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KIT-OF-PARTS: A REVIEW OF OBJECT-ORIENTED CONSTRUCTION TECHNIQUES

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Abstract: In pursuing construction and design concepts appropriate for the information age, the authors have considered kit-of-parts theory. A kit-of-parts is a collection of discrete building components that are pre-engineered and designed to be assembled in a variety of ways to define a finished building. Since a well-designed component can be mass-produced and used over and over again, fabrication processes can be worked out in advance for real-time manufacturing and automated assembly. This paper briefly traces the history of kit-of-parts construction techniques and categorizes some current methods from an architectural design perspective. Four categories of kit-of-parts systems are: JOINT-BASED, PANEL-BASED, MODULE-BASED, and SPECIAL CONSTRUCTION. The paper concludes with descriptions of case study design investigations conducted by the authors which demonstrate the advantage of pursuing kit-of-parts concepts in conjunction with architectural design processes and automated construction applications.

Keywords: kit-of-parts, architectural design, automated construction, design grammar.

1. INTRODUCTION

Kit-of-parts components can be thought of as objects in an object-oriented programming environment. With well-defined interfaces which are rigorously followed, the component itself can assume any form. Interfaces can include grasping and mounting points, rules for the transfer of loads, specifications for thermal performance, and maximum cost constraints. In short, a kit-of-parts approach lends itself to cheaper and more efficient manufacturing and is a clean way of constructing a building without having to deal with loose ends associated with the complexities of unorganized raw materials.

Following a brief discussion of design philosophies and building techniques that have contributed to the kit-of-parts concept, examples of designs that have been conceived in preparation for this work are described.

2. KIT-OF-PARTS CONCEPT

Kit-of-parts architecture involves organizing the millions of individual parts in a building into assemblies of standard easy-to-manufacture components, sized for convenient handling or according to shipping constraints. The construction of the building is generally carried out on the assembly level as opposed to the part level. This requires much thought at the architectural conceptual design level, and coordination between the architect, engineers, manufacturers, and builders. The architect defines a parts library describing every major assembly in the building. The library could be similar to an interactive LEGO set, which has many standard parts already available but is open for additions by creative users trying to meet new needs. The assemblies are conceived in a systematic way, perhaps based on a certain increment or size or shape grammar. Standard connections between the assemblies are defined, allowing greater freedom in the form itself: anything is possible as long as the connection rules are observed. After rules of connection and increment are established, the number of possible shapes and appearance the parts can take is limitless. Rules of connection and increment may include requirements for materials, structural strength, force reaction paths, center of gravity, thermal or sound insulation qualities, and transparency.

2.1 Appropriate for the Information Age

Kit-of-parts philosophy lends itself toward advanced manufacturing, automation, and computer and information technologies. Handling multiple identical components as instances of a master element is an efficient use of the computer in the planning stage, and use of standard components can take advantage of mass-production technologies.

In addition, spaces can also be divided up and thought of as components as well, where digital blocks of spatial volume have their own attributes and enclosing structure. Using an object-oriented approach to manage the digital spatial cells, automated construction systems that generate the enclosure of a single cell (or parametric multiples thereof) can be developed.

2.2 Traditional versus kit-of-parts methods

In traditional construction methods, buildings are erected in what can be called "final line" construction, where raw materials, tools, labor and such are all gathered to the site and processed on the spot. The measuring, cutting, and processing of raw materials constitute the majority of labor in manufacturing and construction. Assembling these cut and processed parts into major assemblies such as walls or floors consumes even more time and labor on the building site. The use of prefabrication and kit-of-parts construction turns the entire building process into "assembly line" style, where many different manufacturing events can occur in parallel in safe, controlled environments, and the actual assembly on site of the resulting components is fast, clean, and safe, and lends itself toward automation.

3. KIT-OF-PARTS BACKGROUND

Kit-of-parts construction is a special form of prefabrication. The major difference between the two is that kit-of-parts components can be assembled and dismantled over and over again according to need. The majority of prefabrication produces a set of components that generally are permanently connected at the time of construction and can become damaged and unusable when dismantled. Nevertheless, kit-of-parts construction and prefabrication are similar in many ways and share the same history.

