RATIONALIZATION OF BATHROOM SERVICE
SUB-SYSTEMS IN HIGH-RISE PUBLIC HOUSING

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ABSTRACT

Because of the increasing demand for a large quantity of public housing in Taiwan, construction productivity has become an important issue. Among those building elements, the bathroom has been accused as presenting one of the more severe bottlenecks in production, due to the great number of so called "looped" operations which seriously decrease bathroom assembly efficiency in particular and overall building construction productivity in general.

Many foreign countries have developed various industrialized bathroom systems to improve on-site assembly efficiency. These systems have adopted different concepts towards bathroom design and subsystem categorization which are supposed to increase assembly efficiency in their contexts. Since the elimination of "looped" operations serves the same purpose; i.e., to achieve higher assembly efficiency, it seems clear that it may also lead to the task of conceptually redefining conventional bathroom subsystems that are currently being produced and used in Taiwan.

Given the situation that, in Taiwan, we should first try to rationalize our construction methods instead of leaping directly into industrialized ones, a situation which has been taken for granted by both the government and the private sectors as a remedy for the current housing shortage dilemma, this thesis tries to rationalize conventional Taiwanese bathroom assembly processes by examining the "looped" operations in relation to bathroom subsystems as a pilot study for more rationalized, assembly-efficient bathroom designs, and eventual or possible industrialization.

Title: Associate Professor of Architecture.
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CHAPTER 1: INTRODUCTION.
1.1. PURPOSE OF STUDY.

The objective of this thesis is to rationalize bathroom service sub-system construction methods to provide a higher living standard and greater productivity as a possible and/or potential further step towards housing industrialization in Taiwan.

The industrialization of housing, especially in the area of low-income public housing, has been recommended by many academic institutes and government officials as a remedy for the current housing shortage in the Taiwan area, for the following reasons:

1. Substantial increase in productivity of labor and the substantial reduction of manpower necessary to carry out the large scale construction projects (especially the reduction of high-skilled, specialized workmanship.)

2. Ability to speed up construction, so as to reduce its dependence on climate conditions.

3. Ability to reduce costs of housing, both overall and per unit.

4. Ability to secure standardized high quality products.

It is understandable then that housing agencies and officials in Taiwan have displayed great interest in the
concept of industrialized housing. This thesis attempts to further the success of this construction method. However, I am convinced that before fully industrialized systems can be adopted and utilized to gain the greatest possible advantages of the four aspects mentioned previously, there are many pre-requisite questions to be asked, such as:

1. How big is the market for these systems?
2. How skillful is existing labor?
3. Is the development on the economic level compatible with the heavy investment required by fully industrialized systems?
4. What is the existing level of service and social infrastructure of the context?

Failing to ask these questions and to distinguish between myth and reality concerning industrialized housing, particularly in developing areas, invites many dangers that frustrate housing officials who import into their own countries large, sophisticated and costly housing manufacturing plants of the highly industrialized countries without factoring into the process all the secondary prerequisites for establishing not only a new type of industry, but also a more efficient one (i.e., more efficient than the existing one.)

In the range of industrialized housing techniques, the partially-industrialized construction technique called
"rationalization" of housing construction comes to mind first, as it requires less radical technical changes to existing technology, and at the same time can provide a relatively simple, inexpensive, but highly productive approach leading eventually to fully industrialized methods.

Rationalized methods may be adopted by nations which have less developed technologies, but which eventually intend to take advantage of fully industrialized construction methods. It promises equal or greater housing production gains in the long run than the immediate introduction of large imported systems without additionally creating an adverse balance of payment situation, and without a radical disruption of established conventional methods of construction.

Terner, in his book, "Industrialized Housing. The opportunity and The Problem in Developing Areas.», raises the concept of "partial industrialization". He points out that:

"industrialization is a composite process, part of which is immediately appropriate and useful in developing areas, and part of which are not."

The composite process of industrialization can be described as a process embodying four independent variable aspects:

1. Systemization.
2. Labor Specialization.
3. Concentration of Products.
4. Mechanization.

The concept of partial industrialization derives from the composite nature of full industrialization and is used to describe a manufacturing or production strategy that selectively uses some industrialization aspects, while avoiding or postponing the use of others.

Thus, according to the four variable aspects mentioned above, full industrialization will have to fulfill all four of these aspects, while different combinations of these variables represent different levels or patterns of partial industrialization. Conventional construction methods may include very few or none of these variables.

Many developing countries, and even some developed ones as well, have found that it is hard and also impractical to satisfy all four variables due to a variety of social, economic and technological constraints. The concept of a "partial industrialization" strategy is thus especially suitable for these nations to improve their current building productivity and to advance in an orderly fashion towards further industrialization.
The following diagram (Fig. 1) best illustrates the concept of "partial industrialization". In this diagram, the whole evolution of industrialization is represented by two supplementary characteristics:

1. Product Technology.

The central cell indicates the product and process characteristics of partial industrialization and it is the most suitable position in the whole range of industrialization for those countries that are not capable of, or wherein it is not feasible to maintain the four variable aspects mentioned previously.

Fig. 1
Industrialization of process compared to product technology. Source: Ian D. Terner, "Industrialized Housing. The Opportunity and The Problem In Developing Areas."
1.2. THE BACKGROUND.

From my personal experiences in architectural practice, it has been clear to me that the construction industry in Taiwan is not yet fully prepared to accept a fully industrialized method for the following reasons:

1. There is still an abundance of unskilled, inexpensive labor (Unskilled labor represents almost 70% of the total construction population.)

2. Except for foundations and heavy construction, the industry is still labor-intensive and uses less mechanized construction methods.

3. Government investment in housing, which is a very important prerequisite for industrialized housing, has been very low, especially when compared with that of the adjacent countries which have a similar geographical and environmental situation but which have adopted fully industrialized housing methods, such as Japan, and to some extent, Singapore as well (Table.1).

<table>
<thead>
<tr>
<th>Year</th>
<th>1973</th>
<th>74</th>
<th>75</th>
<th>76</th>
<th>77</th>
<th>78</th>
<th>79</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>8.82</td>
<td>8.09</td>
<td>7.75</td>
<td>7.86</td>
<td>8.52</td>
<td>7.41</td>
<td>7.34</td>
<td>--</td>
</tr>
<tr>
<td>Singapore</td>
<td>7.97</td>
<td>8.16</td>
<td>7.75</td>
<td>9.17</td>
<td>8.43</td>
<td>5.92</td>
<td>5.21</td>
<td>5.52</td>
</tr>
<tr>
<td>Taiwan</td>
<td>3.08</td>
<td>2.80</td>
<td>3.20</td>
<td>3.29</td>
<td>3.59</td>
<td>4.22</td>
<td>4.49</td>
<td>4.51</td>
</tr>
</tbody>
</table>

Table 1. Housing Investment as Precentage of GNP From 1973-1980.
4. No modular coordination of building materials and coordination of the different parties involved in the building industry has been established yet. Without nationwide product standardization, the possibility of producing "open" systems is not likely and the situation would result in developing only "closed" systems which essentially invite high risks and heavy capital investment. Unless there is a strong incentive, i.e., vigorous government financial support in the early stage of industrialization, it is nearly impossible for "closed" system producers to survive financially. Since government participation in this area has been non-existent, and with poor modular coordination of the various participants in the building industry, it is clear why most of the industrialized building manufacturers in Taiwan have shut down since the 70's.

However, granted that Taiwan has these difficulties, there is nevertheless a great potential for housing industrialization in this country. The unskilled labor force is gradually decreasing; a huge amount of low-cost housing is needed due to rapid of urbanization*. In addition to those factors, the production system of the building industry as a whole is changing from labor-intensive towards technology-intensive methods, which

* The current public housing demand is 60,000 units per year over a ten year period (from 1982-1991); if this goal is to be reached, the productivity of construction labor has to be increased by 1.5 times within this ten year period.
means that labor costs are becoming expensive as well. Thus, the progressive industrialization of building construction certainly seems to be an effective way to manage this emerging new situation in the building construction industry.

Nevertheless, before the full benefit of the industrialized housing construction method can be obtained it seems necessary to rationalize current conventional construction processes by means of partially industrialized processes and products to pave the way for future improvements, and to introduce the full discipline of industrialized methods and processes.

In this thesis, an example of such a process of rationalization leading eventually to full industrialization has been chosen which seems to be an ideal candidate for rationalization; namely, bathroom service sub-systems in public housing. The choice of the bathroom as a case study example also was determined partially by available time for completion of this thesis, and, more important, by the recognition of the critical influence of such sub-systems on overall construction time and cost in public housing projects.
1.3. THE PROBLEM.

Bathroom assemblies are characterized by their inefficient and time-consuming work flow problems, i.e., so-called "looped" operations which seriously impede the smooth flow and productive environment of the trades involved in the assembly process, and which lead to severe construction delays in conventional construction and tend to generate chaos in the industrialized work process.

