flexible partitions, mini-duct/ductless air distribution systems and plastic plumbing systems depend on engineered wood joists (especially those with open-web designs) to achieve their maximum level of flexibility. The service systems also make demountable and movable partitions more mobile.

  Combined-flexibility rating: 9

- (acde, acdf, acef): Long-span joists plus flexible stairs vs. the combinations of flexible electrical, HVAC and plumbing systems

  The flexibility of engineered wood long-span joists, surface raceways, mini-duct/ductless air distribution systems and plastic plumbing systems would not be influenced by the use of the STAIRFRAME systems.

  Combined-flexibility rating: 5

- (adef): Long-span joists plus flexible electrical, HVAC and plumbing systems

  The engineered wood joists would have little effect on the flexibility of the surface raceways, but the open-web joists could make the installation of the mini-duct/ductless air distribution systems and the plastic plumbing systems easier.

  Combined-flexibility rating: 5

- (bcde, bcdf, bcef): Flexible partitions plus flexible stairs plus the combination of flexible electrical and HVAC and plumbing systems

  The independent STAIRFRAME systems could be omitted from the assessment of joint-flexibility of various flexible products. Nevertheless, the surface raceways, mini-duct/ductless air distribution systems and the plastic plumbing systems would help when relocating flexible partitions.

  Combined-flexibility rating: 5 to 6

- (bdef): Flexible partitions plus flexible electrical, HVAC and plumbing systems

  Without the use of long-span engineered wood joists, the flexible partitions may not be able to provide the maximum flexibility for changing interior layouts. However, the mobility of the surface raceways, accessible ceilings, mini-duct/ductless air distribution systems and the plastic plumbing systems could make demountable and movable partitions more flexible.

  Combined-flexibility rating: 7

- (cdef): Flexible stairs plus flexible electrical, HVAC and plumbing systems

  The STAIRFRAME systems would have no impact on the flexibility of the flexible electrical, HVAC and plumbing systems. Also, each of these systems is independently flexible and would not become more so when combined with any other building components.

  Combined-flexibility rating: 4

5.1.4 COMBINATIONS OF FIVE COMPONENTS

Five of the six combinations of flexible building systems include flexible stairs. Since the STARIFRAME system does not affect the flexibility of others, it will be excluded from the assessment of joined-flexibility. Therefore,

(abcde) becomes (abde),

(abcdf) becomes (abdf),

(abcef) becomes (abef),

(acdef) becomes (adef) and,

(bcdef) becomes (bdef).

- (abcde, abcdf, abcef): Long-span joists plus flexible partitions plus flexible stairs and the combinations of flexible electrical, HVAC and plumbing systems

  Flexible partitions attain their highest flexibility by using engineered wood long-span joists and other flexible electrical, HVAC and plumbing systems. Since the utility systems tend to be independent, there would be little conflict between them.

  Combined-flexibility rating: 7

- (acdef, bcdef): Flexible electrical, HVAC and plumbing systems and the combination of long-span joists, flexible partitions and flexible stairs

  These combinations have already been mentioned above.

  Joined-flexibility rating: 6

- (abdef): Long-span joists plus flexible partitions plus flexible electrical, HVAC and plumbing systems

  The use of engineered wood long-span joists (as the Support), flexible partitions, and flexible service systems (as the Infill) exhibits the most flexibility of all the combinations.

  Combined-flexibility rating: 7

5.1.5 COMBINATIONS OF SIX COMPONENTS

- (abcdef): Long-span joists plus flexible partitions plus flexible stairs plus flexible electrical, HVAC and plumbing systems

  This is the only combination available which puts together all the flexible products presented in this thesis. Since the independent STAIRFRAME systems do not contribute to the flexibility of other systems, the rating is similar to the combination of (abdef), which was described earlier.

  Combined-flexibility rating: 8

In summary, more flexibility could be obtained by combining products from the Support category with those from the Infill category. Since the utility systems presented in this thesis were designed to increase flexibility in traditional wood frame house construction, using engineered wood joists would improve the flexibility by fitting the utility systems more efficiently. However, products from the same category (especially the utility systems from the Infill category) would not gain additional flexibility when put together due to the modular designs that make them entirely independent of one another.

5.2 OTHER THOUGHTS

Do the construction products in this study contribute to flexibility in house construction? Yes. The products would deliver their promised results if other building systems do not physically interfere with the installations, maintenance and modifications. However, there are other considerations that mitigate the potential benefits of these products.