Prefabrication techniques arose from three basic needs that traditional construction methods could not meet: the need to create shelter quickly with little effort, the need for unusually large numbers of buildings at a low cost, and the need for periodic renewal. Since prefabrication lends itself toward the "assembly line" model more than the "final line" process, large amounts of identical or similar components can be mass-produced quickly and cheaply. The "assembly line" technique allows the processing of raw materials to be performed in advance, thus reducing the amount of time and labor needed to erect the structures on site.

3.1 Early prefabrication attempts

Prefabrication and kit-of-parts construction has been around since the dawn of civilization. The first clay bricks of ancient civilizations prepared in advance with the intent of fitting them together on site fall well within the definition of prefabrication. To this limited extent, prefabrication has persisted in all cultures in some form or other, most likely due to the need for reducing the "bottle neck" of time and labor while waiting for bricks to cure or stones to be dressed. In ancient Japan wood kit-of-parts systems for the assembly of shrines produced a whole range of snap-together / take-apart joints that have been standardized over the centuries. This was partly borne out of the Shinto tradition that shrines be renewed and rebuilt every twenty years.

In more recent history the need for quick or movable shelter led to the use of prefabricated buildings. In 1624 English fishermen brought a panelized house to the Americas that was assembled and disassembled several times. Settlers used some prefabrication in the 1700's to provide shelter immediately upon arrival to the New World. Cast iron was used in early attempts at prefabrication from around 1830 and resulted in the spectacular mass-produced Crystal Palace in 1851 by Joseph Paxton.

By the early 1900's prefabrication moved to more complex systems. Prefabricated plumbing and service stacks that were completely standardized were produced. In addition to panel systems and prefabricated structural members, entire dwelling unit-sized modules were also developed. One firm LeTourneau produced welded, all-steel houses in 1937 that were moved and placed in one piece, including the garage. Some LeTourneau houses were moved from plant to site by water, floating on their own bottoms. Le Corbusier experimented with manufactured modules that plugged into a main superstructure. Similar work by Frank Lloyd Wright attempted to link with the development of the mobile home that is popular in the United States today.

Early designs of package kitchens and baths culminated in the development of Buckminster Fuller's Dymaxion House. In the world of prefabrication, Buckminster Fuller was clearly ahead of his time and his research has provided a great deal of basic concepts and knowledge that influenced Archigram, the *Metabolists*, and the *Hi-tech* movement.

3.2 Contemporary prefabrication practices

Today, prefabrication is a given. It can safely be said that there is probably no construction project that does not use some form of prefabrication, whether it is the use of pre-cast or pre-cured masonry units, precut lumber, or other pre-sized building materials. Since the use of parametric building materials has become so common place, they are no longer considered to be within the realm of prefabrication. Today "prefabrication" means pre-cut or pre-assembled components designed to fit together in a certain way such that no other processing of the raw materials is necessary. In the simplest application, many commercial applications can be found that produce pre-cut logs, lumber, or metal parts prepared for mail-order homes and industrial buildings with follow-the-directions, do-it-yourself assembly, such as Neville Log Homes, Topsider Building Systems, and Butler Buildings. In more advanced systems, entire modules and major assemblies are produced using mass production techniques, such as Sekisui, Misawa, or Toyota Homes. In Japan, almost the entire housing industry has come to use these advanced prefabrication and systematic assembly techniques. Those construction companies that do not have the capability for advanced prefabrication techniques are being pushed out of the market because they cannot meet competitive prices and time schedules.