These assembly interfaces between bathroom components, and the subsequent "looped" operations, are not only the result of the conflicts between various traditional trade disciplines involved in the overall building construction process, but also the result of assembly conflicts between traditionally perceived and defined bathroom physical constituents. When facing a rapid growth of public housing demand and the parallel need for higher construction productivity, the traditional environment for bathroom assemblies in particular and the construction industry's perception of bathroom constituents in general have to be changed, if industrialized housing methods are to be introduced as a better or more efficient way to manage the current housing dilemma.
In this thesis, I shall try to examine the conceptual transformation of bathroom constituents in relation to the increase of bathroom assembly efficiency by analyzing "looped" operations and component interfaces in current bathroom constructions in Taiwan.

"Looped" operations, as defined by Nuttal*, are:

the "type of operations which require a trade or gang to halt before finishing work in a construction site, and return to complete it at a later time." (Fig. 2)

Eliminating or decreasing the number of these types of operations means rationalization with higher productivity, and requires the examination of the various interfaces between bathroom components and their assembly sequences. A network diagram analysis of the assembly process will be used to examine where these "looped" operations take place and how they can be reduced in relation to bathroom constructions.

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subsystems.

In high-rise residential buildings, the impact of such operations on construction flow and construction time are of special significance due to the repetitive and recurrent nature of tasks carried out on different floor locations in the same building, and to the much higher productivity that could easily be gained by:

"1) maximizing the use of the learning curve by each task trade and 2) the minimizing of moving task trades off and on to a site once his task has begun 3) the minimizing of starting and stopping of task trades on each flow of similar tasks (on floor locations)."*

Since the population density in Taiwan is high, it is the government's policy to encourage high-rise housing projects instead of low- to medium-rise apartments. The elimination of "looped" operations in bathroom assemblies to rationalize high-rise residential building construction and to speed up construction duration for solving the housing shortage dilemma thus becomes virtually important.


***
CHAPTER 2: METHODOLOGY
Since this thesis is written in the hope that the current bathroom assembly processes in Taiwan could be more rationalized in order to make public housing more efficient and more affordable, it is believed that the conventional Taiwanese bathroom assemblies should be first analyzed to get insights into assembly interfaces between trades, tasks and components involved in the process, and looped operations mentioned previously.

Before doing this analysis, a conventional Taiwanese bathroom will be conceptually subdivided into its subsystems. These subsystems are generated in such a way that each contains components which:

1. have similar assembly characteristics, i.e., components of each subsystem are assembled
   a) by the same trade discipline,
   b) by using identical tools,
   c) by using the same material.

2. cause similar assembly interfaces with components of other subsystems.

3. serve similar bathroom functions.
According to these principles, a Taiwanese conventional bathroom can be conceptually subdivided into three subsystems:

1. Plumbing Core,
2. External Envelope,

Following this subsystem categorization, Chapter 3 will concentrate on describing the interface characteristics between the three subsystems when they come together to form a bathroom. However, this discussion will stay on the subsystem level to establish only a general picture about the role each of these three subsystems plays, and about the influences each of them has on the other two in the bathroom assembly process. Since most of the looped operations are the result of the interfaces between these subsystems, the description in this chapter is extremely important to the analysis in Chapter 4.

Chapter 3 also serves another important function: to generate a clear basis and set of definitions of terms for the detailed component assembly analysis of looped operations and component interfaces, to be dealt with in Chapter 4.
in Chapter 4, detailed component assembly interfaces and looped operations will be analyzed in terms of a network diagram. This diagram externalizes the assembly precedence of tasks involved in a specific operation (Fig. 3).

Fig. 3  A network diagram for identifying looped operations.

Three "operations" will be analyzed. They are:

1. washbasin installation.
2. bathtub installation.
3. lavatory installation.

The reasons for choosing these three operations for analyzing component assembly interfaces and looped operations are the following:

1. All the components in a bathroom are essentially assembly-interrelated; the examination of one component will have to cover almost all the others.

2. The completion of each of these three sanitary fixture operations usually has to involve the completion of most of the component assemblies of the other two subsystems.
These three operations will then be analyzed by using a network diagram. The network diagram makes the looped operations explicit by presenting the tasks involved in these three operations in their sequential order. Since a task is usually executed by one trade; therefore, if two tasks which are carried out by the same trade are not consecutively executed, a looped operation can thus be identified. All the looped operations in the three sanitary fixtures installation operations will be analyzed in this manner.

Since the categorization of bathroom subsystems is closely related to the assembly interfaces and assembly efficiency, I shall keep examining how the categorization of these subsystems has affected the assembly efficiency by analyzing the relationships between each subsystem categorization and perceived looped operations.

In the meantime, possible improvements for eliminating looped operations will also be analyzed by reorganizing the assembly sequences in such a way that the number of looped

* A network diagram is constructed on the basis of tasks rather than trades; one task may involve more than one trade. However, experience has shown that in general, in bathroom constructions, due to the relatively small floor area, a bathroom occupies relative to that of one apartment unit, a task usually involves only one trade.
operations can be minimized and the component interfaces can be simplified.

These improvement strategies are developed purely from the point of view of an efficient assembly of the physical bathroom components; other software* variables which are also major determinants in achieving overall efficiency, require further studies and are not included in this thesis.

In Chapter 5, cases of existing foreign bathroom systems will be given as examples, to contrast current conventional Taiwanese practice in terms of subsystem differentiation in relation to the capacity of reducing looped operations and component assembly interfaces.

Again, these systems will be first categorized in terms of levels of industrialization, which they fall into. It is believed that the more industrialized a system is, the more assembly-efficient it will be, assuming that other software determinants are well managed. For each category, several typical examples will be given to demonstrate the ways these examples have been adapted to achieve on-site bathroom

* The term "software" here refers to general economic, sociological and environmental aspects of a context in which a system is developed. Such issues as building codes, trade disciplines, technology level of the building industry, and hygienic habits of the population are some of the major elements considered as software.
assembly efficiency, and the way these systems are subdivided into subsystems.

Chapter 6 will conclude this thesis by reviewing the concept of bathroom subsystem recategorization to eliminate looped operations. Several suggestions for such a recategorization will be discussed and areas that need to be further examined will be raised as well. Two issues will be the stressed:

1. The forming of "hybrid" elements.
2. The transformation of component interdependence.
CHAPTER 3: DESCRIPTION OF CONVENTIONAL BATHROOM SUBSYSTEMS.
3.1. CLASSIFICATION OF SUBSYSTEMS.

A conventional bathroom can be conceptually divided into three subsystems:

1. External Envelope.
2. Sanitary Fixtures.
3. Plumbing Core.

Fig. 4 Schematic classification and hierarchical locations of conventional bathroom components.

Each of these three subsystems consists of components which have similar functional, material or assembly characteristics. On-site assembly of a bathroom causes assembly interfaces mainly in positions where the three subsystems meet. Thus, efficient assembly of a bathroom is principally concerned with reducing the interfaces between components of different subsystems and the various looped operations resulting from these interfaces (Fig. 4).
3.2. DESCRIPTION OF SUBSYSTEMS.

3.2.1. EXTERNAL ENVELOPE:

The external envelope subsystem includes at least four vertical space separating components and two horizontal floor/ceiling components. Space separating components can be windows, doors, or simply partition walls (Fig. 5). These components refer to only rough and unfinished components. When finished, they are referred to as "finished" external envelope components.

![Fig. 5 External envelope components.](image)

In high-rise residential buildings, the bathrooms of two adjacent apartment units are usually attached to each other and at least one vertical bathroom envelope component is shared by two adjacent apartment units as a party wall.
The plumbing core is always located adjacent to this vertical envelope component (Fig. 6) in order to economize on both the plumbing service space and the plumbing material cost (if each apartment unit had its own vertical duct, the material cost of pipes would be doubled.)

![Diagram of plumbing cores and bathrooms of adjacent apartment units.](image)

3.2.11. PRIMARY AND SECONDARY EXTERNAL ENVELOPE COMPONENTS.

Conventional Taiwanese sanitary fixture component assemblies rely heavily on the erection of envelope components as reference planes (details on this will be given later in the analysis of the Taiwanese bathroom assemblies). Sometimes a sanitary fixture component assembly depends on the completion of two or even three envelope components. Those (one or several) on which a sanitary fixture component depends as a reference plane and
which the plumbing lines penetrate to connect the fixture outlets are called the "primary external envelope components", the others are called "secondary external envelope components".

For instance: as mentioned earlier, the assembly of a bathtub in a bathroom construction depends on the completion of at least two envelope components; but only the one that is adjacent to the plumbing core has to be penetrated by the pipe lines. In other words, this envelope component interferes with both the plumbing core subsystem and the sanitary fixture components, while the other one interfaces with only the bathtub itself. The former is a "primary external component" and the latter a "secondary external envelope component" (Fig. 7).

![Diagram of primary and secondary envelope components of bathroom sanitary fixtures.]
3.2.12. PRODUCT VS. PROCESS OF ENVELOPE COMPONENTS.

Brick and cement are the main materials for envelope component construction in Taiwan. Bricks are transported from the factories to various sites and directly assembled on site into four vertical envelope components; they mainly represent "direct application" *, since no off-site or on-site pre-assembly process involved (Fig. 8). The other two horizontal external envelope components are concrete-made, and are independent of the vertical assemblies of vertical envelope in terms of overall building construction process because these two horizontal external envelope components are not included in the workflow of bathroom assemblies. Instead, they are included in the workflow of infrastructure construction in high-rise buildings.

