

Robot Oriented Modular Construction System - Part II: Design and Logistics

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Abstract

The 3-Dimensional Modular Unit Construction System involves constructing a) in fixed cycle time using b) 3-D Modular Unit Building Blocks which are assembled at a c) "factory" automated staging area on the jobsite prior to being lifted into place on the building. This system has great potential to facilitate the use of robots on the jobsite and dramatically reduce the construction period. In order for this system to succeed, Logistics and Design become critical issues. We proposed a) a time scheduling model which incorporates the jobsite logistic requirements and b) a concurrent design flow model combining functional design and production design. Production design considerations and the Unit Building Block concept must be introduced in the early stages of design. CAD/CAP/CAM systems must be improved to the point where a) concurrent design is feasible and b) information used during the design process can be integrated into management tools during construction.

1. Introduction

In recent years, many construction robots have been developed with the goal of reducing the construction period. Unfortunately, as of yet there have been few cases where these robots have found application on the jobsite. Even in the cases where robots have been used, the resulting reduction in the construction period has been small. There are two main reasons for this phenomena:

(a) Conventional construction is very labor intensive. In order to use robots on the construction site, we must develop highly sophisticated robots, e.g. self judging, able to perform complex motions, highly mobile. This type of robot is very expensive to produce and difficult to operate and maintain.

(b) The possible reduction in the construction period, even in the case of fully automated construction, is limited by the difference in the work rate of the robot in comparison to the human worker.

Therefore, in order to facilitate the use of robots on the jobsite and reduce the construction period, we must reevaluate the construction process. This means that we must develop systematized construction methods that will 1. facilitate the use of robots and 2. dramatically reduce the construction period.

Based on the issues discussed above, the authors previously presented the concept of a 3-Dimensional Modular Unit Construction System (3-D MUCS) at the 9th ISARC. In this paper, we will review the concept of 3-D MUCS and present two issues which are critical to the success of this construction system. Finally, we will propose a design flow model which integrates function design and production design for the 3-D MUCS.

2. The Concept: 3-Dimensional Modular Unit Construction System (3-D MUCS)

In conventional construction there are many constraints and problems which affect construct ability :

- Many activities are complicated, making the construction complex.
- Materials used on the jobsite represent various levels a sophistication in terms of prefabrication and technology. (raw materials, prefabricated panels, nails and bolts)
- The working area moves about the jobsite, following the working schedule. This makes it difficult to streamline material delivery to the working area.
- There are often many activities proceeding simultaneously in the working area. This creates 1. inefficiencies which reduce productivity, as well as 2. unsafe, unstable working environments high above the ground.

These constraints inhibit the development of automated construction methods. The 3-D MUCS was developed to overcome these constraints.

In 3-D MUCS we construct a building a) in a fixed cycle time using b) 3-D Modular Unit Building Block which are assembled at a c) "factory" automated staging area on the jobsite prior to being lifted into place on the building. (Fig. 1)