Some innovative, long-lived kit-of-parts systems have come out of surprising corners of the construction industry. Construction support systems, such as container-type job site office structures and snap-together scaffolding systems have come to wide use. Japanese companies like Hory Corporation have developed adjustable span trusses and girders that can be used over and over again. Japan Steel has developed a series of deployable stairways that fold compactly for shipping and can be hung tens of stories off of scaffolding. European firms like Plettac and SGB International have special slip joints for scaffolding that can be connected or taken apart by hand and require no special tools. An Italian firm, Alpi, has designed an attractive but functional bolt-together system that can be used for scaffolding or for form work construction. While the container job shacks are generally spartan and dull, Fuji Sash has developed a system with plug-in toilet or kitchenette capsules and snap-in cladding parts. Using certain window components, the modules can be made quite attractive.

3.3 Prefabrication / kit-of-parts system categories

Kit-of-parts and prefabricated systems fall into four main category types: joint-based, panel-based, module-based, and special construction, which includes deployable and pneumatic inflatable structures. With exception of the special construction types, the systems have each evolved out of traditional construction methods. In some cases it is even hard to distinguish the difference between traditional and prefabricated structure, since the only difference is where and how the raw materials were processed.

JOINT-BASED: On the simple end, a common prefabrication technique is to pre-cut materials for later assembly and construction. These individual pieces may look the same as their traditionally prepared counterparts, except that they are prepared in advance. More advanced applications which fall into the joint-based category have clear distinctions between the members and joints, and often celebrate the joint with some special design or connection technique that either enhances the ease of assembly or speeds erection time. Highly refined joint-based systems are good candidates for kit-of-parts concepts since the connectors are so clearly defined and can be designed for easy de-mounting as well as easy assembly. Joint-based systems are easy to represent virtually in a computer. A well-designed joint-based system can also lend itself toward automated construction techniques.

PANEL-BASED: Some of the earliest prefab systems were panel-based. In the West where shear panel construction gained popularity (as opposed to wood post and beam construction in Japan and other Eastern countries), prefabricated panel concepts naturally evolved. The first systems were wood frame, but today materials range from wood to metal to pre-cast concrete. Panel-based systems essentially incorporate structure and wall / floor cladding and decks into one-piece assemblies. An assembly consisting of raw materials becomes a discrete component that works as a single structure or cladding member. Upper-end panel-based systems also often have special joints that ease the construction process. Panel-based systems can also be good candidates for kit-of-parts concepts as long as joints and connectors are designed properly for disassembly as well as assembly. Panel-based systems are also easy to represent geometrically in the computer. In general, components in panel-based systems can be bulkier, but fewer in number than joint-based systems. For this reason, panel-based systems may be more suited for automated construction technology than joint-based systems.

MODULE-BASED: Some of the most advanced prefab systems are module based. Modules are entire portions or blocks that are assembled in advance and set into place at the site. Because of the size and scope of each component, the number of necessary modules required in a construction is usually much less than panel or joint-based systems. As was mentioned earlier, module-based construction can represent an entire self-contained building with a single unit. This would be impossible with panel or joint-based systems. Module-based systems are also ideal considerations for kit-of-parts concepts, and might be the easiest to represent in virtual form. Considering large blocks or modules, designing appropriate robotic construction systems for site assembly would be even more natural than those designed for panel systems. Modules themselves could be manufactured in off-site factories using similar technology as that which the automotive industry uses for the assembly of cars.

SPECIAL CONSTRUCTION: Special construction systems consist of deployable structures (including folding trusses and swing-open modules), and inflatable structures. Candela [2] describes research in deployable folding truss systems. Various ingenious truss designs, domes, space trusses and folding vaults for the purposes of maintaining a compact and / or lightweight profile have been researched and developed for instant site deployment. The appropriate use of these structures is often difficult to define. Since they are so perfect and balanced, and the removal of even a single member destroys the integrity of the entire frame, it is difficult to provide openings for entrances and other holes. Still the technology has great potential for quickly deployable structures as is called for in many kit-of-parts construction environments.