* Direct application is defined by Kenneth Claxton as "systems which are assembled on site from components.", while indirect application is defined as "systems which are assembled from elements and spatial units."

3.2.2. SANITARY FIXTURE COMPONENTS.

Sanitary fixture components are all located within the external envelope and are affixed to at least one of the external envelope components.

As mentioned previously, high-rise residential buildings have each of their service plumbing cores shared by two adjacent apartment units. Thus the most rational and economical layouts of the sanitary fixture components are those which are arranged in such a way that all the primary external envelope components associated with sanitary fixtures are virtually the same (i.e., one integral envelope component) acting at the same time as the apartment separating wall (the party wall) (Fig. 9).

In this thesis, analysis will be concentrated on
rationalizing the assembly process of the case (b) shown in Fig. 9. Case (a) shown in Fig. 9. is in itself considered "irrational" because of its inefficient use of materials and excessive consumption of construction time.

3.2.21. PRODUCT VS. PROCESS OF SANITARY FIXTURE COMPONENTS.

Sanitary fixture components have reached the highest level of off-site prefabrications among the components of other subsystems. However, most of the sanitary fixture components may be considered as "closed" in the sense of system interchangeability and interface adaptability. They are made to their own specifications, to match dimensionally only certain specific types of compatible brand-name plumbing fixtures or other proprietary sanitary fixtures. We can hardly find any general or universal dimensional coordination and/or compatibility between existing sanitary fixture components.

In terms of rationalization and component standardization, these prefabricated "closed" sanitary fixture components offer little help for upgrading the overall current level of bathroom assembly efficiency.
But, regardless of these "closed" components, there are many conventional sanitary fixtures on the market, such as bathtubs, washbasins and lavatories and other related accessories which incorporate more compatible standard and/or interface compatibility between each other. These conventional components are routinely assembled on the site with external envelope components and plumbing fixtures into complete bathrooms. Some of these sanitary fixtures involve more or less integrated off-site pre-assemblies, such as pre-assembling the plumbing faucets with bathtubs off site, before being sold on the market. Figure 10 shows the relationships between the application of these sanitary fixtures and the initial primitive form of these fixtures. Most of them are for direct application, except for some prefabricated components which involve some degree of indirect application.*

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* See page 30 for definition.
3.2.3. PLUMBING CORE COMPONENTS.

The plumbing core is mainly composed of plumbing fixtures such as pipes and fittings. These are considered as basic components. The enclosure that forms the duct containing these plumbing fixtures is categorized as part of the envelope subsystem, rather than as part of the plumbing core subsystem.

The plumbing core contains mainly only vertical plumbing components; i.e., vertical waste and supply lines. In the case of Taiwan, horizontal plumbing lines are usually either integrated in the vertical external envelope components, usually the primary one, or are placed underneath or above the horizontal external envelope component (Fig. 11).

---

Fig. 11
As we can see from the above figure, the horizontal lines run within the external envelope components or underneath or above the floor only when the sanitary fixtures do not share the same primary external envelope component (see Fig. 11). In this case, the horizontal lines have to branch out from the vertical lines and then run either through the wall (envelope component) or above or beneath the floor to reach the fixture outlets.

When the sanitary fixtures are arranged in such a way that they share the same primary external envelope component, i.e., they are all affixed to the same piece of wall, the vertical lines can be located on the other side of the wall right behind the fixtures and thus can easily be connected to the sanitary fixtures without using long horizontal lines. This arrangement concentrates the fragmented locations of component interfaces between the plumbing lines and the envelope components in a bathroom to a smaller area where assembly contingent situations may be the minimum. These horizontal lines run within the vertical duct then penetrate through the primary envelope component, to be eventually connected to the sanitary fixtures; it is not necessary to incorporate horizontal lines into the envelope components in this case, nor do the horizontal lines have to run beneath or above the floor (Fig. 9 and Fig. 11).
3.3. INTERFACES BETWEEN SUBSYSTEMS.

The existence of the previously described interfaces between the three Taiwanese bathroom subsystems defined on page in Taiwan, are usually caused by so-called "reciprocal component interdependence" that we are going to see in this section.

Based on the linkage between activities of organizational subunits, Thompson, in his book "Organizations in Action"*, identifies three types of interdependence as follows:

1. Pooled interdependence, which occurs in situations where a unit renders a discrete contribution to the overall organizational effort but does not interact at all with a second unit.

2. Sequential interdependence, which exists in situations where the output of one trade becomes the input of a second trade.

3. Reciprocal interdependence, which exists in situations where the output of two trades becomes input for each other.

The reciprocal type of interdependence best illustrates the characteristics of component assembly interfaces between the three subsystems in Taiwan, where dimensional coordination between components of different subsystems is poor. In such a case, dimensional contingency is created by an earlier trade operation for a subsequent one, and many mutual on-site dimensional positional adjustments have to be carried out by trades as required or ad hoc. These adjustments create many additional component assembly interface situations and eventually require frequent returns of trades and thus lead to unnecessary looped operations. For instance, the installation of a medicine cabinet on the wall may create not only an extra assembly interface between the wall and the cabinet, but may also lead to a looped operation in terms of the wall erection work. This may occur if these two components are of positional or dimensional reciprocal interdependence, or if a recessed space larger than the actual dimension of the cabinet has to be provided in the wall in order to assure the needed contingency for the subsequent cabinet installation adjustment since the cabinet installation is usually carried out only after the completion of the wall erection work. Aside from this, the workers of the wall erection task may have to return to patch up the reserved extra "tolerance" space around the cabinet after the cabinet has been installed: thus a looped operation is created.
In most of the assembly processes in Taiwan, this type of reciprocal component interdependence exists in positions where two components belonging to two different subsystems join with each other.

In the case of Taiwan, two main factors are creating this reciprocal type of component interdependence:

1. Functionally interdependent assembly components.
2. Dimensional incompatibility.

Bathroom components of different conventional Taiwanese subsystems are not only functionally interdependent, in that without the completion of the one component, another one may not be installed. They are also dimensionally interdependent: dimensional fitting contingency has to be reserved by a previous trade for the subsequent one. Both the functional interdependency and the dimensional incompatibility are critical to the reduction of component interfaces and elimination of "looped" operations.

Improvements of these two aspects, i.e., functional interdependence and dimensional incompatibility, would mean a transformation of component interdependence from reciprocal to sequential type. As outlined in the definition of sequential interdependence, components of different subsystems tend to be assembly-independent from each other, with little dimensional fitting contingency; the
sequence of tasks of a particular operation is thus made more flexible and thus can be pre-planned. This sequential type of component interdependence exists in most foreign bathroom systems as we shall see in Chapter 5.
CHAPTER 4: SUBSYSTEMS AND LOOPED OPERATIONS.
4.1. INTRODUCTION.

In this chapter, we shall look at the conventional Taiwanese bathroom assembly process in detail to examine how looped operations come about in relation to the three conventional subsystems, as defined in Chapter 3, to see to what extent these "looped" operations have influenced the transformation of bathroom subsystems, while we are trying to increase the assembly efficiency.

Three operations were selected on the basis of the complexity of operations for detailed analysis, so that the analysis of these operations will eventually involve most component assembly interfaces in conventional Taiwanese bathroom assemblies. In the context of Taiwan, the complexity of the three sanitary fixture installation operations qualify themselves to be chosen for detailed analysis due to the fact that the installation of these three sanitary fixtures are usually among the last few tasks in the overall bathroom construction and also due to the fact that they are located in the innermost hierarchical location of the conventional Taiwanese bathroom three subsystems hierarchical locations *. Thus, the completion

* See Chapter 3, Fig. 4, for reference.
of these three operations exhibits virtually the whole process of bathroom assembly and involves not only the most complex assembly interfaces and the largest number of looped operations, but also the most interesting characteristic of the three bathroom subsystems chosen for analysis.

These three sanitary fixture installation operations will be analyzed by using a network diagram, and subsequently a possible scheme for reorganizing the assembly sequences to eliminate interfaces and looped operations will be discussed. This scheme should provide us with a good chance to examine the relationships between component assembly interfaces and the three conventional bathroom subsystems in relation to bathroom assembly efficiency in Taiwan.
4.2. ASSEMBLY ANALYSIS OF THREE SANITARY
FIXTURE INSTALLATION OPERATIONS.

4.2.1. BATHTUB ASSEMBLY.

4.2.11 WORKFLOW ANALYSIS.

Bathtubs occupy a unique portion in residential building systems because they are large, prefabricated components with special structural, service and performance requirements imposed on their joints with surrounding components (such as external envelope components and plumbing core components).

Bathtub assemblies involve the largest number of component interfaces with walls, floor and plumbing systems and thus create the most serious looped operations compared to other sanitary fixtures.

A bathtub interfaces with four pieces of unfinished envelope components and the plumbing core components (Fig. 12). Two trades - the plumber and the bricklayer - are involved in the assembly process of the tubs.
Since the bathtubs are supposed to be affixed to at least three envelope components*, the size of the tubs and the space provided by the building designer to accommodate the tub become most important; any difference between the tub size and the width of space provided causes extra work for the bricklayer (Fig. 13).

The relationship between:

1. the size of the tub (a,d,e)
2. the space provided by the building designer (a+b), and
3. the accuracy of the piping work (c,d),

are closely related; any incompatibility creates extra or more looped operations.

