DEVELOPMENT OF INDUSTRIALIZED, FLEXIBLE AND DEMOUNTABLE MULTI-FAMILY BUILDING <IFD COLLECTIVE HOUSING>

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Current practice in design of multifamily buildings exhibits an important partitioning of design and construction process for spatial systems and structural systems into two distinct phases. Uncontrolled overlapping of different functions and components in the building structure needs both: reconstruction of building design and construction process and network between functional systems and technical systems based on functions' independence and components' exchangeability aspects. New network aspects support the systematization of the subsystems and components into Industrialized, Flexible and Demountable IFD systems' configuration for the building structure.
IFD systems' configuration stand to support the fluctuations of the three main variables in contemporary housing: changing dynamics in use; adaptability and transformations of building systems and functions; optimization of the building life circle impact and adaptability costs. Industrialized-to replace the conventional construction process and reach high level quality and lower costs; Flexible-to facilitate changes over time of spatial and technical systems; and Demountable-to meet the needs for systems transformations without demolitions.
Contribution of this work is threefold. Main findings come from an analysis of the resent apartment buildings in Europe, based on *open building principles and strategies* for IFD systems' configurations. First is a systematization of industrialized components and systems according to *open building* independent levels and systems' building method. Providing independence and exchangeability of functional and technical systems and focus on structure's configuration design as the main boundary condition for housing transformation capacity. Second is a description of the IFD systems' configuration and giving the initial design characteristics. Third is reduction of the fixed connections for simply demountable dry joints which implies reducing the cost of the disassembly in the network and demolition actions of the whole system.
Finally, the improvement of buildings capacity to adapt to spatial and technical changing requirements and consequently extend the service life of the building and its systems has been considered as a key issue of sustainable development in the future. First is the design of flexible systems' configuration and later on, systems disassembly and transformations.

INTRODUCTION

Variables versus constants

Collective housing is passing through the period of the great changes and the predictions are not along with the closed systems and "constants". Dynamic changes in residential life versus static building configuration are withstanding the sustainable approach. Collective housing industry is still strongly dependent on traditional building process for massive – closed system. The question is about how the industrialized components and systems are put together? Mixed functions generate strong dependency conditions for the functions and parts with different service life. Inflexible connections between components, under the transformations, result with the high level of material and waste disposal by demolition and degradation. The adaptability of building to dynamic changes in modern life has become a very powerful variable in building life.

Three main variables in multifamily housing are: changing dynamics in use and spatial transformations; service and technical life of the building and its systems transformations; and optimization of building life circle impact and costs (fig.1a). The major changes and negative impacts come from closed building structures and inability for adapting according to new requirements.

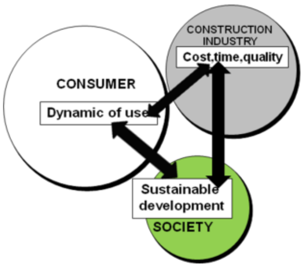

Fig.1a: 3 housing variables

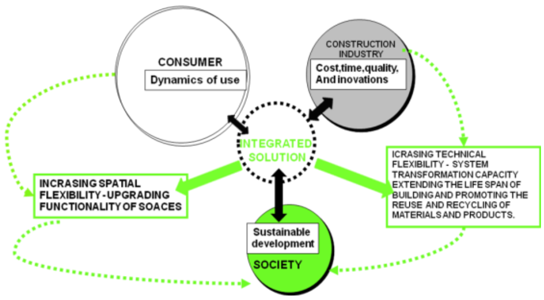

Fig.1b: Integrated solution for spatial and technical systems flexibility

Dynamics in use

Different adaptations and changes of the functional and technical systems for building's upgrading according to new requirement define dynamics in use in collective housing. Progressive diversity of living systems justifies new approaches for building's design and construction that are flexible and demountable. Spatial and structural transformations depend on the flexibility and processability of the structural systems' configuration and how the more permanent building parts (load-bearing structure, façade, services) are put together so as to generate decomposition of systems and components. Assembly and disassembly of building structure are the main conditions for the transformation capacity level of the housing and it systems.

