INDUSTRIALISED BUILDING SYSTEMS: THE "*PALETTE*" **OF OPTIONS**

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INDUSTRIALISATION

Industrialisation has demonstrated a capacity to reduce the costs, improve the quality and make available to the vast majority of people almost all the products offered on the market today, including most construction materials and components (trusses, pre-stressed slabs, curtain walls, etc.). But, so far, it is not really the case for the building as en entity.

Industrialisation is first and foremost a strategy: a large market (the "power of quantity") will amortise a process capable of simplifying the production, thereby reducing the efforts (i.e. the costs) required to produce each unit while assuring quality.

Industrialisation implies a continuous generic organization based on quantity and offering an individualised finished product. The situation with buildings is quite different from most other types of industrialised products: the buildings could never be entirely completed at the factory as it is by definition related to a site. Therefore, the products are usually not finished buildings but Industrialised Building Systems.

INDUSTRIALISED BUILDING SYSTEMS

An Industrialised Building System is a set of coordinated parts and rules where the same details are applicable to many different and individualised buildings located on various sites. The System's parts and their details are aiming at a large number of buildings while allowing for diversity and individualisation. Therefore, construction details are not re-invented each time a building is planned, as it is often the case with the conventional "professional service" approach still present nowadays.

The main parts of the Industrialised Building System are its Sub-Systems, which correspond to the main functions of the building. The System is usually composed of five major Sub-Systems: STRUCTURE, ENVELOPE, PARTITIONS, SERVICES and EQUIPMENT; whereas the Structural Sub-System usually plays a transcendental role.

Many systems do not include all the sub-systems, either because a sub-system is outside their technological scope or in order to accommodate local situations. Then, Open interchangeable Sub-Systems can come at the rescue. Open Sub-Systems can stand alone or be part of another system; they can offer more choices to the user and a larger market to any manufacturer that abides by the rules in terms of quality (performance criteria), dimensions (modular coordination) and interfaces (compatibility).

Many systems are integrating two (sometimes three) sub-systems within the same component, in order to further simplify the process while reducing the operations as well as the costs. For instance, a load-bearing sandwich panel can meet both the structural and envelope criteria, a transversal load-bearing precast concrete wall panel supports the floor slabs while assuring fireproofing and soundproofing between two different apartments, a modular closet kit can provide a partition between two rooms of the same apartment, etc.

THREE CATEGORIES OF INDUSTRIALISED BUILDING SYSTEMS

Based on the fact that building is site-related and technology factory-related, three basic Industrialised Building System categories are obviously prevailing. The first two categories represent the two extremes whereas the third category is reaching for the best of both worlds (Fig. 1).

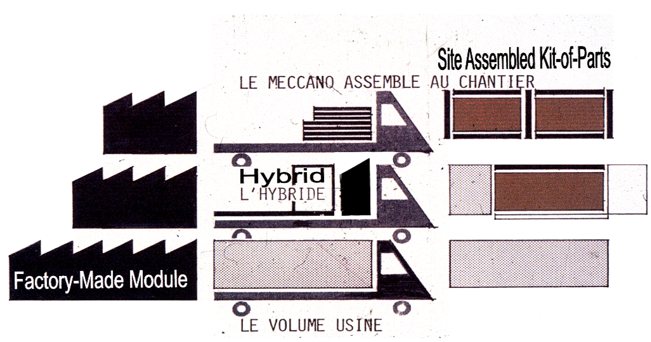

Figure 1. Relationship between the factory and the site. © Roger-Bruno Richard 2000

The Site-Intensive Kit-of-Parts: the sub-systems are made at specialized plants and delivered separately to be assembled at the site.

The Factory-Made 3D Module: since maximizing factory production is the goal of Industrialisation, the building is divided into volumetric modules assembled at the plant and connected to the infrastructure (foundations & main service conduits) and between themselves once at the site.

The Hybrid: Producing at the plant the complex parts of the building and entrusting the site with the heavy or simple operations.