The assembly workflow of a washbasin in a Taiwanese bathroom is typically as follows:

* They are primary external envelope component, secondary external envelope component and one horizontal external envelope component.
1. PIPE ROUGH-IN (THE PLUMBER).

This task asks for an accurate positioning of all the pipes in order to connect them to the tub outlets after the primary envelope component of the bathtub has been installed. All the plumbing fixtures are connected and the pipes cut on site.

2. ENVELOPE COMPONENT ERECTION (THE BRICKLAYER).

This task includes the erection of all the envelope components that have not been previously erected. The primary envelope component is always included in this task.
3. BATHTUB PLACEMENT (THE PLUMBER).

All the pipes that have been previously set up by the plumber in Task 1 are connected to the correct inlet of the tub. The plumber usually has to readjust the pipes in order to match them to the inlet of the tub. The space provided by the building designer to accommodate the tub is normally larger than the actual size of the tub, because the designer is usually not sure about the exact size of the tub that will eventually be used at the time the bathroom is designed. The designers usually assume that there are certain sizes that are commonly used for bathrooms, but often these sizes are not compatible with the variety of bathtub sizes that are actually used on site.
Consequently, in order to make sure that the bathtub can be accommodated in the designed space, this space is usually designed larger than the actual tub size.

4. BRICK PATCHING (THE BRICKLAYER).

In this task, the bricklayer is supposed to patch the space between the edge of one side of the bathtub and the envelope component with brick and cement (Fig. 17). When the bathtub does not have a side panel, the bricklayer has to cover this side with the same material as well (Fig. 18).

5. FINISHING (THE BRICKLAYER).

This task is mainly concerned with the positioning of wall tiles which are the main material for bathroom wall surface finishing (Fig. 19).
Wall tiles have to be cut when the operation reaches the end of a piece of envelope component, or to a place where the tub meets other external envelope components.

This task cannot be carried out until all the sanitary fixtures are in place. The ceramic tiles also function as joint seal for the joint between the tub and the external envelope components.

6. THE CONNECTION OF TAPS (THE PLUMBER).

This task cannot be carried out until all the sanitary fixtures are in place and Task 5 is done as well. Thus, Task 6 and Task 5 cannot be carried out immediately after Task 4 is finished.
4.2.12. NETWORK ANALYSIS.

According to the preceding workflow analysis, a network diagram can be constructed as shown in Fig. 20.

Fig. 20  Network diagram of bathtub a conventional Taiwanese bathtub assembly.

In the diagram above, two looped operations are identified: the plumber and the bricklayer interrupt each other twice in the bathtub assembly process. This is mainly because of the task locations of the plumber and the bricklayer: the plumbing core is located outside the envelope while the sanitary components are located inside the envelope; both plumbing task and the sanitary component installations have to be done by the plumber in Taiwan (Fig. 21).
From the interface diagram, the installation of the bathtub, which is Task 3, depends on the erection of both primary and secondary envelope components, which is Task 2, in particular on the accurate positioning of the tubs.

In other words, in conventional bathtub construction, the primary and secondary external envelope components have to be erected before the bathtub can be installed; similarly, the plumbing work has to be completed before the primary external envelope component can be installed.

As to the plumber, he has to visit the same site for the third time after the finishing work is done by the bricklayer to install all the caps which have to be fixed to the finished envelope components.

Thus, it has become clear that various interfaces between the piping and the primary envelope component erection is the main cause for most of the looped operations in the conventional bathtub assembly as practiced in Taiwan at this time.

Another serious interface problem, as far as the
bathtub installation operation is concerned, is the problem of the joint between the tub and the external envelope components. Since a bathtub has to be positioned in relation to at least two external envelope components as reference planes, the logical implication is that the edges of a bathtub should be closely attached to these reference planes. A problem of jointing between these two types of components thus tends to arise. This problem causes not only unhygienic bathroom conditions (i.e., accumulation of filthy body waste), but moreover, assembly inefficiency. The reason for this is as follows.

Traditionally, functions served by different subsystems were clearly separated; bathtubs were designed for bathing activities, while envelope components were constructed to provide space separation and moisture insulation functions. But when they are made to meet and are assembled closely together, jointing becomes a big problem. Water leakage and positioning inaccuracies are commonly found in locations where the two functions/components meet. The designs of a bathtub and the adjoining primary and secondary external envelope components have never taken into consideration the "cross" functions created by their meeting in addition to those traditionally served separately and distinctly by different subsystems.
Several principles can be stipulated for improving the joint problem:

1. Seal joints. This principle is commonly used for current bathroom assemblies in Taiwan where no "cross" function consideration is integrated into the design of bathtubs and envelope components.

2. Remove joints to positions where water leakage problems are less severe and assembly can be made more efficient.

3. Eliminate joints. New products which serve not only as a bathtub, but also as an envelope component have to be developed as a unified element.

Since looped operations can be identified by means of a network diagram, it should be possible to reorganize this task sequence to eliminate unnecessary operations. The following schemes are examined according to this principle to see what the consequence of such eliminations are.
Scheme 1 reduces the number of looped operation to only one – only the plumber has to revisit the same site. But, the task left for his second return is actually marginal and requires no modification to the work previously done by the bricklayer (Fig. 22).

![Diagram of assembly sequence reorganization. Scheme 1.](image)

In this scheme, the bricklayer has to visit the site only once to finish Tasks 2-4-5 continuously. The plumber has to install the bathtub immediately after the completion of piping work, then he has to leave the site to perform the same tasks at another site on the same floor or upper floor. Following are a package of wall erection tasks, which include Tasks 2-4-5, to be completed without being interrupted. Since the installation of the bathtub has already been finished while the wall erection package task is being carried out, the bricklayer does not have to worry
that his work will ruin the position of the pipes set up by the plumber. Task 6 is the work that causes the second visit of the plumber to the site.

Although the number of looped operations is reduced to only one, this scheme does create a new problem for the plumber when he is installing the bathtub. As mentioned before, the installation of the bathtub relies on the completion of the tub installation task before the erection of envelope components, which means that the plumber will require a new tool or a new utilization of existing tools for measuring the positioning of the tub to make sure that the tub edge will eventually meet the envelope. Thus, even though the number of looped operations is reduced, and the interface between the plumbing core and the primary envelope component is eliminated, a new interface between the bathtub and its surrounding vertical envelope components for tub positioning becomes a problem.

- (2).

Scheme 2 reduces the number of looped operations to 0 by reorganizing the network diagram of Scheme 1. In other words, Task 6 is removed to the position which follows immediately after task 3; therefore, the plumber can finish his work in one continuous operation and the rest of the bathtub assembly work can be left entirely to the
bricklayer (Fig. 23)

Fig. 23 Assembly sequence reorganization. Scheme 2.

To remove Task 6 to the position following Task 3 is not hard to achieve. In the conventional bathtub assembly process, Task 6 includes only the installation of the taps of the cold and hot water supply lines and the shower head. These two items can be installed immediately after the installation of the tub with a certain range of tolerance left available to accept the envelope finishing material that will be installed later.

- (3).

Scheme 3 examines the possibility of constructing the envelope components before the completion of plumbing work under the condition of a non-looped operation (Fig. 24).
By using conventional assembly tools or methods, this scheme seems not possible due to the sequential nature of Task 4 and Task 3, i.e., without the completion of Task 3, Task 4 becomes meaningless. But, on the other hand, if the bathtub can be modified to the point where Task 4 becomes unnecessary and can be eliminated entirely from the assembly process (Fig. 25), then this scheme becomes actually feasible.

Reversing the assembly sequence of Scheme 2 also creates some new component interfaces between the plumbing core and the bathtub assemblies, which are hard to solve.
unless some more advanced component innovations can to be introduced. For instance, this scheme asks for the erection of the envelope first, with the work of plumbing carried out after. In the conventional assembly method, the initial task of bathroom construction seems always to be the piping work of the vertical plumbing core; erecting the envelope component first would require two sets of vertical plumbing systems (Fig. 26). Otherwise, it is almost impossible to carry out the piping work of the plumbing core after the envelope has been finished (Fig. 27).

Since using two sets of plumbing systems for two adjacent units is neither economical nor very rational, as previously discussed, the following innovations might have to be introduced in order to make this scheme possible:

1. Introduce a "functional wall" which satisfies both the function of envelope and plumbing core. The workflow would be like the one shown in Figure 28.
2. Remove the vertical plumbing system to inside one of the two adjacent bathroom units (Fig. 29). In this case, one of the bathroom units that does not have the vertical plumbing system in it will have to adopt the Scheme 2 assembly sequence while the other unit uses the Scheme 3 process for the bathtub assembly. An extra innovation would have to be introduced to the unit that uses the Scheme 3 assembly process: a partition as shown in Fig. 29 would have to be added to separate the vertical plumbing pipes from the sanitary fixtures. This piece of partition may be pre-assembled to the tub in an off-site plant or may be integrated later with the tub.

Note that all these innovations involve the idea of either combining components of conventional subsystems to form new elements, or redefining constituents of subsystems, which may eventually lead to bathroom subsystem transformotions.

Fig. 28

Fig. 29
4.2.2. WASHBASIN ANALYSIS.

