The 5th International Symposium on Robotics in Construction June 6-8, 1988 Tokyo, Japan

ROBOT-ORIENTED DESIGN

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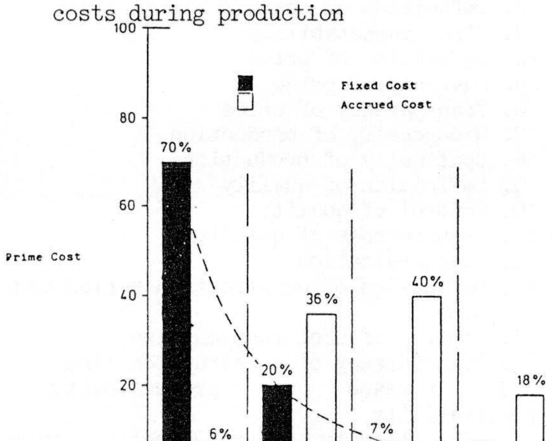
ABSTRACT

The aim of this paper is to give architects and engineers who are involved in the design of buildings and components certain guidelines for the "robot-oriented design and re-design" in order to support further spread of robotic technology in construction. Most of the construction and building costs are determined at the design stage. Final on-site construction operations should already be considered at the design stage of buildings and elements. Modern buildings consist of many subsystems, a coordination of all building subsystems is necessary considering constraints of robotic technology. In order to establish determined conditions for robotic on-site operations, the elements of building subsystems have to be geometrically and physically well defined. The problem of varying accuracies can be controlled by designing a compliant building system. The assembly stage is one of the final production phases before the product can be utilized and therefore the shorter the on-site assembly lasts, the higher the profitability of the building becomes.

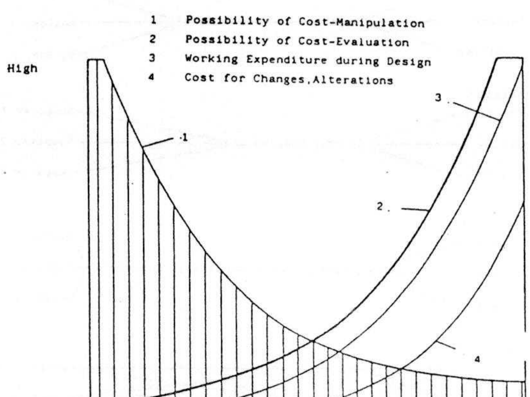
INTRODUCTION

The design determines not only the appearance of a building but also its construction and running cost, serviceability, construction method, physical and geometrical qualities. During the design stage most resultant construction cost are fixed, which are more than 2/3 of the total cost.(Graph 1) However engineers are preoccupied to fulfill the required product functions and architects are preoccupied with the cosmetic part of the design. In many construction companies engineers and architects postpone cost-effective design decisions assuming that the foremen and subcontractors will work it out. However, any design changes that might occur at any later stage will be very expensive to execute.(Graph 2)

Graph 1
Distribuion of fixed and accrued costs during production



Graph 2
Evaluation and manipulation of cost during design process



5th ISRC

Especially for the successful implementation of robot technology into construction, all building production stages become very important to consider as whole for incetance final on-site operations are consider at the early stages of to concept and designing. Conventional construction operations are primarily designed for manual execution, thus implementation of robot technology becomes difficult as long as manual-oriented thinking is prevailing. The following chapters show possible ways to adjust to the requirements of robot-oriented construction.

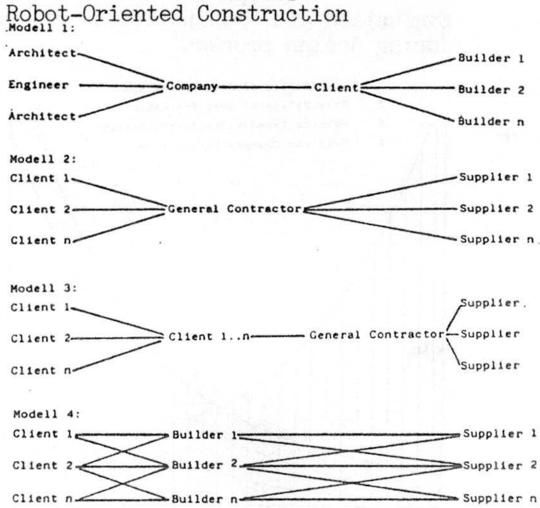
1. Global strategy for robot-oriented construction