By analogy, the three building system categories can be considered as the basic three colours (i.e. blue/red/yellow) from which the "Palette" of 9 building system types is generated: from "A" to "I", with the addition of a 10th element, the "Open" Sub-Systems (Fig. 2).

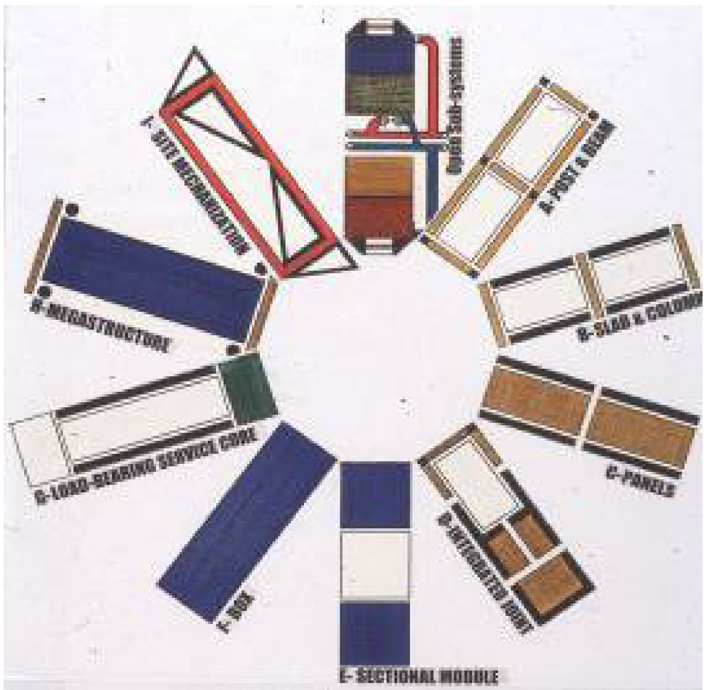

Figure 2. The "Palette" of options. © Roger-Bruno Richard 2000

THE SITE INTENSIVE KIT OF PARTS ("Meccano") CATEGORY

The Site-Intensive KIT OF PARTS ("Meccano") involves a few simple components produced in large quantity at specialised plants and delivered separately to be assembled at the site, thereby implying elaborate jointing operations.

The four types of systems within the Site-Intensive KIT OF PARTS category are governed by the geometry of the Structural Sub-System: the Post & Beam ("A"), the Slab & Column ("B"), the Panels ("C") and the Integrated Joint ("D").

Strategically, the initial capital investment can be reduced significantly when the components are simple and when the most demanding parts of the production are sub-contracted to specialised manufacturers who in turn amortize their own investments over many other clients.

I- Site-intensive KIT OF PARTS	**The sub-systems are made at specialized plants and delivered separately to be assembled at the site**
 **A- POST & BEAM**	Skeleton open to horizontal and vertical infill at the site
 **B- SLAB & COLUMN**	Continuous horizontal elements open to vertical infill
 **C- PANELS**	Load-bearing flat horizontal and vertical components providing a linear distribution of the loads
 **D- INTEGRATED JOINT**	Monolithic component simplifying the connections by distributing the jointing outside the geometrical meeting point

Figure 3. The Site-Intensive KIT OF PARTS. © Roger-Bruno Richard 2004

Functionally, when dry (mechanical) joints are used, all the components/sub-systems are easily and rapidly assembled at the site as well as easily and rapidly dismantled without any demolition in order to be reconfigured or relocated elsewhere; thereby allowing for adaptability through space and time, in full conformity with the sustainability agenda.

As one moves from "A" to "D", the work at the site is simplified: a Post & Beam system needs more connections and infill than a Slab & Column one; the Panels adopt a direct linear distribution of loads and the Integrated Joint distributes all the joints outside the geometrical meeting point.