4.2.21. WORKFLOW ANALYSIS.

The essential precondition for the washbasin assembly in a Taiwanese bathroom depends on the completion of at least one envelope component erection task, to support the weight of a washbasin. Without the presence of this envelope component, the washbasin installation operation is almost impossible to accomplish. Aside from this, the piece of external envelope component on which the washbasin depends for support seriously interferes with the pipe line rough in task, because the erection of the envelope component often disturbs the accurate positions of the pipe lines, and consequently renders the washbasin installation task inefficient. As seen in the hierarchical locations of the three subsystems, and the sequential assembly order of these three subsystems in relation to the washbasin installation operation, the envelope component is of critical importance and interferes with the installation of both the sanitary fixtures and the plumbing core as related to the case of the washbasin assembly operation.
One interesting feature regarding the washbasin installation is that this task accepts more positional fitting contingencies created by previous tasks, such as pipe rough-in and wall erection. The reason is that the washbasin itself can "absorb" certain fitting contingencies by horizontal and/or vertical adjustment with respect to the primary component (Fig. 30), and also that the distance between the trap and the washbasin ("A" in Fig. 30) can "absorb" certain range of vertical positional fitting difference between the pipe outlets and the washbasin. (See Fig. 30).

However, this feature at the same time creates another dimensional problem for the subsequent envelope finishing task, mainly attaching tiles to the primary external envelope component. The bricklayer never knows exactly where the washbasin is to be eventually located on the wall, thus he has to do the finishing task after the washbasin has finally been fixed to the wall. This represents a typical reciprocal looped type interdependence between components in conventional Taiwanese bathroom assemblies.

The assembly workflow of a washbasin is shown in the following pages.
1. PIPE ROUGH-IN (THE PLUMBER)

In this task, the horizontal supply and waste lines are set up. The installation of the supply lines does not usually call for high accuracy because their outlets are not immediately connected to the inlets of the wasbasin; usually a distance outside the wall can be used for connection adjustments during the washbasin installation. The waste line has to be set up accurately in both horizontal and vertical directions because once the subsequent wall erection has been completed, this position becomes fixed and cannot be adjusted to match the basin inlet which has strict trap and pipe installation specifications.
2. ENVELOPE ERECTION (THE BRICKLAYER).

This finishes the erection task of the envelope component through which the pipe lines set up in Task 1 penetrate. The position of the waste pipe (A) is important to the efficient installation of the washbasin: (A) is not supposed to be higher than a certain maximum limit.

3. WASHINBASIN INSTALLATION (THE PLUMBER).

This task completes the installation of the wasbasin. Since the washbasin has strict installation specifications (B,C), whether or not the task can be efficiently completed depends heavily on the accuracy of (A), which again depends on the carefulness of the wall erection work. (D) is adjustable to absorb waste line positional fitting contingency.
4. FINISHING (THE BRICKLAYER).

Ceramic tiles are often used as a bathroom finishing material. Joints shown in Fig. 34, between the ceramic tiling, envelope component and the washbasin, are causing trouble in terms of waste leakage. Ceramic tiles often have to be cut when they come to meet the washbasin on the envelope component. Ceramic tiles also serve the function of joint seal in meeting with both the washbasin and the external envelope components. Cap is fixed to the ceramic tiles after the finishing work is done (Fig. 35).
4.2.22. NETWORK ANALYSIS.

A network diagram can be constructed according to the previous workflow analysis.

In this network diagram, a looped operation is identified: the bricklayer and the plumber again interfere with each other's work. Because of the fact that, both in function and in dimension, the assembly components involved in the washbasin assembly are reciprocally interdependent, the bricklayer cannot erect the envelope component and fix the ceramic tiles in a continuous manner without worrying that the washbasin will not be able to precisely fit into the unfinished area reserved for that purpose on the primary envelope component (Fig. 36).
The same is true for the plumber. He cannot assemble the plumbing lines concurrently with the washbasin without worrying that the washbasin will eventually not be precisely positioned on the unfinished envelope surface to prevent leakage and to assure use-related stability of the washbasin. Each has to wait for the other in order to use the other's output as part of the input of his other's next task.

The following two schemes avoid looped operations completely, but the first one starts the washbasin installation operation with the piping task, while the second one tries to reverse this order, by starting the sequence with the envelope erection task.
Although Scheme 1 eliminates the looped operation existing in the original assembly sequence, it also creates a new assembly interface between the washbasin of the sanitary fixture subsystem and the wall of the envelope component subsystem. As we can see from Fig. 38, the installation of the washbasin is carried out by the plumber immediately after he has finished his plumbing core piping task in order for the plumber to be able to finish his tasks in one operation continuously. Since the plumbing and the washbasin are now in place, the bricklayer then can come to the job site and start his task of envelope component erection and finishing. However, the question of washbasin support arises; using this assembly sequence, there would be no wall to support the washbasin while the plumber is trying to accomplish his task. In such a case, and in order to achieve an increase in assembly efficiency, the...
earlier-mentioned concept of introducing the concept of cross function between the envelope component and the washbasin has to be considered, i.e., the washbasin has to be able to perform not only the function of being a washbasin, but also part of the function that used to be performed by the envelope component to support the weight of the washbasin.

- (2).

Scheme 2 reverses the assembly sequence of Scheme 1. The bricklayer visits the site first, followed by the plumber. Most important, they all can finish their tasks in a single visit to the site.

![Diagram](fig39.png)

As a consequence of reversing the assembly sequence of Scheme 1, the external envelope component erection and finishing tasks have to be totally completed prior to the visit of the plumber; holes for plumbing lines to penetrate
the wall must be reserved for lines to connect to the washbasin sanitary fixture in advance.

Due to the fact that, in high-rise residential buildings, plumbing cores are always located between two adjacent apartment units to economize plumbing cost*, completing external envelope component task as the first task would make it hard to assemble plumbing fixtures on site in the narrow space between two bathroom units. Pre-assembled plumbing trees, that can be inserted from outside the building and can be connected to each other and to the sanitary fixtures, have been used in many countries to deal with similar situations. Other methods, such as a precast concrete panel with integrated plumbing system which can additionally function as part of the envelope, might also be helpful if Scheme 2 is to be adopted.

Both Scheme 1 and Scheme 2 show the tendency that the primary envelope component in most of the cases shows that one part of its function can be shared by and integrated into other subsystems in terms the forming of new elements, which combine components of two, three or more different subsystems.

* See Chapter 3, page 28, for reference.
4.2.3. LAVATORY ASSEMBLY.

4.2.31. WORKFLOW ANALYSIS.

Two envelope components are involved in the lavatory assemblies: a vertical one and a horizontal one (Fig. 40). The assembly interfaces with the vertical envelope component involved in lavatory assembly process are similar to those involved in the washbasin assembly, except the functional interface between the lavatory fixture and the vertical external envelope component does not exist in the case of the lavatory assembly process because the lavatory does not depend on the vertical external envelope to support its weight. Instead, the horizontal external envelope does it.

Fig. 40

Interfaces between lavatory sanitary fixture and two external envelope components.

* In the conventional Taiwanese bathroom assembly practice, wall-hung lavatories are seldom used in residential buildings.
This implies that in conventional Taiwanese bathroom assemblies, the floor has to be completed before the lavatory can be installed. If a siphonic-type lavatory is used (Fig. 41), the interfaces between the lavatory and the envelope are simpler, because only two components are involved (the lavatory and the floor envelope component). But, if an s-type lavatory is used (Fig. 42), the interfaces become significant, because accurately dimensioned holes in the floor have to be reserved for the waste pipe lines, to be provided during the flooring construction phase. In this case, three components of different subsystems are involved and dimensional accuracy is critical to the efficient assembly of lavatories.

Fig. 41  Fig. 42

The typical workflow of a lavatory assembly is shown in the following pages. By listing these tasks involved in the assembly process, a network diagram is then constructed.
1. PIPE ROUGH-IN (THE PLUMBER).

The position of the horizontal waste pipe is important to the efficient assembly of the lavatory fixture because of the dimensional and functional specifications of the lavatory.

Horizontal water supply lines for the water closet are allowed to have some fitting contingency which may or may not affect the installation of the lavatory. If an s-type of lavatory is used, the horizontal main waste line will have to run beneath the floor and through an accurately positioned and reserved hole to connect to the lavatory outlet.
2. ENVELOPE COMPONENTS ERECTION (THE BRICKLAYER).

As usual, the main problem with this task is its interface with the positions of lines set up by Task 1. However, if an s-type lavatory is used this interface becomes insignificant, since the only line that penetrates through the envelope component is the supply line, the position of which is not influential as it is allowed to have a relatively large range of positional fitting contingency in relation to its position.

If a siphonic-type lavatory is used, the position of the waste line outlet, both horizontal and vertical, is important. The erection of the external envelope component often incautiously shifts the position of the required waste pipe, and makes the subsequent task hard to carry out.
The positional fitting contingency of the waste pipes are often intentionally made quite generously "loose" by the bricklayer in order to allow mutual adjustments of the subsequent plumbing tasks.