5.2.1 COSTS

The high installation cost of some products, such as flexible partitions and mini-duct or ductless HVAC systems, may persuade the builders or occupants to choose other traditional, less-flexible alternatives. The cost of hardware also contributes to the high initial expense because the products were designed to accommodate future changes. Although these costs can be reduced by doing self-installation, householders must posses a degree of construction skill to install the systems on their own (Yamin 1990). The users must learn to install products themselves in order to avoid paying the high labour rates of professionals. This implies that housing flexibility is meant for people who know about building construction. Also, this presents the possibility that flexibility products would not be more economical.

The author suggests that governments provide a financing option to cover the high initial cost, plus subsidize a training program to get people familiar with basic house construction. With the support of the governments, these products could become more flexible and affordable, and, therefore, more acceptable to the public.

5.2.2 QUALITY

Quality can be measured by the dweller's satisfaction and the durability of the products. It is also proportional to the cost and the degree of flexibility. Therefore, the quality level varies from project to project. However, high-quality products do not necessarily contribute to higher flexibility. For example, quality-oriented movable partitions[18] focus on solid construction, precise fit and finish and the use of good materials. These partitions are heavier and often require special tools to install. The manufacturers recommend that certified installers carry out the setup. This delivers the best results, but does so at the users' expense. The high price coupled with the "sturdy" assemblage of parts may create a counter effect that reduces flexibility. The author believes that there should be more research into the relationship between flexibility levels and quality levels.

5.3 RECOMMENDATIONS FOR FUTURE FLEXIBILITY CONSTRUCTION PRODUCTS

In addition to improving these products' quality, flexibility, and efficiency in terms of labour use and materials, the industry should develop new construction products that contribute to increased flexibility. First, the products would gain higher acceptance if they were considered to be a means of keeping the home building industry efficient,

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[18] Movable partitions are normally better than demountable partitions because of their consistency in quality. In this study, the most expensive (also the highest quality) movable partition is the Palliser Series from the Partition Systems Ltd.

productive, and competitive (Sternthal 1994). To this end, more new materials, components and systems should be introduced. However, these innovations should avoid introducing dramatic changes to the existing home-building practices. Otherwise, the risk of rejection may be high.

Second, because the entire building system is separated into components and independently developed by manufacturers, new organizational concepts and management techniques are required to integrate these systems in a more efficient way. Hutchings (1996) mentioned: "The modular construction industry's evolution has been disorganized. Different manufacturers make different things, ... which led to fragmented business with noncohesive industry direction or representation." With the arrival of new technologies and new products, a method must be established to ensure the efficient connection/transition between the new and the old. The installation works and tools should also be simplified and standardized. It takes time to train workers (or even dwellers) to use new procedures, and money to purchase the tools that are necessary to implement a new product. The future products should prevent a drop in efficiency due to users' adaptations.

Third, the offer of too many flexibility options can become confusing at times. The author suggests that, in the future, a study focusing on builders' and occupants' needs be done to enable them to determine the level of flexibility appropriate to any given project. The new products should also help their users to find the appropriate degree of flexibility for home design, production, marketing and occupation. The industry could develop a standard rating system to indicate the product's degree of flexibility. With it, the manufacturers could "calculate" the range of flexibility for one or a mix of products. When the flexibility is expressed as an "index", the products could be more comprehensively and efficiently selected by its users. This could help them avoid making an unnecessary investment in unwanted features.

In conclusion, the use of construction products that contribute to increased flexibility in wood frame low-rise housing is closely associated with the degree of flexibility of a project. In the future, when new technologies or techniques are invented, more components can become flexible. However, their full potential can only be met if system entanglement is solved, cost is reduced and installation is made more accessible to common users. With support from the government and the construction industry, we can benefit more from an expanded range of housing flexibility.