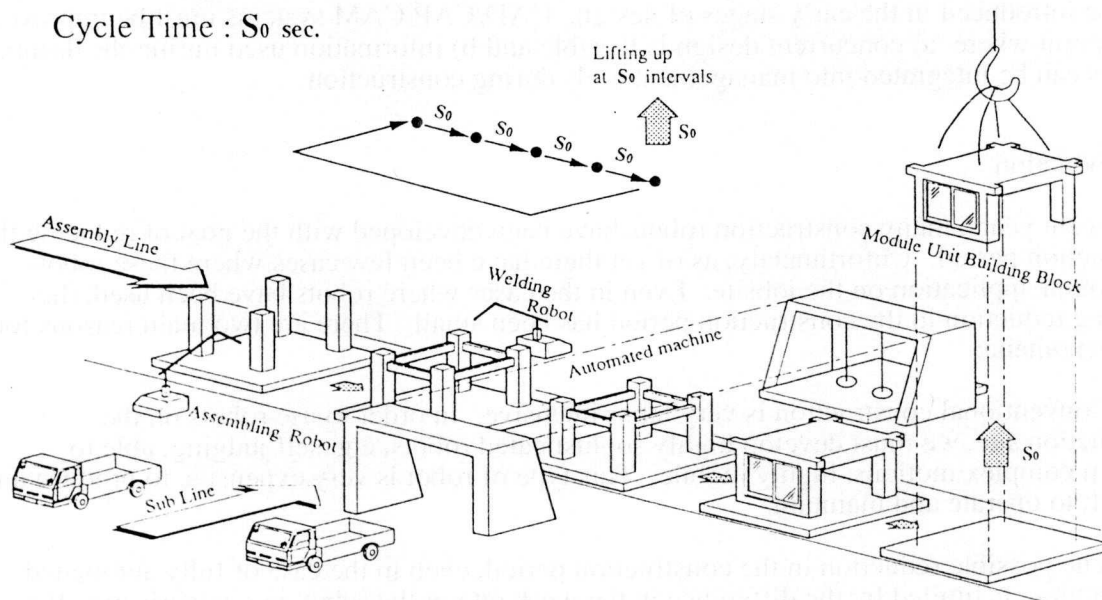


Fig. 1 The Concept Image of the 3-D Modular Construction System

The 3-D MUCS has three main characteristics which facilitate the use of robots on the jobsite:

- (1) Work is divided into discrete work packages which are performed repeatedly at one set location.
- (2) This method reduces the number of activities on the working floor, simplifying the construction process, streamlining material delivery to the working area.
- (3) The activities in the different work packages are synchronized to a fixed cycle time, allowing the construction schedule to proceed at a steady rate.

In order to realize the successful application of the 3-D MUCS, there are two issues that we must consider; a) Logistics and b) the Design Process.

a) The key to supplying the 3-D Modular Unit Building Block in a fixed cycle time is in synchronizing the following activities:

- 1) the material delivery
- 2) the jobsite factory automation cycle
- 3) lifting the building block up to the working floor
- 4) work area activities on the working floor

Furthermore, each type of building element (raw materials, parts, building block unit, etc.) should be delivered using Just In Time (JIT) scheduling in order to optimize the efficiency of each activity. A time scheduling model has been developed, incorporating the logistic requirements of the 3-D MUCS.

b) Generally speaking, the construction method used on a given project depends on the design of the building system. However, to successfully apply the 3-D MUCS, the opposite must be true. The design process must be changed. In 3-D MUCS, the building system and the construction process must be chosen during the design process

3. Logistics

In this chapter we will present a model of the time schedule and logistics of the jobsite. Our discussion will focus on the activities performed on the jobsite itself. Our scheduling model will not encompass the offsite factory production or the delivery of Building Block elements and materials to the jobsite. Our model is based on the assumption that all parts and materials are delivered to the jobsite using JIT scheduling (Fig. 2).

Jobsite Factory Automation Line for Assembling Building Block Unit

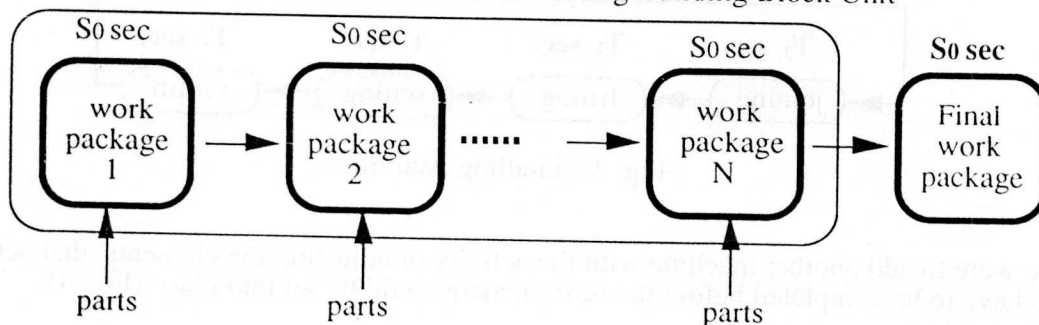


Fig. 2 Logistics of the Jobsite

In 3-D MUCS, activities are divided into discrete work packages with each activity progressing in a fixed cycle time. The "best fit" cycle time is defined by the critical path activities. Other activities are then adjusted to synchronize with the activities on the critical path.