A. Post & Beam: Skeleton open to horizontal and vertical infill at the site.

- Advantages: loads concentrated on points, offering maximal planning freedom; suitable for “Open Sub-Systems” since the skeleton can serve as connector; adaptability on the three axes.
- Limitations: higher structural costs due to the concentration of loads on the beams and the columns; large amount of site connections and infill.

Post & Beam systems are featuring either segmented components requiring a connection at each joint, continuous columns to reduce the number of vertical joints or cantilevered beams to provide additional spans.

The components can be designed to incorporate multiple options, very much like the many modular holes on the pieces of the Meccano set; actually, some metal systems are almost identical to it (Bone in Canada, Asahi Kasei Hebel Haus in Japan, Schulitz in Germany, etc.). Several laminated timber systems rely on ingenious metal connectors (Shawood and Muji + Infill in Japan, etc.) while some housing manufacturers will assemble the timber components into panels right at the factory (Huf Haus and DaVinci Haus in Germany).

The Munich *GenterStrasse* townhouses project designed by Otto Steidle shows the versatility of multiple-corbel precast concrete columns: split-levels, 1½ storey rooms, etc.. The precast concrete system developed by Vittorio Gregotti for the Scientific University of Palermo shows the rich architectural vocabulary possible with imaginative component design.

B. Slab & Column: Continuous horizontal elements open to vertical infill.

- Advantage: horizontal integration of the structure to provide a large area with a single slab element; adaptability in two directions.
- Limitation: conflict between the uniform distribution of loads expected in a slab and the concentration required in connecting with a column.

In order to accomodate the interfacing between the slab and the column, the “Ribbed Slab” and the “Slab Incorporating a Perimeter Beam” are the prevailing options.

The most spectacular applications of the Slab & Colum type are provided by the Broad Group in China. The Slabs are steel frames transported flat, together with the posts and all the interior components installed between them in a sandwich fashion. At the site, once the Slab is hoisted and the columns inserted, the crew is immediately positioned to complete the inside and the façade panels will follow soon after.

C. Panels: Load-bearing flat horizontal and vertical components providing a linear distribution of the loads.

- Advantages: economical distribution of the loads from the vertical to the horizontal axis without any transfer; facilitating the soundproofing and fireproofing performances.
- Limitations: the vertical axis generates a continuous wall which governs the planning, an acceptable situation in housing due to the large number of partitions required; adaptability limited to the structural bay.

Different materials can constitute a Panel system: lightweight steel or wood framing, reinforced or pre-stressed concrete as well as various mixed compositions.

The wood framed panel is the most popular form of prefabrication, but most manufacturers (except Misawa Techno) don’t take advantage of the structural savings offered by the stressed-skin approach.

Due to its layers of solid wood pieces, the Cross-Laminated Timber (CLT) panel is entitled to meet the soundproofing and fireproofing performances required in a low-rise building.

Of course steel panels bring higher precision. In North-America, they are mainly combining different cold-formed sheet metal profiles (K-tect, Canam, etc.). In Japan, they are produced by automation and robotics (Sekisui House, Daiwa House, PanaHome and Sanyo Home).

Precast concrete panels are still widely used around the world; notably for 54% of the high-rise housing in Hong Kong. The hollow core pre-stressed slabs combined with precast walls are very efficient for large multifamily housing projects. However, a competitive building can be entirely made of small precast concrete panels manufactured on an automated production line, like the one (equipped by Weckenmann) operated by the Preuksa Real Estate company in Thailand.

D. Integrated Joint: Monolithic component simplifying the connections by distributing the jointing outside the geometrical meeting point.

- Advantages: simplification of the jointing operations through a series of single (one to one) connections rather than dealing with 4 to 6 sometimes heavy components converging at the same geometrical meeting point; accelerated site assembly; reduction of the structural requirements by meeting both positive and negative moments.
- Limitations: some components can be quite bulky; adaptability conditioned by the geometry of the structural sub-system.

The Integrated Joint can take a point-to-point, a skeleton or a multi-plane approach.