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APPENDIX A

FLEXIBLE PARTITIONS SUMMARY

		Demountable Wall Partition System			
General Data	Model	PC350 Gravity Lock	PS350	PS350 Edge Clip	Envirowall battenless
	Type	Non-Progressive	Non-Progressive	Progressive	Progressiv
	Manufacturer	Partition Components Inc.	Partition Systems Ltd.	Partition Systems Ltd.	Envirowall Systems L
Economy	Cost of Components	$30 per L. ft.	$30 per L. ft.	$30 per L. ft.	$49 per L.
	Cost of Installation	$25 per L. ft.	$25 per L. ft.	$25 per L. ft.	Incl. Abov
Technical Data	Feature	Gravity Lock Panel Clips fits into three rows of horizontal channels making installation quick and easy	Support clip and carrying bracket system is another alternative to Gravity Lock system	Monolithic-like Edge Clip system is used on regular gypsum board to make demountable partition	Enviroclip clips can b adjusted fo positioning
	Useful Life	50 years	50 years	50 years	25 years
	Electrical Wiring	Within wall or optional PVC/ aluminum electric raceway base	Within wall	Within wall	Within wa
	Fire Rating (hr.)	1 hr.	1hr.	1hr.	1hr.
	Sound Rating (STC)	34 - 48 (with insulation)	43	46	35 - 50
	Fixing Conditions	Suspended ceiling/double floor not required	Suspended ceiling/double floor not required	Suspended ceiling/double floor not required	Suspende ceiling/do not requir
	Panel Dimension	Max. 4' x 8	Max. 4' x 8	Max. 4' x 8	Max. 4'
	Panel Weight	58 kg	60 kg	60 kg	60 kg
	Installation Time	1.6 man hour	1.6 man hour	1.6 man hour	1.4 man h
	Installation Tool	Light weight tools with 1 electrical equipment	Light weight tools with 1 electrical equipment	Light weight tools with 1 electrical equipment	Light weig with 1 ele equipmen
Appearance	Modular Characteristics	Hairline panel joint, PVC batten covers appear at wall intersection and corner	Hairline panel joint, PVC batten covers appear at wall intersection and corner	Hairline panel joint, PVC batten covers appear at wall intersection and corner	Hairline p PVC batte appear at intersectio corner
	Color	9 choices of trim colors; 20 choices of panel colors	Any customized color and texture	Any customized color and texture	34 standa colors/pa plus custo componen

tition System			Movable Wall Partition System			Drywall
lip	Envirowall, battenless	Envirowall, batten	Palliser Series	World Wall Series	V-Wall	Gypsum Wallboard
	Progressive	Non-Progressive	Non-Progressive	Non-Progressive	Progressive	Monolithic
ms	Envirowall Partition Systems Ltd.	Envirowall Partition Systems Ltd.	Partition Systems Ltd.	Partition Systems Ltd.	Herman Miller Inc.	Westroc Inc.
	$49 per L. ft.	$49 per L. ft.	$135 per L. ft.	$50-60 includes hardware, door/window frames	$60 per L. ft.	$53.5 per L. ft.
	Incl. Above	Incl. Above	$20 per L. ft.	$25 per L. ft.	$35 per L. ft.	Incl. Above
e tem jular l to ntable	Enviroclip panel clips can be adjusted for positioning	A more traditional approach to demountable partition construction that is easy to install, remove, replace and make addition	Spring-loaded upper guide pins and leveling feet to enhance installation positioning	Trimmable unitized panel module at wall-end	Action Office Hanger Strip/ Connector permits wall hung furniture be installed at any height	Trimmable, easily installed and demolished
	25 years	25 years	50 years	50 years	20 years	20 years
	Within wall	Within wall	Not possible within wall; must use external electric raceway	Within panel joint (vertical electrical/data chase)	Not possible within wall; must use external electric raceway	Within wall; must bore across studs or use steel stud
	1hr.	1hr.	1hr.	1hr.	1 hr.	1 hr.
	35 - 50	35 - 50	39	25	38	40
e floor	Suspended ceiling/double floor not required	Suspended ceiling/double floor not required	Suspended ceiling/double floor not required	Suspended ceiling/double floor not required	Suspended ceiling/double floor not required	Fastened on top of wood members
	Max. 4' x 8	Max. 4' x 8	Max. 4' x 8	Max. 4' x 8	Max. 4' x 8	Max. 4' x 8
	60 kg	60 kg	80 kg	60 kg	80 kg	60 kg
r	1.4 man hour	1.4 man hour	1.2 man hour	1.6 man hour	1.6 man hour	3 man hour
tools cal	Light weight tools with 1 electrical equipment	Light weight tools with 1 electrical equipment	Light weight tools with 1 electrical equipment	Light weight tools with 1 electrical equipment	Light weight tools with more than 1 electrical equipment	Light weight tools with 1 electrical equipment
el joint, covers ill and	Hairline panel joint, PVC batten covers appear at wall intersection and corner	PVC batten covers are visible at every panel joint, intersection and corner	PVC batten covers are visible at every panel joint, intersection and corner	PVC batten covers are visible at every panel joint, intersection and corner	Hairline panel joint, or noticeable arrays of hanger strip/connector	Uniform flat surface
zed xture	34 standard colors/patterns, plus custom component color	34 standard colors/patterns, plus custom component color	Any customized color and texture	Any customized color and texture	16 colors	Any color