For the purposes of this paper, we will assume that the final work package, which includes the activities of a) lifting and b) connecting the building block units, defines both the critical path and the cycle time. All other work packages are adjusted to synchronize with the cycle of this final work package. Basically, the cycle time is a function of the a) number of robots and equipment used and b) the efficiency of these machines. In order to simplify our model we will assume that all of our machines are equally efficient and assign a ratio of one machine per work package.

We assume that the cycle time of the work packages and the handling time (e.g. time required for a robot to manipulate an object) are as follows:

1) The Cycle Time for Work Packages: S_0 seconds.

2) The Handling Time: H seconds.

The cycle time, S_0 , is defined as follows:

$$S_0 \geq T_{bj} + T_{bl} + T_{bs} + T_{br} \quad (1)$$

T_{bj} : activity time for connecting Building Block Unit to the lifting machine

T_{bl} : activity time for lifting up Building Block Unit

T_{bs} : activity time for setting the Building Block Unit into place

T_{br} : activity time for returning to the starting position

Similarly, the handling time, H , is defined as follows (Fig. 3) :

$$H = T_j + T_l + T_s + T_r \quad (2)$$

T_j : activity time for connecting element to lifting machine

T_l : activity time for lifting element

T_s : activity time for setting element into place

T_r : activity time for returning to the starting position

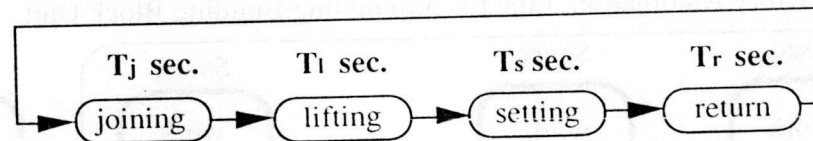


Fig. 3 Handling Activities

If we were to add another machine with the activity of adjusting the elements, that activity would have to be completed before the next element could be set into place (Fig. 4).

$$T_{ad} \leq T_b + T_j + T_r \quad (3)$$

T_{ad} : activity time for adjusting elements or parts

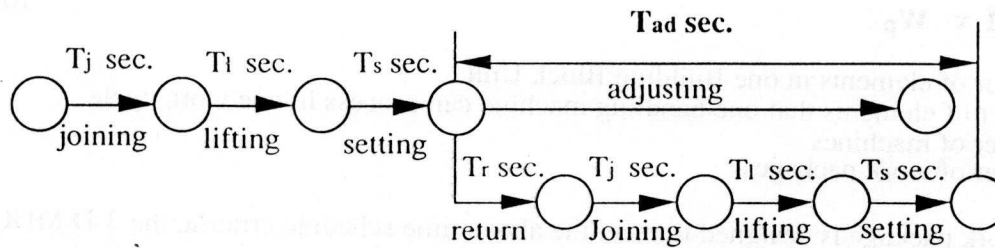


Fig. 4 Adjusting Time

Next, we assume that one handling machine can process n elements during the cycle of one work package (Fig. 5). The cycle time, S_0 must also be defined as follows:

$$S_0 = nH + T_{ad} \quad (4)$$

Trucks will deliver elements to the jobsite. The cycle time between the last element being picked from a truck and the next truck moving into place for the next pick is defined by T_t :