Industrialized systems' transformations

Homes often suffer a transformation due to the degradation of the more dependent materials and components by frequent changes of the user needs and the technical systems' upgrading. Conventional building is inflexible in the service phase due to the massive support structure, and mixed functions; inflexible and fixed connections; and lack of accessibility for the components with the shorter life-cycle. For this reason, the structural transformation is related with partial or total demolition, significant loose of energy, materials and waste production. Although the life of buildings is between 50 to 100 years is evident that the lifetime is much shorter because of the closed systems' configurations. The first step to handle the temporal tension in construction is through the independence and exchangeability of the less-lasting components. The three variables and impacts that occur as a result of uncontrolled overlapping of functions and systems influence on the final result with very high adaptation's costs and strong negative impact by demolition of buildings. To remove the interior walls for the functional upgrading of the space, the conventional system undergo the process of demolition of the walls. After each use phase, an industrialized systems' configuration should be design and built to indicate the building suitability for the new changing requirements. Closed systems configuration and fixed connections in technical levels are the principal motive for the low level of housing transformation capacity.

Building life-cycle impact

The increasing number of buildings that face critical issues (expensive reconstruction or demolition) produce an enormous amount of waste through energy consumption and CO2 emissions. The key issue of sustainability is the development of design and construction integrated strategies to transform the inflexible building structures into flexible and decomposable, whose parts can be easily removed and reused / or recycled (fig.1b). The assembly and disassembly of building structure are the first condition for upgrading of systems and functions. Demountable structure may last longer by the fact that its parts can be exchanged easily (removed, added or replaced...), so the homes could be adapted for the new requirements.

METODOLOGY

The main issue of sustainable development is to find the balance between dynamics in use, adaptability of buildings, economy and the fundamental principles of environmental ecology by providing more transformation capacity of systems' configuration. Open Building principles and strategies (Habraken, 1976; Kandel, 2014) will be analyzed and applied for the IFD systems' configuration design rules. Systematization of industrialized components and subsystems to achieve flexible and demountable structure is based on open building independent levels. The arrangement of the components and systems into independent technical and functional levels and demountable-dry joints will support IFD collective housing approach. The analysis of the recent apartment buildings in Europe has been done according to open building principles and the main findings will be used to highlight a new tendency toward IFD collective housing.

Spatial and technical building flexibility

Two factors that initiate transformation in the apartment buildings are the inhabitant for functional upgrading of spaces and system's components to be replaced and reused or recycled at the end of their life span. Dynamics in use and spatial adaptations needs more flexibility of the technical systems' configuration. Term transformation is introduced to meet the changing needs of the users for special systems' transformations and to meet the "changing needs" of the building configuration respecting the systems and components with the different life span. Transformations of spatial and technical levels depend on the transformation capacity of the systems' configuration (fig.2).

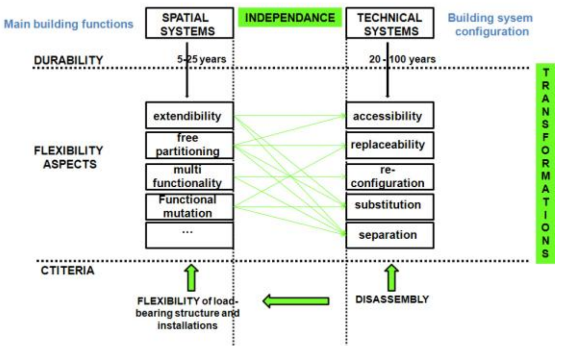

Fig.2a: Relations between technical and spatial systems *(source: modified from Elma Durmisevic, 2006)*