Another form of deployable structures may also be classed as furniture. Ambasz [1] introduced a group of Italian designers that have produced swing-open modules and capsules that range from self-contained structures to package kitchen units. Alberto Seassaro created a "central block" in 1968 that is a simple cuboid when folded up, and when deployed functions as the core of a residence. Bed, table, wardrobe, toilet, and shelves all expand from the cuboid. Joe Colombo designed a similar structure that included kitchen appliances and entertainment electronics such as television. Another of Colombo's designs was the Mobile House, which was a compact package that could be transported on the back of a truck and dropped off on the site, to expand to two or three times the stored size. In another project Colombo devised a series of block capsules with different functions that could be stacked or rearranged beside or on top of each other to form a custom dwelling. The capsules were targeted for use during disasters when emergency housing becomes necessary, or for use by workers on large-scale construction and civil works sites.

Other examples include military barracks, bridges, and other structures that are meant to be deployed, stored, and relocated in a minimum amount of time. Design exercises dealing with transformable and folding space, such as Origami and "Transformer" robot toys, have been inspiration for several architects and students.

Included in special structures is the development of inflatable modules and structural systems which also are designed to be lightweight, compact, and portable during shipping and storage, but expand to appropriate-sized volumes when inflated. Inflatable structures in themselves can be considered kit-of-parts systems, but are especially so when combined with joint, panel, or module-based systems.

4. KIT-OF-PARTS DESIGN

Using prefabrication and kit-of-parts techniques as a superior construction technique has its advantages, but using the methods in an aesthetic way may be a little more difficult. In the United States, the mobile home industry is flourishing. Mobile homes are perfect examples of module-based construction. Still, very few design professionals would agree that mobile homes have any architectural aesthetic value. Just using the technology is not enough. The kit-of-parts theme must be taken as the center of design investigation in order for it to have any merit in design methods research. Since before the 1930's manufacturing, prefabrication, and kit-of-parts concepts have occasionally been the subject of excellent design-related research. Starting with the Bauhaus in Germany and work by Le Corbusier and others, the foundations of the Modern movement was partially based on this theme. Though this chapter is not intended to be a historical review of such work, some discussion of various movements and their contribution to the kit-of-parts concept is in order.

4.1 Metabolism and Structuralism

In 1950, Charles Eames designed his own home almost entirely from catalog parts. The Eames home took commonly available consumer products and used creative expression to transform them into something exceptional. Such a result can only come through rigorous design investigation, which is mostly lost on modern manufactured homes. In the same post-war era, other designers were interested in linking the consumer with commonly available building products. The Plug-in City by Peter Cook in 1964 proposed an environment that recycled itself based on consumer needs. Self-contained pre-manufactured modules could be "clipped-on" to a basic structure and dissected or discarded when their need no longer existed. The Archigram group, of which Cook was a member, had radical ideas, and their design research with plug-in modular building concepts provided inspiration to designers around the world.

One of the most important design philosophies to employ the use of module-based kit-of-parts building concepts was the *Metabolism* movement. Starting in 1960, Kenzo Tange led a group that began defining architectural volumes and building systems conceptually based on natural systems that occur in nature, such as the cell, skeletal structure, and circulation systems. Traditional Japanese design concepts such as "ma," which means the void or space in between, combined with new ideas about prefabrication and industrialization produced exciting new design investigations. The *Metabolists* not only explored module-based building systems, but considered the spatial volumes themselves as celular modules that could be added for expansion in any direction as needed.

Kurokawa [6] explained the *Metabolism* movement's use of the capsule through his Nakagin Capsule Tower of 1972 and other projects. The Nakagin capsule apartments are still in high demand to this day. The Takara Beautillion erected for the Expo '70 in Osaka, Japan was a prime exemplar of using a skeletal structure to define space (or inversely, to be defined by modules of space). The system used a truss which was fabricated from 90 degree bent pipes, where the bends welded back to back formed an orthogonal node with the legs reaching outward. The legs, when bolted to legs of other trusses, became beams and columns in a volume-generating cuboid. The legs that were not engaged reached out in space as if waiting to clasp future truss additions. Unfortunately this wonderful example of the *Metabolist* movement was dismantled after the expo ended. Still, the Takara Beautillion remains one of the best examples of a module-based kit-of-parts, and can be considered an exemplar of how refined and extensive design investigations have gone in regards to kit-of-parts research.