1.1 Transitions of building market towards robot-oriented construction

Normally when a client needs a building, he will ask a company, for which architects and engineers are working, for the design, planning and disposition of the construction project. Later one or more builders will be assigned to execute the construction works. (Model 1) A major disadvantage of this model is the way of defining the quality. Since there is no sufficient quality control of works between company and builder even though specifications are usually listed. Due to the fast development of science and technology, building related specifications of up to date technology is hardly available especially to small builders. The smaller the builder is, the less successful is the definition and control of quality. Since technological know-how is related to production technology which is varying from one company to other, the quality of the building as a product is differently decided by each builder. Furthermore the architect is sometimes not aware of the state of the art of technology. This dilemma can be seen at the fact that former tasks of architects are now executed by specialized engineers. This development supported the establishment of large general contractors offering turn-key-system in construction.(Model 2)

If the client is confronted to few large contractors which decide the quality and guaranty of the building, he can only choose between some companies and there is no transparency of prices. Model 3 shows powerful public or private clients which also run their own planning office. In this case, the client can partly influence the producer, but the producer will always decide the variety of building types for the production and construction of large projects. The robot-oriented building and construction system will allow to satisfy the requirements of all parties that are involved in construction. Due to the inherent character of robotic technology, all standards of soft- and hardware have to be well defined. Suppliers have to provide the geometrical and physical qualities of building elements that are required for robot-oriented construction method.(Model 4)
This robot-oriented building market will be achieved, if the following 15 parameters can be simultaneously fulfilled without excluding each other:

Transitions of building market towards
Robot-Oriented Construction



1.2 Parameters of robot-oriented construction

1. Flexibility in planning and design
2. Definition of cost
3. Clear marketability
4. Definition of price
5. Guaranty of price
6. Transparency of price
7. Homogeneity of production
8. Continuity of production
9. Definition of quality
10. Control of quality
11. Transparency of quality
12. Standardization
13. Definition of construction period and time
14. Control of construction time
15. Transparency of construction time

1.3 Increase of productiovity and profitability

Productivity of construction industry can be increased through production of highly differentiated building elements which are suited for many function. A major improvement in Robot-Oriented Construction is the reduction of on-site construction time through higher working speed and almost 24hours working hour a day. For example, it takes a mason about 1 to 1 1/2 hours to construct 1 SM. of masonry. The same job, a robot could do 10 to 50 times faster. Thus the cost of the building will decreased by reducing the intermediate financial burden. The profitability of the building will increased because the building can be utilized shortly after it has been ordered or purchased.

1.4 The transitions of building processes towards robot-oriented construction

The traditional building process is characterized by a long construction period, which is resulting in a lower profitability of the building and therefore uncertain prices but a big variety and flexibility of design.(Figure 1) The rationalized construction process is characterized by typification of planning and well defined supply system already before the contract is signed thus reducing the construction time but also limiting variety and flexibility of design through the use of large sized elements.(Figure 2) The industrialized construction process is characterized by a reduced construction time thus allowing higher profitability and security of price through homogeneous and continuous production of mass-produced building elements.(Figure 3) But this model is weak for fluctuations of the building market. The robot-oriented construction process will be characterized by minimized construction time, high variety and flexibility of design. The flexibility of software allows the production to adjust to fluctuations in demand. This system requires a certain product hierarchy which results in well defined and specially designed building elements for robotic construction.(Figure 4)

Figure 5: Cost Distribution in the Ancient Building and Modern Building

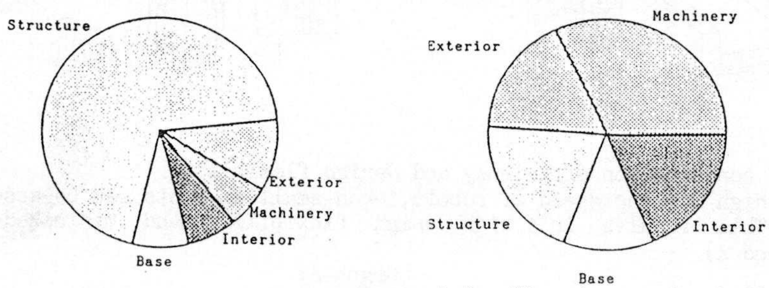


Figure 1:
Conventional Construction Process

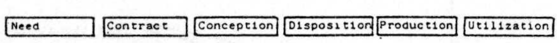


Figure 2:
Rationalized Construction Process

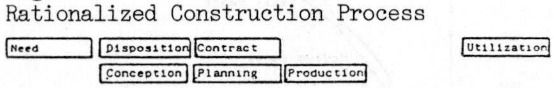


Figure 3:
Industrialized Construction Process

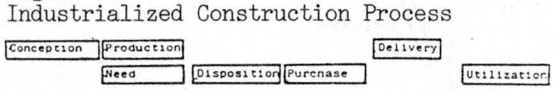
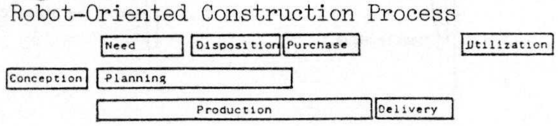