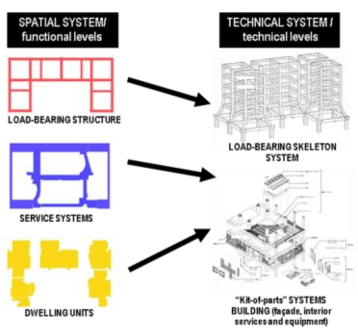

Fig.2b: NEXT 21 Technical and special systems (Osaca Gas 2002)

To be able to understand and address these important issue, the result will be highlighted as post-analyse of the resent collective housing projects in Europe. It was quickly established that the open building independent levels and exchangeability of components define the strategy for flexible and demountable IFD configuration. The assumption is that structural adaptability of the more permanent systems and components by disassembly options stands for more transformation capacity. The solution strategy is based on systematic design and construction rules for building structure's configuration.

IFD (Industrialized, Flexible, Demountable) systems

The future vision of multifamily buildings is to satisfy the needs for adaptability by disassembly transformations on technical, spatial and material levels. Habraken (1976) divided the building on 'support' and 'infill' and established the method for design and construction of the flexible (F) 'support' as independent level. IFD is an extended approach of Habraken's 'support-infill' method for upgrading of building functionality by more transformation capacity of systems' configuration composed of many and different industrialized components and subsystems. IFD integrated configuration will approve the construction industry for the 'support' subsystems to be more customer-focused and to permit more dynamics in use of the building layout (fig.3).

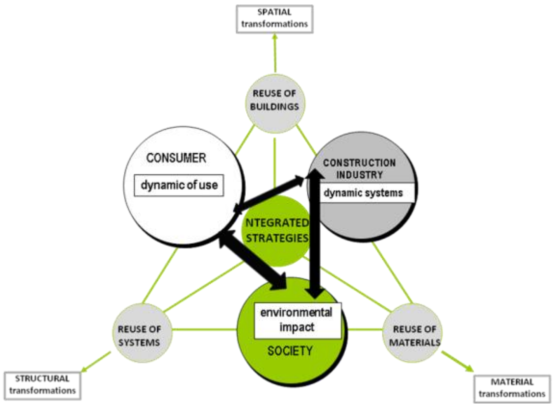

Fig 3: IFD integrated solution and main objective

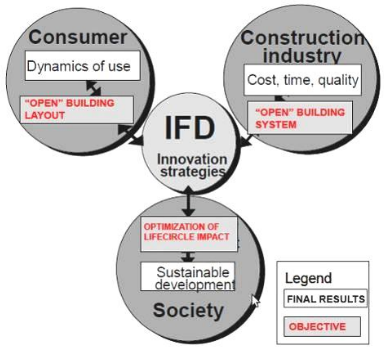

Fig.4: IFD integrated strategies

The new focus is on the industrialized, flexible and demountable systems' configuration to extend the total life span of the building structures by spatial and structural systems transformation (fig.4). Industrialized – to adapt the process for flexibility issue, simplifying the production for high quality and lower costs and offering an individualized finished product; Flexible – to accommodate changes at the 'infill' level over time, without destroying components and subsystems and to be reconfigured and/or relocated without demolition. Flexible systems' configuration should allow: adaptability, combinability, pre-configuration, re-configuration, re-adjustability and disassembly of the complete system or some subsystems; Demountable – to make possible the separation of building components or subsystems without demolition. For high level of industrialization and demountable system, factory-made components can incorporate the precise details required for adaptable systems' configuration. Demountable building system comprises a set of compatible and interchangeable components.

SYSTEMATIC APPROACH ACCORDING TO INDEPENDENT LEVELS AND SYSTEMS' BUILDING METHOD

New planning approach which is flexible and demountable is based on systematization of industrial components and subsystems according to 'independent functional and technical levels and systems' building method' (Habraken, 1976). Two main aspects for systematization are independence and exchangeability of elements. Each technical level (all components, subsystems) has a function and a theoretical life span that dictate its need for alteration or transformation. The more often a component (subsystem, system) needs to be replaced, the more accessible it ought to be. Independent functional levels for components systematization are established according the principal housing functions: load-bearing, servicing, enclosing, interior partitioning, equipment. Every function and spatial level in systems' building has corresponding technical level where different components and subsystems make physical connections. Technical building levels and conditions for the systems' and components' connections have the direct influence on building transformation capacity. Independent levels for different housing functions are applied at the design stage to isolate building functions that have different service life. Levels that have longer life span (load-bearing structure) should be designed and constructed as high flexible and demountable configurations to allow transformations of the lower levels. Load-bearing system with the long life should be designed as industrialized, flexible and demountable - IFD configuration.