$$T_t \leq T_l + T_s + T_r \quad (5)$$

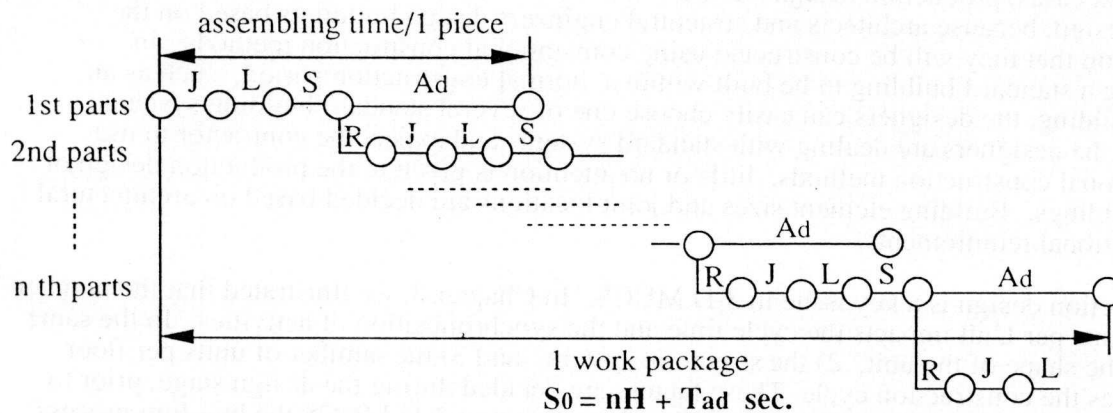


Fig. 5 Schedule Based on Work Package

Each of the above equations must be satisfied in order for all of our activities to be balanced. The number of elements that make up the Building Block Unit affects the efficiency of our 'assembly line'. To achieve 100% efficiency in the use of the handling machines, the number of elements per Unit should be an integral multiple of n , the number of elements that one handling machine can process in one work cycle. By satisfying the following equation, machine stand-by time is eliminated:

$$A_p = n \times M \times W_p$$

A_p : number of elements in one Building Block Unit
 n : number of elements that one handling machine can process in one work cycle
 M : number of machines
 W_p : number of work packages

If each work package is designed to meet the above time schedule criteria, the 3-D MUCS will be completed in a fixed cycle time.

4. Design Process

In this chapter we will discuss the new design process required for the realization of 3-D MUCS.

The design of a building is made up of three parts: 1) architectural design, 2) functional design, and 3) production design.

Architectural design encompasses the exterior design (shape, color, texture, etc.) and the design elements which define the atmosphere both inside and outside of the building. Functional design is based on the building purpose or function; the basic structural requirements and safety considerations. Production design, on the other hand, involves designing the shape of the elements and joints within the parameters of construct ability and cost.

In most cases, production design and ease of construction is not generally a consideration during design, because architects and structural engineers design buildings based on the assumption that they will be constructed using conventional construction methods. In designing a standard building to be built within a normal construction period, such as an office building, the designers can easily choose one of several standard building systems. Because the designers are dealing with standard systems and expect the contractor to use conventional construction methods, little or no attention is given to the production design of most buildings. Building element sizes and joint locations are decided based on architectural and functional requirements.

Production design is a key issue in 3-D MUCS. In Chapter 3, we illustrated that the number of elements per Unit impacts the cycle time and the synchronization of activities. In the same way 1) the shape of the unit, 2) the structural system, and 3) the number of units per floor influences the construction cycle. These factors are decided during the design stage, prior to construction. Therefore, to efficiently utilize the concept of 3-D MUCS the building process and the Building Block design must be designed concurrently with the architectural and functional design.

A 3-D Modular Unit Building Block must be a core element of the design process from the schematic design through working drawings. The design must reflect the production requirements of a) the factory assembly line, b) the construction process and c) robot and equipment technology to be used (Fig. 6).