Figure 4:
Robot-Oriented Construction Process



1.5 Planning of building system and coordination of building subsystems

The more advanced and industrialized a construction process becomes the more important the design stage becomes, since most building elements are designed and produced before the construction of a building is ordered. The accuracy of subsystems vary: The low accuracies of foundation work are insufficient for other construction works and the higher accuracy of floor wall or installation assemblies are not required for earth works. Different categories of accuracies should be defined for different construction works, considering with ompliant interfaces of building sub-system. This is also true for the production of complex elements which are composed by e.g. wood, plastic, steel section whose tolerances also vary, effecting each other and therefore have to be compliantly coordinated. Due to the increased complexity of modern building compared with the ancient building this kind of coordination of subsystem is required.(Figure 5)

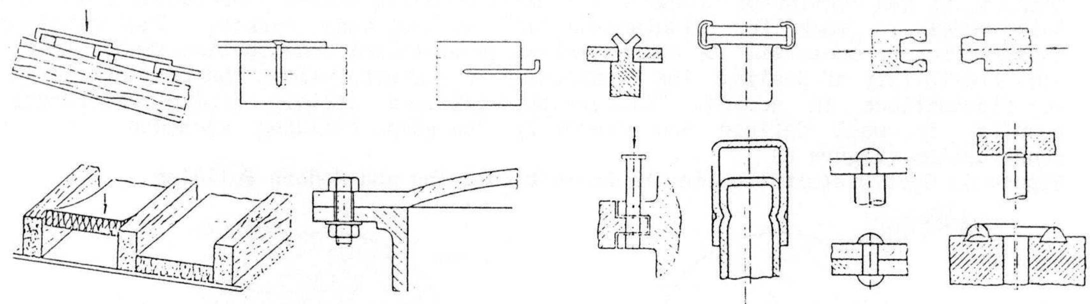
1.6 Integrated design method

Building system should not only be designed for robot-oriented construction but also for usual maintainability, reliability, stability, serviceability, safety and aesthetics. This require coordination of production related engineers with planners and architects. The robot-oriented design of small standardized, functional and material elements are required for robotic construction in order to adjust to any project. This requires the modular coordination of smallest elements of building kit as well as modularization of robot software. Specifications and building systems have to be designed as kits which consist of highly differentiated parts which fulfill any functional requirements and regional building codes.

1.7 Importance of joining operations in construction

In construction more than 2/3 of the production time is used for some kind of assembly operation. (DIN "FUEGEN" 8593) Therefore efficiency of construction can be mostly increased if building elements are designed for automatic assembly. Figure 6 shows variety of assembly operations.

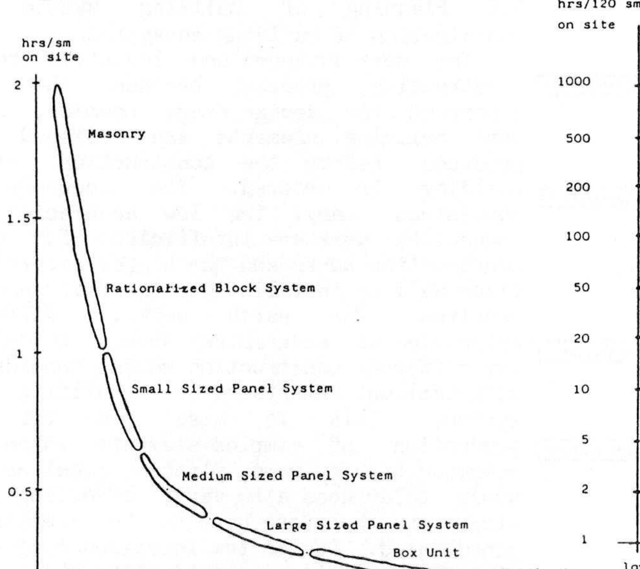
Joining:



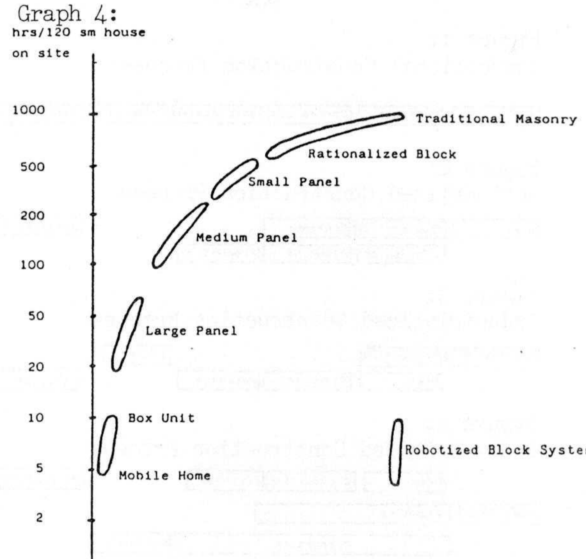
1.8 Increase of construction efficiency and design flexibility