Experience with IFD projects has shown that the real problem of sustainable construction doesn't lie in product development itself but in development of an integrated system that makes use of industrial, flexible and demountable components and subsystems into open assemblies. In other words, a systematic integration of issues from use scenarios would be needed in order to see IFD as an alternative to the way we built multifamily buildings today. The type of joints and the interface geometry of the elements in connections play the main role for the disassembly of the systems' configuration.

Independent technical levels are applied for systematization of building components according to their function and different life span. Components with a shorter life should change more rapidly and the configuration should be assembled to allow easy access for fast changing components to be repaired or replaced. Components that perform the same function are assembled into the assembly gropes. Every assembly group is based on demountable dry-joints between its components. Figure 5 highlights the principal systematization rules for open assembly. If P is a systems' configuration than A, B, C are its systems: A-facade, B-services, C- load-bearing structure. The Load-bearing system is composed of five independent subsystems and components: columns, prestressed columns, cross beams, longitudinal beams, integrated floor subsystem (c1, c2, c3, c4, c5).

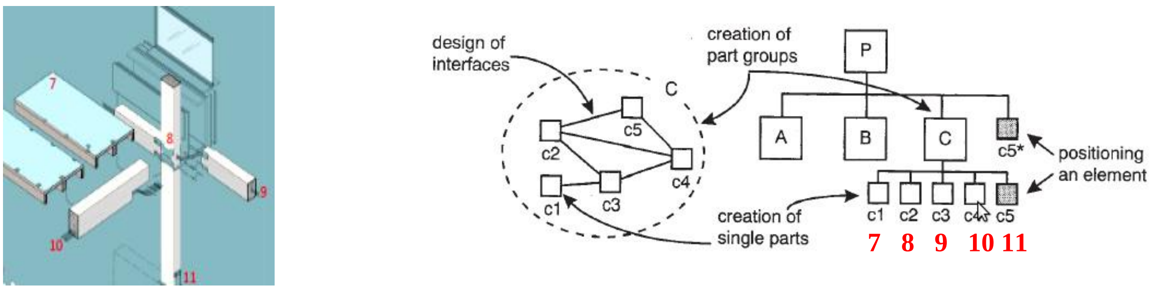

Fig.5: Right: Systematization of building parts *(*Tichem, 1997*)*, left: Wood constructive system, *(current research,, Parma, Italy, 2012)*

STRUCTURAL ADAPTABILITY: NEW PLANING APPROACHES WHICH ARE FLEXIBLE AND DEMOUNTABLE

IFD systems' configuration is planned to be transformable at all levels of technical integration by disassembly and reconfiguration. Focussing on the long-life building structure and the way its parts are put together the IFD approach can offer a high disassembly potential for systems' configuration. Key issue of the sustainability is the development of the design strategy that will transform design of the inflexible massive structure into dynamic and flexible systems' configuration. IFD systems' configuration is designed to provide the flexibility of the space, and is constructed as decomposable to be disassembled at the end of its components' life.

Resent residential open building projects provide an important review about the current developments toward IFD collective housing. Figure 6 shows open systems' assembly for building structure assembled into independent functional, technical and material levels. This allows for functional spaces to be retrofitted; for technical systems to be decomposed and re-assembled, and for the materials to be extracted and reuse or recycled. Finally the systems that have long life span (load-bearing structure) are designed for flexibility and constructed for decomposition (fig.6). Design and construction of flexible and demountable systems' configuration stands to extend the total building life.