Another post-war movement was the Dutch *Structuralism* movement. As explained by van Heuvel [7], *Structuralism* also dealt with modular volume generation, and resulted in exciting spatial transitions between interiors and immediate surroundings. Some outstanding examples include Hertzberger's Head offices Central Beheer of 1972 which had dynamic interiors and exteriors, and skeletal box structures cantilevering in some areas and protruding in others. Another exemplar is PEN offices of 1982 by Abe Bonnema that took a sloped shed roof element and effectively repeated it in a dynamic composition. *Structuralism's* main characteristics included modular blocks of space that were defined by bold concrete structure systems. Wall and floor panels were inserted within the structure as needed, leaving the impression of expandable cells.

Moshe Safdie conceived of his Habitat and other projects as an impressive use of *Structuralism*-like methodology using actual kit-of-parts apartment modules. The modules themselves were pre-cast and finished off site, then lifted into place in a *Structuralist*-type dynamic super volume. Though quite an expensive project, the attractiveness of the design has made the Habitat an exemplar of kit-of-parts construction applied as a central theme in rigorous design investigation. To this day there is a waiting list of would-be tenants.

The *Structuralism* movement has a modern day grandchild called the Skeleton / Infill or Structure / Infill (SI) construction concept. The SI concept started as early as the 1960's when John Habraken talked about using permanent superstructures with less permanent infill in mass housing schemes. Delft University has done much research on an SI concept called Open Bouwen Ontwicklungs Model (OBOM) which has a permanent concrete superstructure and a joint or panel-based kit-of-parts system making up interior partitions and other infill. The Japanese have joined in and applied centuries of wood kit-of-parts construction culture to several modern SI projects.

4.2 Hi-tech movement

The *Hi-tech* movement is a special group of architects that, through extensive design investigations and research, have brought the aesthetic of the building to the point of celebrating the kit-of-parts / manufactured concept in its very appearance. Inspired by Buckminster Fuller, Archigram, the *Metabolists* and others, *Hi-tech* was born as a British movement. A *Hi-tech* building is often characterized by exposed structural and mechanical systems and plug-in utility modules surrounding a simple orthogonal plan. The emphasis was not on designing spaces as much as allowing for flexibility. On an imaginary scale of "space-generates-structure" on the left and "structure-generates-space" on the right, *Hi-tech* would be all the way to the right. *Hi-tech* epitomizes the combination of design investigation and kit-of-parts construction technology. Among *Hi-tech* architects, the cardinal rule of kit-of-parts design for demountability was strictly observed in appearance if not in functionality.

Davies [3] explains that the *Hi-tech* movement started out slowly and painful, but finally received needed momentum when Richard Rogers and Renzo Piano won the design competition for the Pompidou Center in 1977. From that time the movement became world class, with the four major players (Rogers, Norman Foster, Nicholas Grimshaw, and Michael Hopkins) producing a wide range of impressive works. Materials and manufacturing methods research was common among the *Hi-tech* group, and often the architects went straight to manufacturers in order to achieve custom results on their exacting kit-of-parts standards. Rogers experimented with different types of glazing designed in-house. Rogers worked closely with manufacturers in the castings development for many of his projects.

5. KIT-OF-PARTS RESEARCH

From 1985 to 1998, a series of architectural design projects conducted by the authors presented opportunities to incorporate kit-of-parts design philosophy into practical and conceptual building solutions. Though the number of projects designed were well over a dozen, two are described in this paper. As exemplars, the LDS Building System (1994), and Plug-in Condominium (1998) projects were designed through practice working with Kajima Corporation in Tokyo, Japan.