Some small multidirectional steel connectors (Simpson Strong Tie) can be considered as point-to-point Integrated Joints. Componoform is the best example of the skeleton approach: it is literally a joint-to-joint system generating a Post & Beam like framework. The planar approach can integrate the advantages of panels: the Triedro system (Italy) is a good example.

THE FACTORY-MADE 3D MODULE

In the Factory-Made 3D MODULE category, all the sub-systems of the building are made, assembled and finished at the plant as structural 3D modules, requiring only simple connections to the infrastructure (foundations & main service conduits) and between themselves once at the site. Therefore, an important capital investment is required to initiate and operate a 3D Module plant.

Of course, carrying the 3D Module from the factory to the site means paying to transport "air", since most of the volume is occupied by empty space whereas transportation is calculated in terms of volume.

The two types of systems within the Factory-Made 3D MODULE category are distinguished by the ratio of factory-made content in the completed building: partial for the Sectional Module ("E") and total for the Box ("F"). In both cases, the dimensions are limited by highway regulations.

II- Factory-Made 3D MODULE	**The building is divided into volumetric modules assembled at the plant and just connected to the infrastructure and between themselves once at the site**
 **E- SECTIONAL MODULE**	Small but insuficient 3D nodule, requiring a complementary process once at the site
 **F- BOX**	Autonomous unit entirely finished at the plant

Figure 4. The Factory-Made 3D MODULE. © Roger-Bruno Richard 2004

E. Sectional Module: Small but insufficient 3D module requiring a complementary process once at the site.

- Advantage: compact transportation as a limited percentage of the space is factory made, the rest being generated at the site.
- Limitation: necessity of an important site team to complete & finish the building, which can easily cost more than the savings on transportation.

Three Sectional Module strategies have been experienced: By Addition, Checker Board and By Compaction.

Kisho Kurokawa's Nakagin building in Tokyo is the classical example of the "By Addition" module: the circulation tower incorporates a steel structure to which factory-made steel "capsules" are suspended through mechanical joints, thereby allowing for disassembly.

Producing one box out of two and assembling them in a "Checker Board" fashion may appear like getting 50% of the space for "free", but the amount of work needed to finish and equip the space generated at the site will more than exceed the costs of doing everything at the plant.

Folding out large size "By Compaction" modules is mostly feasible when small size modules are carried to restricted areas.

F- Box. Autonomous unit entirely finished at the plant.

- Advantages: maximal factory production i.e. freedom from weather, semi-skilled labour, sophisticated tooling, precision & higher quality control, rationalised assembly line and bulk purchasing of components; minimal work at the site.
- Limitations: high initial capital investment and continuity of the demand to amortise it; strict planning discipline; important (but not prohibitive) transportation costs.

The Box will take three forms: panellized structural shell, framed-at-the-edge skeleton and monolithic shell.

The box is mostly relevant in a low-rise situation (3 or 4 stories) as a 3D unit strong enough to meet the transportation stresses would normally be able to support three others once at the site.

The North-American wood-framed boxes are usually large size structural shells (width between 3.6 to 4.8 m and length between 12 to 16 m) built from panels: 2 to 4 boxes are required to generate a regular single-family house. Many architects have developed very contemporary designs respectful of the panelized technology (http://www.fabprefab.com/). A similar approach is applied in Europe; IKEA has notably joined forces with Skanska to produce wood panellized boxes for the Scandinavian and UK markets.

Metal framed and composite panellized shells (Space Box, etc.) are also seriously present on the market.

The ISO container is getting a lot of publicity these days; but it needs to be very well insulated due to the conductivity of its all steel skin and its 2.438 m (± 8'-0") lateral dimension is very restrictive in terms of planning. However, its stacking capacity goes to ± 16 storeys. The Verbus containers are made wider and come with additional ISO fittings in order to keep their status at maritime facilities.