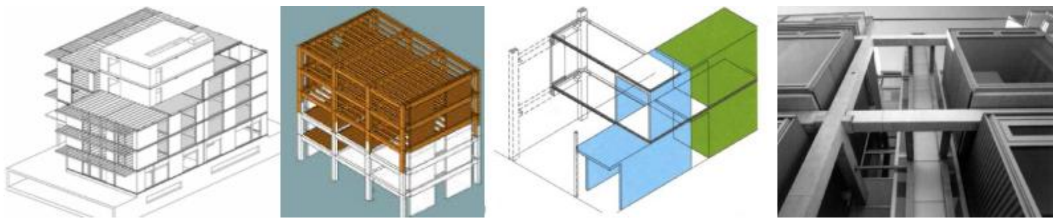

Fig.6: Systems' configurations of building load-bearing structure / Case studies (from left to right): 2003 _ **Siedlung Hegianwandweg** | EM2N Architekten | Switzerland; 2012_ **Collective Housing in Parma** | Italy; 2005 _"**Polvori" Collective Housing** | Barcelona | Spain; State of the art regarding the dynamics of change **(Rigo 99)**

Configuration design of IFD building structure according the figure 6 is based on:
1) Design, composition, dimensions and location of systems and components into independent functional, technical and material levels; **2)** Load-bearing structure is designed as an industrialized, flexible, demountable system (IFD systems' configuration); **3)** Load-bearing structure is demountable configuration based on simple dry-joints, **4)** Flexible distribution of the construction elements in the building layout allows for the dwelling unit a number of different distributions; **5)** Possibility to change the surface of the floor plan, either by additional construction or changes in the boundaries of units out of the 'support' limits / possibility to extend the structure with additional construction modules; **7)** Load-bearing adaptability is adopted by disassembly and reconfiguration; **8)** Connections between removable parts and load-bearing structure are based on simple-dry joints; **9)** Connection between load-bearing components in load-bearing system is based on simple dry-joints; **10)** Positioning of services as independent systems to provide easy access and total system's upgrading.

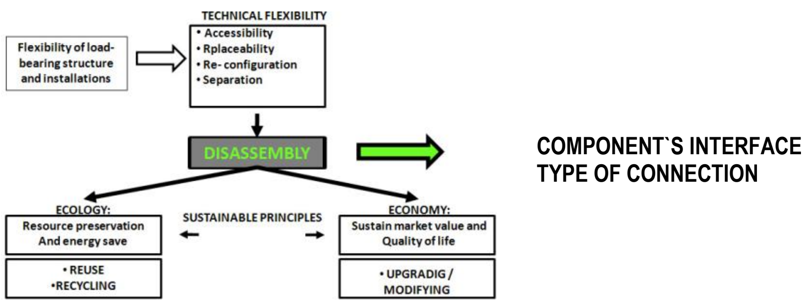

Fig.7: Main disassembly conditions *(source:modified from Elma Durmisevic, 2006)*

IFD STRATEGIES APPLIED TO SUPPORT LEVEL

The key for systems' disassembly are demountable dry-joints and the components' interface geometry in connections (fig.7). Figure 6 highlights the application of IFD (Industrialized, Flexible and Demountable) systems for load-bearing structure. Concerning the problem of inflexibility in collective housing, we can emphasize now that the applications of 'open building' independent levels and systems' configuration in collective housing design and construction process support more transformation capacity. Load-bearing system is isolated as independent functional level and independent systems' configuration and arranged into independent technical levels. Design for disassembly of load-building structure is a new approach towards more transformation capacity in collective housing.

Figure 6 shows that load-bearing structure is integrated systems' configuration composed of independent components and subsystems. The integrated systems based on demountable dry-joints is considered open systems' configuration where components and subsystems can be exchanged. The open configuration can exchange parts, components and subsystems outside its original production contest. This may be an opportunity for many manufactures to participate in the systems re-configuration and re-trofiting. Future research should develop the conditions for components' compatibility and make possible for different manufactures to participate in the systems' configuration upgrading. Design of interfaces between components in connections may be an important issue for the future construction industry innovations.