3. LAVATORY INSTALLATION (THE PLUMBER)

Since the vertical envelope component in Taiwan does not have to carry the weight of the lavatory, fixing the lavatory to the vertical envelope component is easier. If the position (A) of the waste line outlet is correct, once the line has been fixed in the wall (in the case of a siphonic type of lavatory), or the outlet that comes out of the hole in the floor is accurately located (B), then the lavatory can be efficiently installed, and the back of the water closet should be able to be closely attached to the unfinished surface of the envelope component.
Plastic or cement is often used to seal the joint between the lavatory and the floor.

4. FINISHING (THE BRICKLAYER)

Finishing work is mainly concerned with attaching tiles to the surface of envelope components and with covering previous joints between pipe lines and the envelope components, or between fixture and envelope components, with tiles or caps. Caps are usually delivered together with pipe lines supplied by the plumber, and are placed when pipe line outlets are connected to the inlets of the lavatory fixture. Having completed the finishing task, the bricklayer then places the caps along the lines and attaches the caps to the finished envelope components.
4.2.32. NETWORK ANALYSIS.

Similar to the washbasin assembly, one looped operation is identified in the network diagram of lavatory assembly (Fig. 47). Although the number of looped operations is the same as that in the washbasin assembly, the fact that the primary envelope component does not carry the weight of the lavatory fixture in the lavatory assembly makes a considerable difference. Because of this difference, the looped operation in the lavatory assembly is very much a result of dimensional reciprocal interdependence between the components of plumbing core, envelope and lavatory fixture, rather than due to a functionally reciprocal interdependence, like the interface between the washbasin and its primary envelope component as discussed earlier in this chapter.

Fig. 47 Network diagram of lavatory sanitary fixture assembly.
Without the presence of functionally reciprocal interdependence, reorganizing the assembly sequence seems easier and involves to a lesser degree the concept of cross function, which in most the cases is the reason leading to the forming of new elements which combine the components of the three bathroom subsystems; i.e., we can assemble the primary envelope component anytime without affecting lavatory installation. Still, it is necessary to take into account one cross function, which still exists at the interface between lavatory fixtures and the primary envelope component, that is, the primary envelope component remains for all intents and purposes an essential vertical reference plane for lavatory installations. This interface condition can be found in the washbasin assembly as well.

Dimensional accuracy of Task 1, the pipe rough-in task, is of critical importance to the subsequent placing of the lavatory in its correct position. This is in contrast with the placement of the washbasin assembly, whose position can be adjusted within a certain range of tolerance in both the horizontal the vertical directions, to match the supply and the waste pipe lines even if the outlets of these lines are slightly out of position (Fig. 48).

Fig. 48
Horizontal position adjustment of lavatory sanitary fixture.
In the case of the lavatory assembly, this is impossible. The lavatory has to sit on the floor, and thus its position is dimensionally fixed. This means that in the vertical direction, no adjustment can be made for the lavatory fixture to match the supply and waste line outlets if they are out of position; only horizontal adjustments are possible (See Fig. 48). It is very important for both Task 1 and Task 2 to keep waste and supply line outlets in their correct positions, or at least the positions must be correct in the vertical direction.

Given these general features regarding lavatory installation, we shall proceed to suggest a reorganization of the assembly sequence, to test the foregoing assumptions and to see how the assembly efficiency can be improved.

- (1).

Scheme 1 reverses the assembly precedence of Task 3 and Task 2 to create a continuous assembly environment for both the plumber and the bricklayer; no looped operation exists in this case.

Fig. 49
Assembly sequence reorganization of lavatory sanitary fixture.
scheme 1.
This assembly sequence calls for Task 3 to be executed first, before the primary envelope is erected (Fig. 49). As mentioned earlier in this section, this can be done since the lavatory fixture does not need its primary envelope component to carry its own weight when it is installed. Thus, we can install the lavatory first, without the presence of its primary envelope. However, such a sequence presents the danger either that there may be a gap between the lavatory fixture and its primary envelope component, or that there may not be enough space available for the erection of the primary envelope component (Fig. 50).

The two difficulties happening between the external envelope component and the lavatory; i.e., a gap or not enough space, are mainly caused by the fact that the primary envelope component still has the function of a reference plane for the installation of the lavatory. If this scheme is to be applied, another means by which the lavatory fixture can be referenced for correct positioning, without the presence of the primary envelope component, has to be formed; i.e., the cross function concept appears again.

Fig. 50
Positional fitting contingencies of lavatory assembly.
Since dimensional accuracy of the positioning of plumbing line outlets is very important for the efficient assembly of lavatory fixtures, and since first completing Task 1 and Task 3 continuously eliminates the opportunity of creating any dimensional contingency to assure the accurate and efficient connection between line outlets and the lavatory, this scheme seems very promising as far as the interface between envelope subsystem and sanitary fixture subsystem are concerned.

Scheme 2 reverses the order of job visits of the plumber and the bricklayer to the site (Fig. 51). The bricklayer appears first, then the plumber; the envelope is erected first, and only then the plumbing system along with the lavatory is assembled. In this case, the situation is almost the same as we had in Scheme 2 of the washbasin assembly section, as this scheme renders the unique assembly features of the lavatory installation.
c. 4

insignificant: the primary envelopoe component has to be first erected in any case and it does not matter any more whether the primary envelope component has or has not to carry the weight of the lavatory.
4.3. CONCLUSION.

In the previous sections, the conventional bathroom assembly processes have been examined and the main obstacles, i.e., looped operations and complicated or difficult component assembly interfaces which impede efficient assembly of bathroom components, have also been identified and simplified by means of reorganizing the various trade tasks in three operations to eliminate looped operations. It may be noticed that on the basis of the previous analysis, the reorganization of task sequences implies that a new categorization of bathroom subsystems is emerging as a result of an attempt to rationalize existing bathroom assembly processes.

For instance, the elimination of looped operations by reorganizing task sequences often requires the use of various new hybrid elements, which in themselves may contain several components which have been originally clearly categorized as conventional subsystems, that is, to increase assembly efficiency by reorganizing these assembly sequences, new sets of subsystems of a bathroom may need to be established. One of the examples is the installation of bathtubs in conventional Taiwanese bathroom assemblies. As mentioned in Chapter 4, the positioning of the bathtub
depends on the completion of at least two envelope components as reference planes. That means that the plumber has to revisit the site for installing the bathtub after the completion of those two essential pieces of envelope components; a looped operation is thus identified. If we want to eliminate this looped operation, one way of doing this is to reverse the assembly sequence of those two tasks. But given such a situation, the tub would lose its reference planes and thus it would be difficult to install the bathtub accurately. But if we can develop a bathtub in such a way that it has two or three vertical panel-type enclosure elements molded on two or three sides, then the original assembly interface between the tub and the wall components can be shifted to the ceiling or slab or whatever it may be (Fig. 52).*

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* This has been realized by the U.S. industry.
In this case, the installation of the tub no longer needs a separate reference plane for positioning and the plumber can finish his plumbing core task together with the tub in place as one continuous operation. But this means that the traditional concept of bathroom subsystems has to be changed, because the new bathtub now functions not only as a tub, but also as part of the envelope component, it has been transformed into a hybrid element; it has the nature of both a bathtub and an envelope component. This means that traditional and formerly clear-cut boundaries between the three subsystems determining bathroom assembly are losing their meaning. Instead, a new set of boundaries between subsystems has to be established, if we are going to rationalize and eventually industrialize the conventional assembly process.

However, to rationalize conventional assembly processes by introducing new hybrid elements usually requires substantial capital outlays and may be relatively risky in terms of profit and market acceptance, even though this approach can potentially achieve significant reductions of looped operations and component interfaces. We might call this approach a limited, rather "active" one, leading towards increased rationalization of the existing construction process, rather than a radical transformation of the very base of its processes and operations.

In contrast to this approach, another example may show
a rather "passive" way of achieving rationalization. If we look at the lavatory installation operation as described earlier in this chapter, or any other sanitary fixture installation operations, we may find out that the biggest problem in these operations is to keep the bricklayers from arbitrarily shifting the positions of the pipe positions. Consequently, during the second visit of the plumber to the site, he has to adjust the pipe inlet positions to match the outlets of sanitary fixtures. Thus, since all the pipes have become fixed in their positions after the bricklayer put bricks and cement around these lines, it is nearly impossible to adjust the position of these lines unless one decides to knock out or to remove the bricks adjacent to the pipes. This is obviously extremely irrational and time-consuming. To improve this, several attempts have been made in Taiwan to correct this condition. Thus, most of the time, the plumber will use plastic tubes with diameters larger than the supply and waste lines combined, to accommodate within a certain reasonable tolerance range one or several pipe lines which have been accurately set up by the plumber. The bricklayer will then be asked to put his bricks and cement around the tubes during his envelope component erection task.

This cover tube prevents the bricks from fixing and shifting the positions of the inner supply and waste lines and makes sure that these lines can remain in their correct positions and thus can be accurately connected to the
sanitary fixtures and in addition can also be easily adjusted to match the positions of the sanitary fixtures, if needed.

The above example shows a different approach towards rationalizing conventional bathroom assemblies from the active one; it is rather "passive". No new product need to be developed or introduced to improve performance; all it need is a more rationalized utilization of conventional tools or materials. Given this approach the pace of rationalization is slower than the active approach but may be more stable and gradual. However, even in this case, and although not significantly, a new set of boundaries between subsystems is emerging; the mixture of tasks, trade disciplines, and the nature of conventional subsystems begins to affect the conventional process, and tends to eventually suggest a more active approach to rationalize concurrent processes leading towards industrialization.