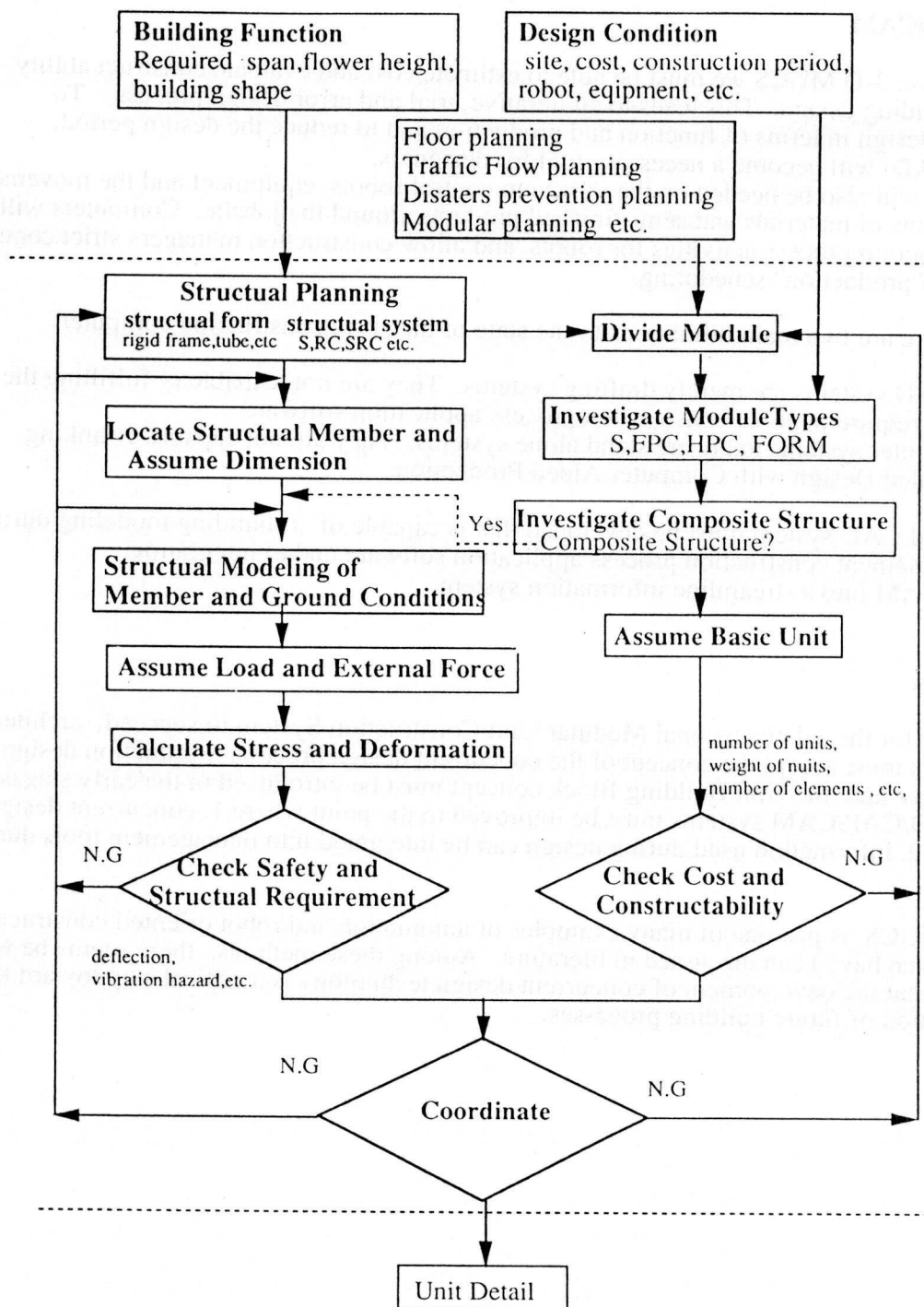


Fig.6 Concurrent Design Flow Model (Structural design and Production Design)
in Design Development Stage

5. CAD/CAP/CAM

In order to use 3-D MUCS we must be able to estimate cost and evaluate construct ability during the building design. This leads to an iterative, trial and error design process. To optimize the design in terms of function and production and to reduce the design period, computers(CAD) will become a necessary tool for designers.

Computers will also be needed on the jobsite to control robots, equipment and the movement of huge amounts of materials and semi-finished products around the jobsite. Computers will be used to program process activities for robots and allow construction managers strict control of the jobsite "production" scheduling.

Presently, there are two main limitations to the state of the art in construction computer technology:

- 1) Present CAD systems are merely drafting systems. They are not capable of fulfilling the data retrieval requirements of construction process application software.
- 2) Most computer systems today are stand alone systems. They are not capable of linking Computer Aided Design with Computer Aided Production.

An advanced CAD system must be developed that is capable of a) building modeling during design b) implement construction process application software and c) integrating CAD/CAP/CAM into a streamline information system.

6. Conclusion

In order for the 3-Dimensional Modular Unit Construction System to succeed, architects and engineers must accept the concept of the concurrent design process. Production design considerations and the Unit Building Block concept must be introduced in the early stages of design. CAD/CAP/CAM systems must be improved to the point where 1. concurrent design is feasible and 2. information used during design can be integrated into management tools during construction.

The 3-D MUCS is just one of many examples of automation and robot oriented construction methods which have been discussed in literature. Among these methods, there seems be wide agreement that the development of concurrent design technology is a critical step toward the implementation of future building processes.