The systems' configuration for load-bearing structure (fig.6) is assembled according to the independent technical levels. Independent technical levels have to support the systematization of components into independent clusters according to their life span. 'SI /support-infill' method proposed by S.A.R. (Habraken, 1976) and 'open building' (CIB 104, 2001) have used the strategy of multipurpose framework to generate flexible load-bearing structure for a variety of 'detachable units'. The multipurpose framework will be systems' configuration composed from I3 (Industrialized, Integrated, Interchangeable) subsystems and component. Figure 8 emphasizes the shift from permanent support to IFD systems' configuration. Adaptability of structures is used to extend the life cycle of long-lasting systems according to frequent changing dynamics in use.

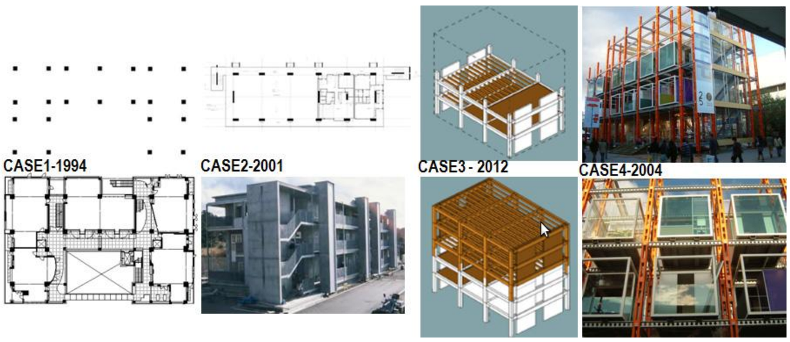

Fig.8: Permanent structure versus IFD systems' configuration;
left to right / from permanent to demountable

SPECIFICITIES OF IFD SYSTEMS CONFIGURATION

- **Functional decomposition:** Design of IFD systems' configuration stands for total separation between different functions at all levels of building integration (fig.9).

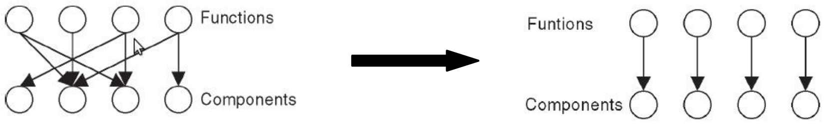

Fig.9:Independnet function and componenets: left/strong dependency conditions ; right/independency (*by Elma Durmisevic, 2006*)

- **Systematization of components and subsystems into independent functional and technical levels**: The systematization of the components and subsystems into assembles minimize the number of relations between elements within the structure. The process is based on specifying the group of parts – subsystems that correspond to the same function. Different groups of elements can be assembled independently from other groups (fig.10). Figure 10 shows different functional and technical levels of systematization. First level correspond to division of the building according to main building functions (loadbearing, stability, installations, enclosing vertical, enclosing horizontal). In the second level components and subsystems that correspond to the specific functions were assembled. For open systems' assembly all subsystems are independent.