Due to the high working speed of robots, even small elements can be assembled quickly at on-site. This results in a high design flexibility and minimized construction time.(Graph 3 and 4)

Graph 3:



Graph 4:



1.9 Physical and geometrical definition of all elements

During early design and concepting phases, a three dimensional space is created in which the positions of all parts are well defined. All conditions of construction have to be defined in their physical and geometrical quality.(Figure 6A,6B)

Figure 6A:

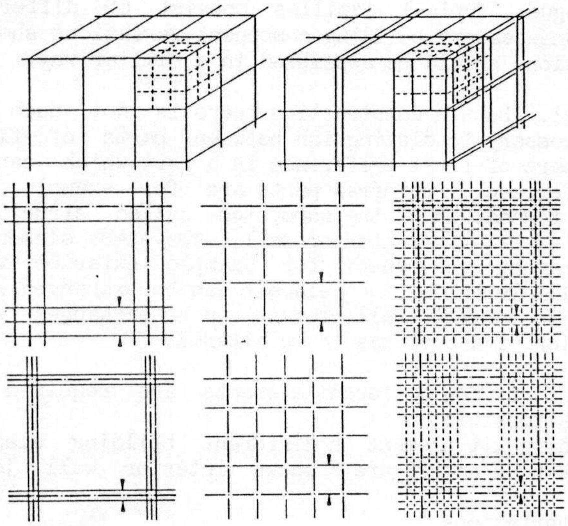
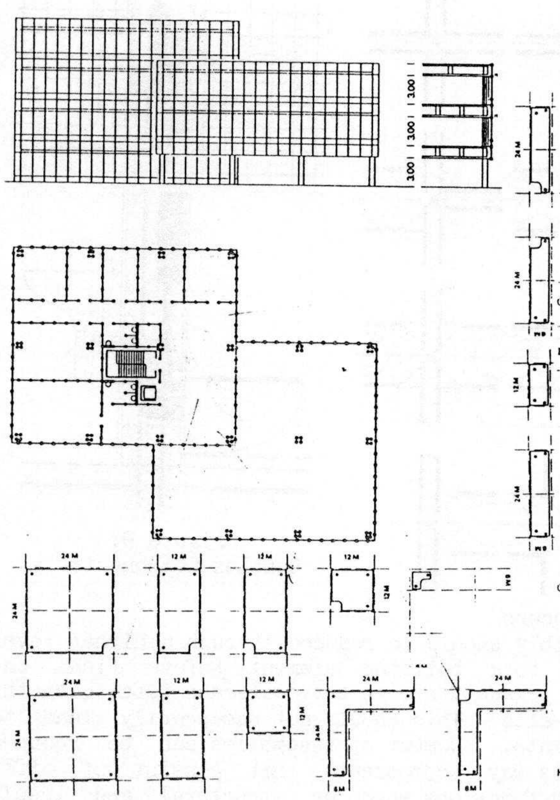


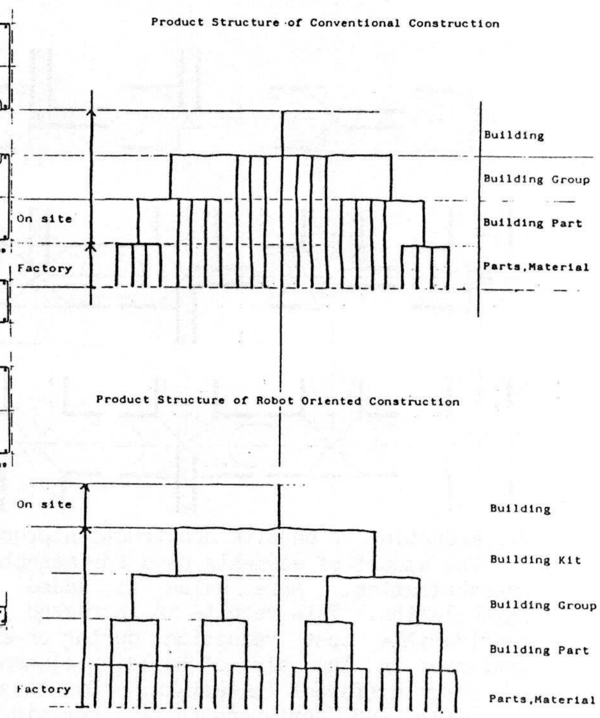
Figure 6B:



1.10 Clear product hierarchy

The clearer the product hierarchy becomes, the easier robots can be implemented in construction. In order to rationalize construction building kits, they are split up into well defined hierachical levels. By this means a product is subdivided into sub-products according to robot-oriented requirements. If a project is realized an hierarchy of all the building parts, elements and groups necessary for the project can be shown. On construction sites, we can see all kinds of parts, elements sections and material that are transported to the site and further processed there. But in case of robotic construction, the site is just the final production stage of building production. Prefabricated, value added, small elements are shipped and installed on-site before the building is utilized. In this case, advantages of Industrial Robotics in the controlled environment of factories for mass-production of small and value added elements can be used thus on-site construction time can be reduced.(Figure 7)

Figure 7: Product Hierarchy



2. Building element range for robot-oriented design

2.1 Group technology

The building element range should be rationalized through group technology or part families. Group technology creates product groups which can be assembled or processed by similar equipment. Such product families can be very different from the final product printed in the companies' house catalogue. Typical families consist of different versions of basically similar products. Unnecessary building component variations should be avoided and minimized. Required variations should be assembled in a similar way.

2.2 Parts of first and second preference

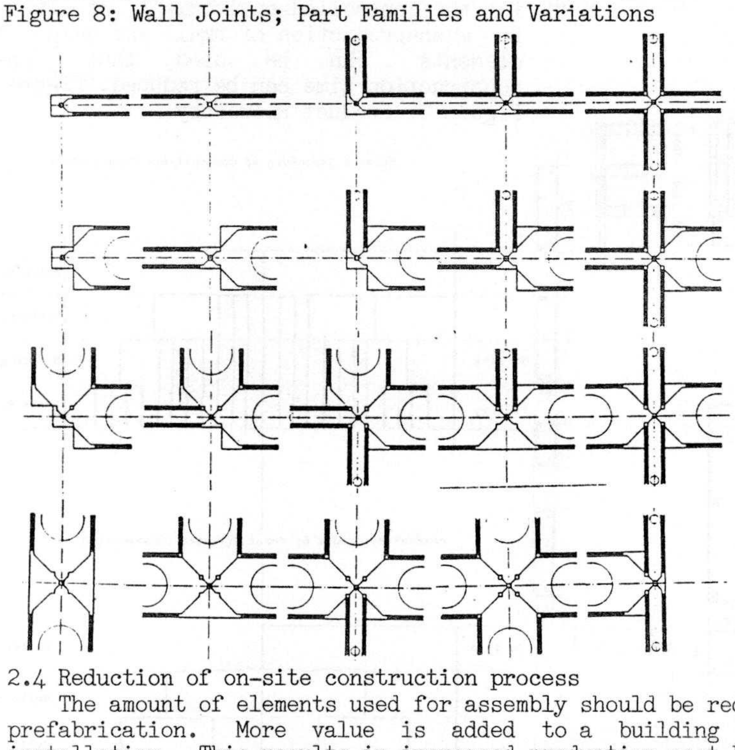
The Lego kit is an ideal building kit. But in construction there is not such an ideal configuration, therefore it is necessary to distinguish between parts of first order and second order or preference. A part of first preference is a part which cannot be exchanged with a part of second preference. Preferred parts are for example the structural parts such as columns, beams, foundation of the subsystem called structural subsystem that can not be exchanged with exterior or interior wall subsystem elements. Equal building parts might be exchanged among each other. for example exterior wall element can be exchanged with interior wall element or roof element can be exchanged with floor element in case a story is added. An interior wall element can be exchanged with an installation wall element if the function of a room has to be altered.

2.3 Range of elements

A building element range is efficient, if few different elements are required to assemble as many different combinations as possible.

N=Number of combinations, k=number building kit element n=different building element types z=total amount $k \times N = z \times n$ and $z = k \times N/n$ Figure 8 shows interior wall joint combinations.