In the next chapter, we shall examine some of the typical foreign bathroom systems which fall into the spectrum of the active and the passive two approaches in order to see:

1. How they have avoided looped operations and component assembly interfaces,
2. What subsystems these bathrooms are using,
3. What is the relationship between 1. and 2.
These examples are valuable in that they may provide experiences which could turn out to be very beneficial for upgrading conventional bathroom assembly processes and assembly efficiency in Taiwan.
CHAPTER 5: FOREIGN EXAMPLES: TRANSFORMATION OF SUBSYSTEMS IN RELATION TO LOOPED OPERATIONS.
5.1. INTRODUCTION.

In this chapter, we are going to use some foreign bathroom systems to further manifest the concept of improving bathroom assembly efficiency in terms of breaking down the three conventional Taiwanese bathroom subsystems and to recategorize new subsystems which are composed of hybrid elements, which in many cases may help to eliminate assembly interfaces and looped operations which exist in the conventional bathroom assemblies in Taiwan.

As demonstrated by the bathroom systems presented in this chapter, many different categories of subsystems have been used for a variety of bathroom systems in different countries and by different manufacturers; all of them are designed to serve the purpose of rationalizing assembly processes and to increase assembly efficiency. These systems may help us to understand the tendency and concept of resetting conventional bathroom subsystems in Taiwan for improving assembly efficiency.

While discussing these foreign systems, we should keep in mind that since functional requirements and assembly environments vary from context to context, the design of subsystems in a bathroom varies accordingly. Thus, it is neither intended nor appropriate for us to make direct
efficiency comparisons between systems or between their subsystems. Emphasis in this chapter will be put on the different subdivisions of these bathroom systems into their subsystems in relation to the elimination of looped operations.
5.2. CLASSIFICATION OF FOREIGN SYSTEMS.

Since almost all the foreign bathroom systems have more or less adopted industrialized pre-assembly methods to increase assembly efficiency and to avoid on-site assembly interfaces and looped operations, the degree and difference of efficiency between these systems seem to be proportionate to the relative level of industrialization according to which they are categorized. Therefore, it seems reasonable to present the systems in this chapter in a hierarchical order as follows:

1. Total Unit.
2. Functional Unit.
3. Functional Envelope.
4. Functional Core.
5. Functional Element. (Fig. 53)
Hierarchical classification of different foreign bathroom systems

Fig. 53
Each of these items represents:

1) a different level of industrialization, ranging from fully prefabricated bathroom systems, which can be regarded as the products of a full adaptation of the active approach* towards rationalization, to the rationalization of existing assembly methods, which at the other extreme can be regarded as a result of adopting the "passive" approach of achieving higher bathroom assembly efficiency.

2) a different degree of integrating conventional bathroom components with each other to form hybrid elements.

A fully-prefabricated bathroom is categorized under Item 1, since when compared with the other four cases it is characterized by the largest number of integrated conventional components to form a ready-to-use bathroom unit. Item 5 may be represented by the type of bathtub with integrated panels around its enclosure, which perform part of the function of the external envelope component. It is listed last since fewer conventional bathroom components have been integrated with each other than in the other four cases.

All these items also share the following characteristics: higher assembly efficiency and a fewer number of looped operations, when compared with traditional

* See Chapter 4, page 83, for reference.
assembly methods in an given identical context.

When discussing the assembly efficiency of existing foreign versus domestic examples, it should be noted that if any of these systems is to be adapted to a different context, it may not be possible to reduce as many looped operations, nor to achieve as high an assembly efficiency as the transferred system would possess in its own native context. This is due to software* incompatibility between the different contexts. In other words, direct adaptation of hardware to a foreign context is to be considered inappropriate, unless proven otherwise.

* See Chapter 2, page 23, for reference.
5.3. ASSEMBLY CHARACTERISTICS OF FOREIGN SYSTEMS.

5.3.1. FUNCTIONAL ELEMENT.

Various bathroom elements of this type have been developed in different contexts and have appeared on the market in different configurations. Most of them deal with reducing on-site assembly interfaces between the conventional envelope and the sanitary fixture subsystems; i.e., many cross functions have been identified between the external envelope and the sanitary fixture subsystems and these "functional elements" have been developed to provide these functions. The transformation of conventional subsystems can be seen in the bathroom systems of this category.

The finished assembly of a functional element often can be coordinated and made to coincide with completing both the erection of an envelope component and the installation of a sanitary fixture. Thus, finished assembly a functional element may mean that both the envelope component and the sanitary fixture are ready to use: many conventional assembly interfaces thus are avoided or shifted by the introducing of these functional elements.
The problems encountered in the example given in Chapter 4, regarding the conventional washbasin assembly in Taiwan, can find their answer in those foreign systems categorized in this functional element category. In Chapter 4, we found that the installation of conventional Taiwanese washbasin sanitary fixture requires the primary envelope component to be completed to support its own weight before it can be installed, and the bricklayer cannot attach the wall tiles until the washbasin has been installed. This was referred to as a functionally reciprocal interdependence between the washbasin and the envelope component. By introducing an integrated functional element which will work not only as a washbasin, but also as a support for its own weight, this reciprocal interdependence is eliminated; the interface between the washbasin sanitary fixture and its primary external envelope component is shifted to other positions. Most important, components of different subsystems begin to be integrated with other components, to generate new combined elements.

A typical example of a functional element is the CONCEPT III system, developed by Eljer Company, U.S.A. The sanitary fixtures of this system are designed in such a way that all the fixtures are actually an integral part of their primary envelope components (Fig. 54). Each of the CONCEPT III elements is also an external envelope finishing material; having completing the installation of the CONCEPT III elements, the external envelope components have been...
finished simultaneously as well.

In addition to this advantage, the CONCEPT III elements can support their own weights without the presence of the primary external envelope components. Functionally, assembly interfaces of components are becoming more sequential; we can always complete any one of these fixture installations first, then move to do the piping task; or the other way around, due to the fact that the sanitary fixtures no longer depend on the external envelope components for support. Moreover, the conventional joints between the sanitary fixtures and their envelope components are shifted to positions where they become less bothersome in terms of either performance and/or assembly efficiency. The bathtub best illustrates
this feature. Fig. 55 shows the conventional joint between the bathtub and the envelope. In the CONCEPT III system, the envelope finishing function is combined with the bathtub by being molded into a single unit with the tub, and the joint with the external envelope is shifted away from its old location to outside the shower space (Fig. 56). This transformation of subsystem constituents results in more meaningful assembly interface and looped operation reductions, which eventually lead to an increase in assembly efficiency.

**Fig. 55** Conventional joint between the tub, envelope and the finishing material.

**Fig. 56** The joint between a CONCEPT III bathtub and the envelope component.
5.3.2. FUNCTIONAL CORE AND FUNCTIONAL ENVELOPE.

Discussing the "function core" and the "functional envelope" together exemplifies best the idea of hybrid elements and the transformation of bathroom subsystems as a result of eliminating looped operations and assembly interfaces.

Both the functional core and functional envelope deal with efficient assembly of only the components of the plumbing core, but some cross functions can be seen in these systems in relation to the functions traditionally served by the plumbing and the external envelope subsystems. In other words, as a result of solving plumbing assembly efficiency problems, both systems show the tendency to integrate part of the nature of other conventional subsystem constituents, mainly those constituent of external envelope subsystems.

The function core type of bathroom systems group all the service utilities in a pre-assembled core, usually contained in a steel-made frame. The functional envelope type of bathrooms are based on the same idea, except that the container is usually made of concrete. On-site assembly efficiency of installing plumbing fittings is significantly increased in both cases. But the most interesting feature
c. 5

of these two types of bathroom systems in relation to looped operations and assembly interfaces is not concerned with the plumbing core at all, but is their built-in nature of being able to function as an external envelope (such as to function as wall studs) - another example of hybrid element and cross function.

Case 1 (Fig. 57) is the KEP system, developed in Japan. As we can see from Fig. 57, a steel frame is used to contain all the service utilities, pre-assembled off site. The plumbing core assembly task is completed by simply connecting the KEP unit with another one on the lower floor. Then, the steel frame works as studs, to which the external envelope finishing materials are affixed during envelope erection task. An envelope component is thus completed (Fig. 58).

In terms of looped operations existing in Taiwanese bathroom assemblies, this system avoids both functional and dimensional assembly interdependence, not only between the
plumbing tasks and the envelope erection tasks, but also between the sanitary fixtures and envelope component installation tasks. The reason is that in this type of bathroom system, the producers have designed a different set of subsystems to avoid unnecessary assembly interfaces: the subsystems seem to be 1) functional core, 2) finishing panel, and 3) sanitary fixture. The KEP functional core has integrated part of the nature of an envelope component into itself, and the rest is taken care of by the finishing panel; the sanitary fixture subsystem remains the same.