The main alternative to the panellized structural shell is the framed-at-the-edge steel skeleton structure. It is used to give more openings and flexibility to the box by many manufacturers like Yorkon in the United Kingdom, Alho in Germany, Radziner in the USA, etc.

Due to very restricted road limits, the Japanese steel framed-at-the-edge 3D "units" are much smaller (± 2.4m in width and ± 5.5 in length). A total of 12 to 16 "units" is required to generate a single-family house. They are produced by large conglomerates on assembly lines quite like the ones in the automobile industry (Sekisui Chemical, Misawa Home and Toyota Home).

In order to go higher, some manufacturers are multiplying the number of columns within the framed box. It is the case with Vision Modular Structures in the UK. A 60mm X 60mm tubular steel column at every 60cm together with concrete flooring allowed them to build the tallest modular building in the world, a 25 storey student residence in Wolverhampton.

Monolithic boxes are mainly precast concrete and they would normally have to be lightweight to reach a competitive level. Yet, US manufacturers like Oldcastle and Tindall do produce them with regular concrete; mainly for prisons, sometimes for hotels and motels.

III- HYBRID	**Producing at the plant the complex parts of the building and entrusting the site with the heavy or simple operations**
 **G- LOAD-BEARING SERVICE CORE**	The "service" area is built and finished at the plant within a structural 3D module
 **H-MEGASTRUCTURE**	Framework to stack lightweight boxes or panels in order to reach a high-rise status without piling them up
 **I- SITE-MECHANIZATION**	Transforming the site into a factory producing a monolithic structure

Figure 5. The HYBRID. © Roger-Bruno Richard 2004

THE HYBRID

The HYBRID is aiming at catching the advantages of the Site-Assembled Kit of Parts while avoiding the limitations of the Factory-Made 3D Module: manufacturing at the plant the complex parts of the building and entrusting the site with the heavy or simple operations.

The three types of systems within the HYBRID category are distinguished by the nature of the technology allocated to the site: the Load-Bearing Service Core ("G"), the Mega-structure ("H") and the Site Mechanization ("I").

Altogether, the Hybrid systems are borrowing features, components and even sub-systems from the other two categories.

G. Load-Bearing Service Core: The "service" area is built and finished at the plant within a structural 3D module.

The "Service Cores" are concentrating into factory-made structural 3D modules all the "SERVING" areas of a residential building: kitchen / W.C. / laundry / mechanical-electrical shaft / stairs / etc. Once at the site, those Cores are set to support slabs and envelope panels between them, thereby generating large flexible "SERVED" areas: living room, dining room, bedrooms, etc. (Richard, 2005).

- Advantages: factory production justified by the concentration of complex high-tech services and equipment; easy transportation (small and enclosed 3D modules); simplified site work since the Cores act as connectors to the other sub-systems; flexible and transversal "served" areas when linear Cores are perpendicular to the façades;
- Limitations: imposition of a strict planning discipline; increased façade width due to the presence of a perpendicular Core (the "serving areas" being usually positioned longitudinally in the middle of a building).

The Load-Bearing Service Core systems can be point-to-point (MAH-LeMessurier) or linear (Richardesign).

The Core itself is a closed sub-system but the "served areas" generated are dedicated to open sub-systems: various floor/roof slab and exterior envelope panel options can be supplied by different manufacturers, notably at the local level when the Cores are exported abroad. The exportability of the Cores is enhanced by the fact that they are filled with value-added services and equipments: they are not "transporting air", unlike the box systems.

H. Mega-structure: Framework stacking lightweight boxes or panels to reach a high-rise status without piling them up.

- Advantage: allowing light-frame factory-made modules or panels to reach higher densities.
- Limitations: costly redundancies as the boxes or panels become live loads to the framework; the jointing between the framework and the boxes could be complex, mainly due to dilatation and capillarity factors.

The Mega-structure may look ingenious, but the structural redundancies can almost double the cost of that sub-system.