Figure 8: Wall Joints; Part Families and Variations



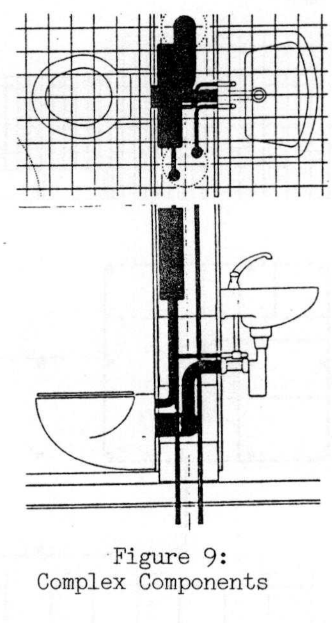


Figure 9:
Complex Components

2.4 Reduction of on-site construction process

The amount of elements used for assembly should be reduced through a higher level of prefabrication. More value is added to a building element before final on-site installation. This results in increased production cost but decreases total cost through considerable cost reduction during on-site. This should not necessarily lead to an increase in the size of building elements. Number of assemblies can be reduced by choosing different materials. By this way, components that consist of different materials and parts to fulfill certain functions such as structural and insulating function, could be build by one or several materials and one or several parts satisfying all requirements.(Figure 9)

2.5 Standardization of elements

In order to achieve well defined building system, the building parts have to be standardized. In order to realize all possible combinations, it is necessary to have identical single parts. Furthermore the joining areas have to be identical to enable assembly. This is only possible if the joining areas are defined geometrically and physically. Standardization and exchangeability are the conditions for the use of a building kit system. Similar as the standards of "Open System", the building parts of the kit should be available from different makers while remaining assemblable and exchangeable.

3. Building element structure for Robot-Oriented Design

3.1 Basic structures

One dimensional structures(column, beam, sections) are well suited for prefabrication processes. Two dimensional structures(boards, walls, windows...) are suited for prefabrication and on-site operations. Three dimensional structures(block, units) are well suited for prefabrication and on-site robotic construction.

3.2 Integrated product structure

The number of joints between elements and simultaneously the joining operation should be minimized. If assemblies will not be disassembled in the future, some joints can be simpler. In order to achieve a reduced number of components and subassemblies which are larger but still easy to handle the product structure of building elements should be integrated. This leads also to less joints and higher accuracy. Integrating production methods reduce components for on-site assembly and increase prefabrication. In order to construct different components the product structure should consist of elements which fulfill certain functions. But to increase series of subsystems and to simplify the product structure it should be planned as a building kit. The composition of building elements can be determined in different ways, that means the variants can be build without high additional cost. In order to avoid costly handling of smaller parts, such as complicated positioning, inlaying and insertion, should be further processed into larger units.

3.2.1 Standardized element structure

In order to achieve functional flexibility, standard parts should be used. Building elements can be easily adapted to existing facilities if their product structure is designed in a highly differentiated way.

3.2.2 Standardized structure between workpieces

Interface of joining areas and points should be standardized. Building parts which have to be assembled need a well-defined joining area. This joining area becomes more important if the assembled structure has to be stable. The assembly of complex structures may require special building parts for the joint at the joining area. These special building parts can also allow disassembly and exchange.

3.2.3 Standardized structures between workpiece and worktool

Geometrical and physical functions of building elements have to be coordinated with robot performance and structure. Simplifying the joining operations by well-defined specifications, for instance hooklike, locking or clamping devise, and unifying direction of assembly. The geometrical and physical qualities of endeffectors have to be coordinated with those of workpieces.

3.3 Compliant structure

In order to precisely place components, the system-structure has to be produced and assembled with minimum tolerances.(Figure 10)

3.3.1 Problem of accuracy

Everyone involved in construction is aware of the problem of accuracy. Man can recognize and correct most inaccuracies. Advanced robotics already provide technology to cope with unstructured and non-defined conditions. However this increase the price of robots and reduces their working speed. The statistical median value of accuracy which is commonly used in construction can not be applied to robotic construction since it does not consider all cases of minimal and maximal accuracy. Therefore all problems of accuracy are described in 2 categories which can be easily incorporated in the robotic construction process:

<u>Category 1:</u>

The dimensions of each building element is known and the total deviations of composed structure are needed. If only one robot is assembling a block wall and the orientation of the robot remains unchanged, all dimensions can be added up. But if two robots work simultaneously in opposite directions or one robot works in many directions, their total sum of accuracies have to be deducted from each other. Due to the opposite orientation of two robots a reference point is chosen and the premise of deviation of one robot and the upper and lower deviations have to be changed before summed up with those of other robot or working orientation.(Figure 11)