The functional envelope, on the other hand, is definitely an envelope component, while it also doubles as a plumbing core (Fig. 59). Because it is usually made of concrete, after being put in place it becomes an envelope component. Since it also has all the plumbing utilities contained inside the concrete panel it acts as a plumbing core as well; thus, it has the nature of both conventional plumbing core and envelope. It is also capable of supporting the
weight of the washbasin; neither dimensional nor functional fitting contingency are encountered, since all the plumbing lines are accurately positioned before the pouring of concrete in an off-site factory where all trades are well coordinated and quality is carefully controlled at each stage of the production sequence.

Both the functional core and the functional envelope type of plumbing systems lend themselves to the development of "closed" systems: only certain types of sanitary fixtures are dimensionally compatible with the functional envelope type of bathroom systems due to the fact that most of the plumbing line outlets are dimensionally fixed, while the ability to avoid conventional assembly interfaces and looped operation is increasing.

In the case of a functional envelope type of bathroom system, the subsystems seem to be categorized as 1) functional envelope, 2) envelope component finishing panel, and 3) sanitary fixture. Note that this finishing panel has different performance requirements from that of the finishing panel subsystem in the function core type of
bathroom system mentioned previously. The latter requires
higher performance standards than the former, since the
functional core provides only the envelope frame, but not
the envelope; fulfillment the performance requirements of
being an envelope mainly depends on the performance of the
finishing panel.
5.3.3. FUNCTIONAL UNIT AND TOTAL UNIT.

The "functional unit" and the "total unit" types of bathroom systems are full spatial units which combine all the core functions and are ready for use once connected to the supply plumbing lines and electricity.

These two types of systems integrate into a completely finished unit containing both conventional external envelope and sanitary fixture subsystems. Since the fixtures of the unit have to become functional after connection to the plumbing core subsystem, all the components of the other two conventional subsystems are pre-assembled together, finished and tested in off-site factories, except for exterior plumbing and electrical connections. These hybrid functional unit and total unit types of bathrooms integrate into themselves the largest number of conventional components, and also are capable of providing the most complete nature of the conventional envelope and sanitary fixture subsystems. In terms of on-site assembly, there is no boundary between sanitary fixture and envelope subsystems. Instead, only two subsystems are left in these functional unit and total unit systems: 1) the plumbing core and 2) the functional unit or the total unit themselves. Obviously, many assembly interfaces...
conventionally existing between sanitary fixture and envelope subsystems can thus be avoided.

The Japanese KEP system has also developed a set of three function units together with a functional core system mentioned earlier in this chapter (Fig. 60). Each of these functional units can perform a specific major bathroom function, such as bathing, human waste elimination, facial cleaning, etc.

By combining any two of these, or all of them, a partial bathroom unit or a total bathroom unit is formed; conventional on-site assembly interfaces between the sanitary fixture and the envelope are totally shifted to position between functional unit themselves and to position between units and the plumbing core (Fig. 61).

In terms of eliminating looped operations in Taiwanese bathrooms, the assembly of a function unit requires only one visit of the plumber to the site for connecting a unit to the plumbing line outlets and, if several units are used, to connect these units to each other. If an additional brick
or concrete enclosure is needed, bricklayers will have to revisit the site for this purpose, but there is no mutual interruption and reciprocal interdependence between the two operations.

The total unit is a completely pre-fabricated bathroom box with all bathroom utilities contained and/or molded together. A variety of bathrooms of this type have been on the market, such as the Unite system developed by Crane, U.S.A. (Fig. 62). This system further eliminates the assembly interfaces that exist in the "functional unit" type, i.e., interfaces between the sub-units themselves, and it requires only one visit of the plumber and the bricklayer to the site. The plumber has to assemble the vertical plumbing supply system first by using a reference rectangle as a sub-floor (see Fig. 63) to locate the vertical positions of the horizontal pipe lines.
to match the inlets of the bathroom box. The enclosure surrounding the box can be done conventionally but in a continuous manner and thus one needs not worry about unintentionally shifting the supply and waste line positions.
CHAPTER 6: CONCLUSION.
Although it is not certain yet how looped operations can be technically eliminated, it is clear that in order to achieve higher bathroom assembly efficiency we have to conceptually recategorize current bathroom subsystems in order to:

1. Form suitable "hybrid" elements.
2. Transform component interdependence from a reciprocal type to a sequential one.

6.1. THE FORMING OF HYBRID ELEMENTS.

Certain steps and directions seem to be advisable regarding the forming of hybrid elements.

(A):

From the hierarchical location of the sanitary fixture subsystem and the conventional workflow of the sanitary fixture installation operations examined in Chapter 4, the first step to reset subsystems in relation to the elimination of looped operations is to form hybrid elements, by combining the components of conventional envelope subsystem and sanitary fixture subsystem (Fig. 64).
The plumbing core subsystem does not seem to be collaborative with either of the two other subsystems, because plumbing systems are subject to various prescriptions of the plumbing code and plumbing load requirements. Combining components of plumbing core subsystem would tend to create closed hybrid elements. Unless a large market is guaranteed, it is not advisable to form hybrid elements by combining components of the plumbing core subsystem with either one of the other two subsystems in the early stage of rationalization.

(B):

Within this new subsystem, that is the integrated subsystem of the external envelope and the sanitary fixture subsystems, three hybrid elements seem to be good candidates, and more capable of eliminating assembly interfaces and of reducing looped operations (See Fig. 64). Each of these hybrid elements consists of one of the conventional sanitary fixtures and a portion of the envelope components surrounding them (Fig. 65). As to which part of the envelope to integrate into these sanitary fixtures, a
more detailed study on the functional requirements of bathroom constituents and on the various construction assembly interfaces between fixtures and their surrounding envelopes is needed to make such a decision; any rational integration will have to satisfy both.

Fig. 65 Conventional bathroom subsystems and components vs. new subsystems and hybrid elements.

Figure 66. is given as an example showing a possible result of this study. In this figure, the envelope surrounding the bathtub is different from that behind the lavatory in terms of performance: the former requires a higher efficiency of moisture and water run-off while the latter does not; also, in terms of assembly efficiency, the envelope surrounding the bathtub interferes with the bathtub in a different way from how the envelope components surrounding the lavatory fixture interfere with the lavatory.
Given the decision that hybrid elements should be formed between sanitary fixture and envelope subsystems and looped operations should be eliminated, these hybrid elements need to be developed and will have different configurations as shown in the figure. This example shows the idea of generating such possible hybrid elements.

6.2. THE TRANSFORMATION OF COMPONENT INTERDEPENDENCE.

As mentioned earlier in this thesis, the components in bathroom assemblies in Taiwan exhibit reciprocal interdependence. Assembly positional fitting contingency is created by previous trades for subsequent ones, as evidenced by the gap left between various envelope components and the bathtub (see Fig. 13 in Chapter 4). Little flexibility exists for reorganizing the sequence of tasks or trades in order to overcome unforeseen situations. On-site assemblies of this type of component interdependence rely heavily on ad-hoc adjustments by the trades themselves. Given the current Taiwanese bathroom assembly processes, the elimination of assembly interfaces and looped operations, by reorganizing task and trade sequences, as analyzed in Chapter 4, would only impose further conflicts and difficulties on the trades, unless hybrid elements are introduced and/or the current reciprocal interdependence of components is changed to a sequential one.
In the sequential type of component interdependence, components become dimensionally and functionally independent with less positional fitting contingency. Tasks can be executed in many desirable sequences. As suggested in Chapter 4, and referring to the forming of a hybrid element which can function not only as a washbasin but also as part of its primary envelope component (in order to support the washbasin’s weight), the assembly interface of this hybrid washbasin with its primary component becomes functionally independent, and looped operations can be easily eliminated. Thus the plumber can finish both the pipe rough-in and washbasin installation first in a continuous operation; the bricklayer then completes his envelope erection task, also without interruption.

Dimensional coordination between components is another important consideration. As evidenced by Taiwanese bathroom sanitary fixture installation operations in relation to the finishing tasks, almost all the tasks involved in a particular operation assembly sequence are creating positional fitting contingencies for subsequent tasks, and creating dimensional problems consequently. The last task in a particular assembly sequence either has to be able to "absorb" the accumulated positional contingencies, or has to be followed by a revisit of a different trade to cover something up. Examples are 1). positional adjustments of the washbasin mounted on its primary envelope component to
"absorb" positional fitting contingency (see Fig. 30 on page 60), resulting from the previous piping and wall erection tasks, which may cause inaccurate alignment of the final position of this washbasin; or 2). the gap between the bathtub and the third associated envelope component, which requires a second return of the bricklayer to fill in the gap with bricks.

Thus, it is the considered opinion of the author of this thesis that, in order to rationalize conventional bathroom assemblies in Taiwan, the two concepts mentioned above have to be conceptually established first. These two concepts are applicable to different contexts for bathroom systems design, but the physical products vary from context to context. The establishment of these two concepts will be helpful to provide more suitable and more assembly-efficient domestic bathroom systems in particular, and further, to increase the overall construction productivity in general, in a more rational way. No foreign fully industrialized or factory pre-fabricated bathroom systems should be directly adapted, unless they are selected by factoring into the selection process these two concepts in relation to the Taiwanese context. Only after the establishment of these two concepts can technical solutions be found to eliminate looped operations to increase assembly efficiency, and to achieve more industrialized construction methods.
BIBLIOGRAPHY.


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