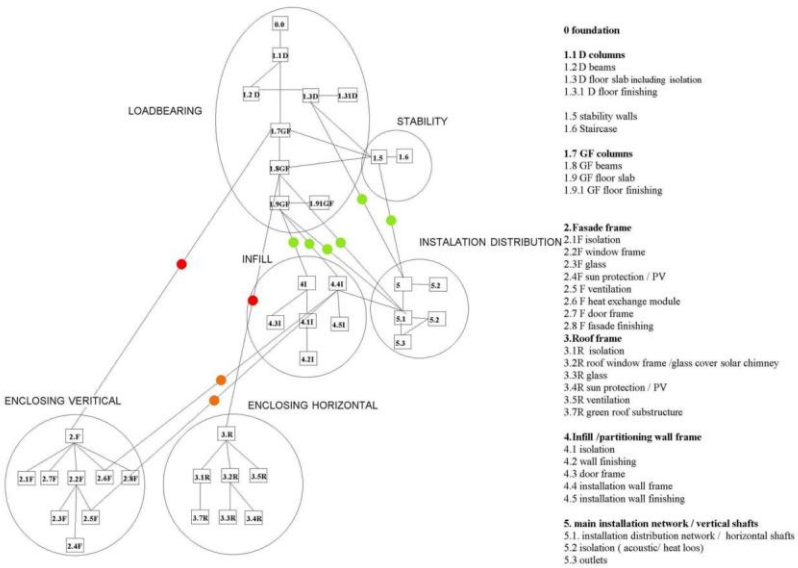

Fig.10: Systematization of building parts into independent technical levels: Relations between subsystems (source: Elma Durmisevic 2011)

- **Open Systems Hierarchy for Adaptability of IFD Configuration**

The evolution of the building configuration from closed to open is represented by transformation of complex relational diagram and closed hierarchies between elements into an ordered path of connections between subsystems end components (fig.10). Open hierarchy for building structure contains a number of independent assemblies. The number of technical assemblies corresponds to different building functions. Each assembly composed from sub-assemblies and components have one element that acts as a base element for connection with other subsystems in systems' configuration. According to this, structure could be defined through the relations between the base elements that are placed into independent levels of technical integration. On the building level the load-bearing structure is the base system for other subsystems, such as façade, roof, floors, installations, etc. On the sub-assembly level such as façade, an element such as a wall-frame is the base element for all other parts of this assembly, such as windows, ventilation openings, doors, etc. Such systematization of building through base elements and their connecting parts stands for the better control of the configuration, the use of exchangeable parts of the building, and total disassembly at the end of the building service life. Open hierarchy allows for the system to be upgraded with additional components and systems (fig.11).

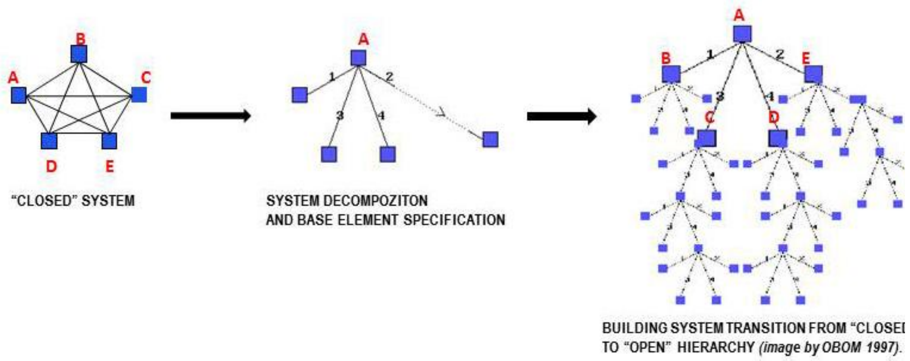

Fig11: Closed versus Opens Systems Hierarchies (*source: OBOM, 1997*): A, B, C, D, E are independent systems

- **Dry- joints and simple interface geometry in connections**

Design of the component's interface and type of connection are the main aspects for demountable systems' configuration (fig.12). In order to evaluate the open system, two types of relations have to be considered: one between assemblies-subsystems and one within assemblies. An important goal of physical integration is to reduce the number of assembly sequences (Durmisevic, 2006).
Physical integration of the systems' configuration is defined by: the type of connection, the geometry of components edge, and the assembly chains of components. Having in mind the level of functional, technical and physical domain in systems' configurations this research supports the development of the new open IFD integrated solutions.