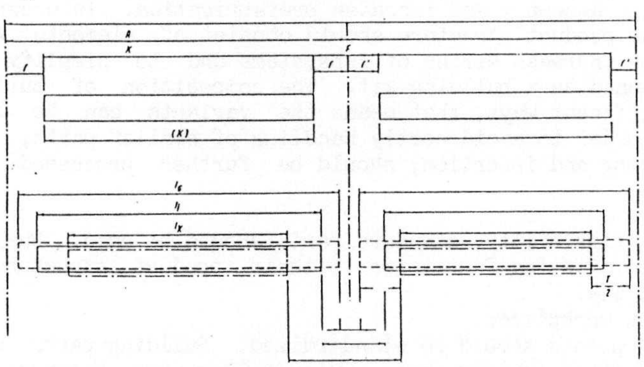
<u>Category 2:</u>

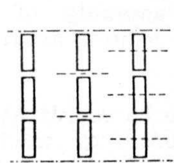
The total allowable accuracy of an assembled structure given and single allowable accuracy of single building element is wanted. Contrary to category (1), the premises of the total size of an assembly and the size of a single building element can not be changed. Identical accuracies that are substracted from each other can not become zero. The resulting accuracy of an assembly consisting of building elements that have negative and/or positive deviations is equivalent to their doubled sum.(Figure 12a, 12b)

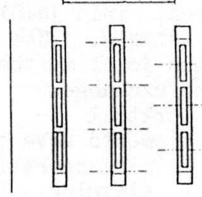
3.4 Reduction of temporary building structures

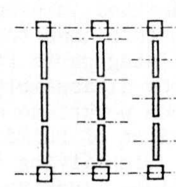
All the temporary joining elements that are widely used on-site should be eliminated by re-structuring the building elements. In such a way that they can be joined without temporary support elements. In order to assemble in a simple way, the building element structure should consist of components that can automatically secure themselves during assembly. Necessary adjustments should be integrated in the joining operation requiring real time measuring feedback and control. To simplify construction robot motions, the patterns of movement during operations should be linear and uniform.

Figure 10: Possible Deviations









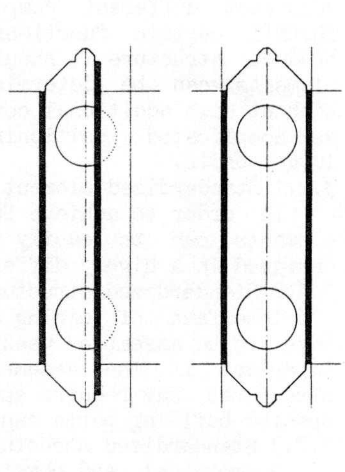


Figure 11
Category 1

Figure 12a Figure 12b
Category 2

Figure 13
Asymmetrical/Symmetrical
Building Component

4. Robot-oriented building element design and re-design.

4.1 Clear and simple design

Building elements should be clearly and simply designed.

4.2 Design for easy orientation

The building elements should be designed in such a way that orientation operations before final assembly can be avoided. If building elements have to be oriented, it should be supported by design for ease of orientation.

4.3 Symmetrical and asymmetrical design

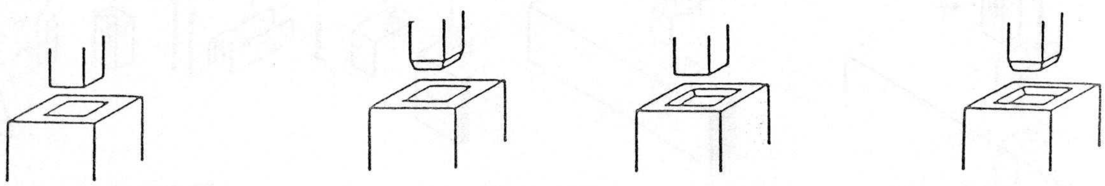
Symmetrical components should be used wherever possible.(Figure 13) This will reduce handling, orientation, identification and presentation problems. If the orientation of a components remains unchanged during construction, it is obviously less expensive than having to orientate the component several times before the assembly task. Many asymmetrical elements can be symmetrically re-designed by adding non-functional features which should not be cost-effective. If a part has to be designed asymmetrically, its asymmetry should be emphasized, so that before assembly, the orientation of the building element can be easily recognized and checked by simple but effective devices.

4.4 Compliant design

The compliant tolerance system has to be considered during design of building elements:

4.4.1 To avoid geometric error between the building element which is handled and the element with which it has to be joined.
4.4.2 To compensate for inaccuracies in the robot control system.
4.4.3 To avoid misalignment of robot gripper to the palet and workplace.
4.4.4 To deal with variations of manufacturing of the building parts.
4.4.5 To allow differences in pickup positions from palets or conveyors.
4.4.6 To avoid varying grasping attitudes of building parts.(Figure 14)

Figure 14: Compliant Design



Difficult to Assemble   Easier to Assemble   Easier to Assemble   Easiest to Assemble

4.5 Design for transport and handling

In order to transport parts without difficulty they should be designed as a balanced part where the center of gravity coincides with the axis of the gripper. Elements should have guiding surfaces for easy placing of elements before joining and adjusting.