5.1 LDS Building System project

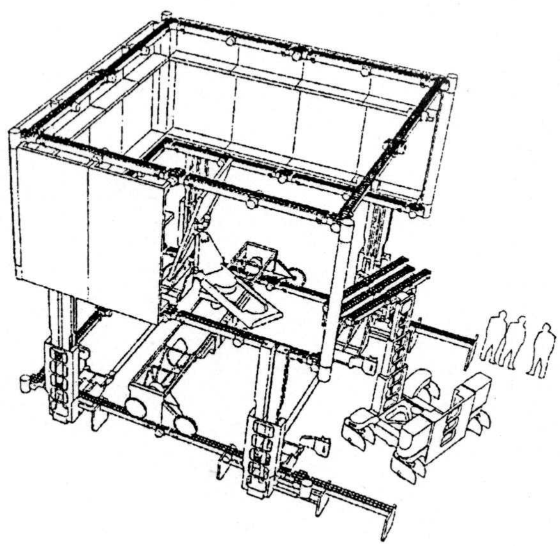

Figure 1: LDS Building System robotic assembly

The LDS Buildiong System kit-of-parts was conceived as a library of components with maximum flexibility for configuration. The components are easily assembled and meant to be demountable for reuse over and over again. The kit-of-parts system is joint-based, which means that a rigorous system of standard interfaces between parts is strictly observed, but the actual members themselves can be up to designers. This could facilitate the use of different materials or the creation of new parts that fit into the system. The joint system would be conceived in such a way that the possibility of incorporating power and communication infrastructures into the parts could be facilitated. This means that structural connection would also automatically complete wiring of the building since the "wiring harnesses" would be integrated into each part.

A rule-based design grammar was established for space design and component placement. The design grammar defined a parametric digital block of spatial volume. A single digital block of space became the work cell of a robotic construction system (fig. 1). Design tools were developed which allowed an architect to simply stack blocks of space which could generate their own enclosing structure [4].

5.2 Plug-in Condominium project

The Plug-in Condominium project (fig. 2) was conceived to be a demonstration project which showcases a new construction concept that calls for the establishment of a site factory. In the site factory concept, traditional "final line" construction is replaced by many parallel manufacturing and assembly processes in the "assembly line" method.

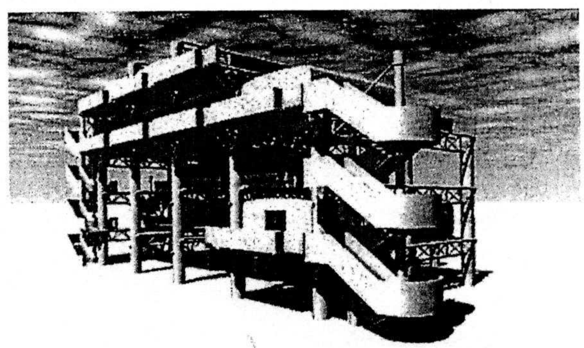

Figure 2: Plug-in Condominium project

Using kit-of-parts construction, *Constructivist* and *Metabolist* spatial arrangement, and Support / Infill (SI) philosophy, the plug-in apartment project attempted to apply an object-oriented approach to construction. Two major systems were developed: the skeletal support superstructure and the plug-in infill module system. The two systems interact with each other using a standard virtual module which defines infill module size, support points, utility connections, and circulation infrastructure. Support systems must be designed to bear the standard virtual module, and the infill components must be enclosed in the module and use the standard interfaces. The standard virtual module is established to allow different manufacturers to develop their own concepts based on the module, in order that various systems can be mixed and matched for individual needs.

Using this system, factory-manufactured modules could be purchased or leased by a tenant and plugged into the support superstructure to create a residence. The apartment can expand later by the purchase of additional modules, or each of the modules can be unplugged and moved to another site.

6. CONCLUSION

In the field of architectural design, there is a well established history of kit-of-parts concepts in the form of JOINT-BASED "linear element", PANEL-BASED "planar element", MODULE-BASED "solid element", and SPECIAL CONSTRUCTION "time element" system designs.

The kit-of-parts concept is truly fitting for the Information Age [5]. Using object-oriented theory, interface rules and component appearance can be developed independently of each other. Both building components and robotic building systems can be designed in parallel using the same interface rules and design grammars. Design using kit-of-parts concepts is more scientific and objective, since unwanted variables resulting from traditional dirty processes and unorganized raw materials are eliminated.

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