I. Site Mechanisation: Transforming the site into a factory producing a monolithic structure.

The basic idea is to transport a concrete precasting factory directly into the building right at the site, rather than transporting precast components one-by-one from the plant and having to use cranes to join them at the site. In some cases, automated devices and even robotics can contribute to the process.

The non structural sub-systems, being both complex and compact, are better served by factory-made "plug-in" or "clip-on" components transported to the site in bundles or containers.

- Advantage: the logic of producing heavy components at a site-plant and avoiding numerous delivery trips as well as doubling the hoisting devices.
- Limitation: elaborate site assembly for the sub-systems other than the structure.

Different technologies are offered.

- Mobile Factory: literally setting up the prefabrication tools on wheels;
- In-Situ Factory: using site-friendly processes like Sprayed Concrete, Tilt-Up, Habitech interlocking blocks, etc.;
- Mechanised Formwork: using a Tunnel Formwork to cast an egg-crate structure within the building or using a Sliding Formwork to extrude a vertical structure;
- Permanent Formwork: asking another sub-system to serve as formwork.

WHICH SYSTEM?

The "Palette" offers a decision tool at the outset of a project. The selection of an appropriate industrialised building system implies a rational decision process, as there is no universal system better than the others. There is no World Champion, only systems more relevant to their context.

Decisions are taken mainly at the Sub-System level because the Sub-Systems represent specific expertise areas which can be distributed to different participants of the generic organisation behind any industrialisation activity. For the purpose of selecting the appropriate system, the "Palette" of options can be articulated to outline the distribution of the work between the factory and the site for each Sub-System, as shown in the following diagram.

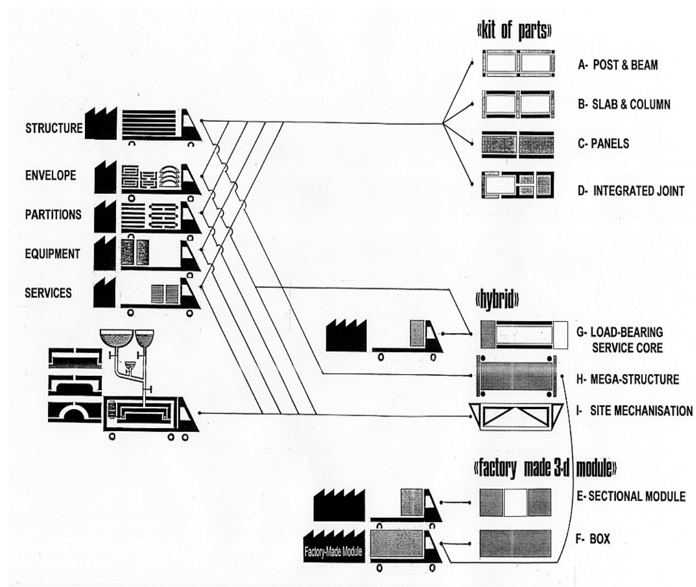

Figure 6. Distribution of the work between the factory and the site. © Roger-Bruno Richard 2004

Once the objective is spelled out in terms of performance criteria, the architectural features of the project will appear in the form of a functional model indicative of the specific Sub-Systems to materialise.

The context should then lead the development or the selection of an appropriate and optimal Building System: matching the criteria with the resources (the four "Ms": Materials, Machinery, Manpower and Money).

In order to respond to the individualised needs through space and time, four mass-customization strategies are available and applicable with most Industrialised Building Systems: Flexibility of the Product, Flexibility of the Tool, Multipurpose Framework and Combinability (Richard 2010).

CONCLUSION

Industrialised Building Systems are introducing a new architectural language that the architects and builders need to study and understand in order to really benefit from their advantages. But the language has to be applied at the outset of a project, as a non-systematic design would be repulsive to most types of systems.

Building Systems do not pretend to easily meet all the architectural programs: they merely want to provide solutions to the large majority of needs and people, through space and time, looking forward to becoming the "ready-to-wear" offerings of architecture.

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