4.6 Redesign method of existing details and building elements

During redesign it is necessary to check every item is justified. A number of redundant components or parts can be identified and replaced by one composite component. Following methods are to redesign an existing detail according to robot-oriented design rules: After the first analysis of the function of an element, the sub-functions of each element are defined within their space or area of effect. The steps of analysis gradually eliminate all sub-functions that were not related directly to sub-functions of assembly and joining. In the next step the elements of subsystem for joining are isolated. These elements are then analyzed through reduction of their physical qualities to purely geometrical qualities, which can be expressed in 1, 2 or 3 dimensions. The physical qualities can be described by symbols and the geometrical qualities by symbols for center of gravity.

Robot-Oriented Redesign: Step 1; Omit Dimensions

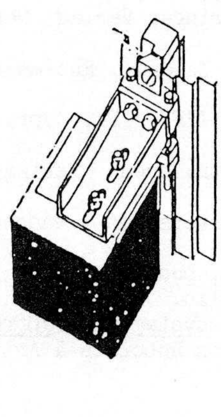


Figure 15

Robot-Oriented Redesign: Step 2; Explosive Drwing

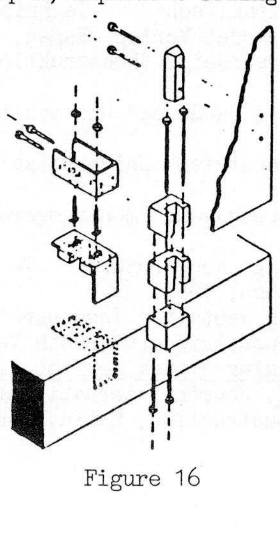


Figure 16

Robot-Oriented Redesign: Step 3; Production Oriented Simplification

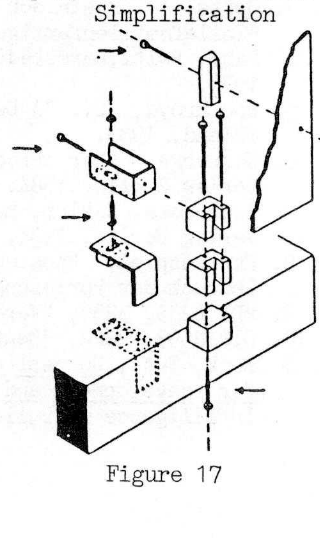


Figure 17

Robot-Oriented Redesign:
Step 4; Function Oriented Simplification

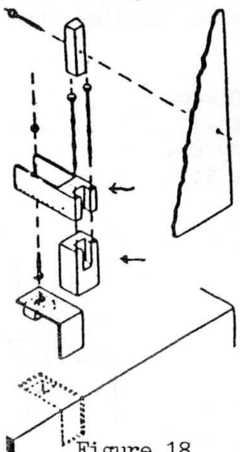


Figure 18

Robot-Oriented Redesign:
Step 5; Assembly oriented Simplification

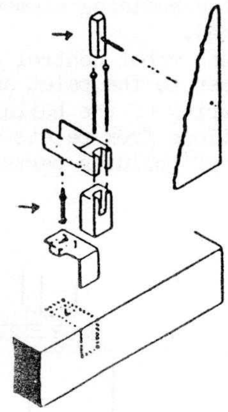


Figure 19

Robot-Oriented Redesign:
Step 6; Structure of Joining system

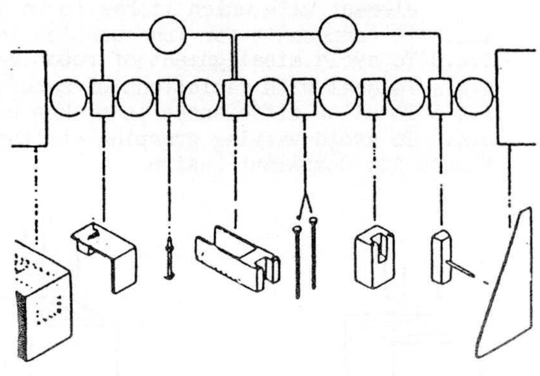


Figure 20

The elements which have similar or identical effects can be combined to certain classes of functional solutions. In the next step the effects of these elements are analyzed according to the assembly process. This analysis can follow the procedure mentioned in VDI 2222: split up function in sub-functions while simplifying. Search for solutions for these sub-functions and combine the solutions of sub-functions to total function. These two steps of analysis are accomplished by simplifying abstractly the joining system. Each joining system can be shown as a structure by a symbol for element and joint. If further information is added to these symbols, the principle of the joining system is shown. Flow of forces and moments can be shown as well as required adjusting during the robotic construction process.(Figure 15-20)

Conclusion

The architect and engineer can successfully support the implementation of robot technology into construction by following above guidelines or rules of "Robot-Oriented Design."

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