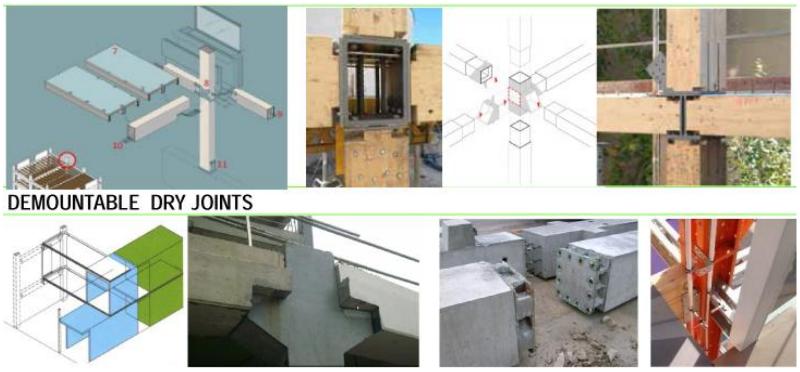

Fig.12: Demountable dry joint in load-bearing structure

CONCLUSION

In the industrialized housing sector, the product should not be the building layout but IFD systems' configuration for the building structure. The systems' configuration is a set of parts (components and subsystems) and rules where the connections are designed to generate integrated and demountable systems. That will work along with the industrialized process by simple, and demountable dry-joints, independent and

interchangeable components and subsystems, modular and dimensional coordination. The industrialization model of independent and interchangeable components and systems and flexible framework highlight the new vision of ‘support’ system as an integrated IFD system composed from industrialized components and subsystems.
The innovative design and construction method for flexible and demountable structure will incorporate effective use of materials into the whole building life span. Flexible and demountable structures improve the building ability to transform with minimal environmental stress. Significant innovation will be required for designing the appropriate physical interfaces and connections between components of the existing construction systems with the low transformation capacity (concrete panel system). IFD systems configuration for load-bearing structure is the principal issue for creating more transformation capacity of collective apartment buildings. Therefore future development should generally address assembly and disassembly of systems and components for reuse, recycling and reducing waste (3 R) to support upgrading and retrofiting of existing massive structures.

References

Brand S. (1994), *How Buildings Learn: What Happens After They're Built*, Viking Press, New York

Durmisevic, E. (2006), *Transformable building structures: Design for Disassembly as a way to introduce sustainable engineering to a building design and construction*, printed by Cedris M&CC, ISBN-10: Delft, TU Delft

Durmisevic, E. (2001) “From massive construction to decomposition of housing-a way to support further industrialization and customization of housing”, Proceedings from the IAHS Conference on Housing, Slovenia 2001

Gibb, A.G., Groak, S., Sparksman, W.G. and Neale, R.H., (1999) *Standardisation and pre-assembly - adding value to construction projects*, Construction Industry Research and Information Association (CIRIA), Report R176, pp. 220, ISBN 0 86017 498 0.

Habraken, N.J. (1976), *Variations: The Systematic Design of Supports*, Laboratory of Architecture and Planning, M.I.T., Cambridge Mass., U.S.A

Kieran, S., and Timberlake, J. (2004), *Refabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building Construction*, McGraw Hill, NY

Kendall S. and Teicher J. (2000), *Residential Open Building*, Ill.,E & FN Spon, ISBN 0-419-23830, London and New York

ManuBuild (2006), Open Building Manufacturing, www.manubuild.org/summary

Mullens, M.A. (2011), *Factory design for Modular Homebuilding*, Constructability Press

Osaka Gas (2000) NEXT21: Osaka Gas Experimental Residential Complex, www.osakagas.co.jp/rd/next21/htme/reforme.htm

Osaka Gas (29.Nov.2002): *NEXT21 Experimental Residential Complex*, viewed 30 January 2011, http://www.arch.hku.hk/~cmhui/japan/next21/next21-index.html

OBOM (Open Building Strategic Studies), (21. Feb.2010), viewed 22 February http://www.obom.org/index.html

Richard, R.B. (2006), “Individualization & Industrialization”, Proceedings of the CIB Co-sponsored Conference, *Adaptables'06 “Adaptability in Design and Construction*”, Eindhoven University of Technology

Tichem M., (1997), *A Design Coordination Approach to Design For X*, TU Delft, Delft University of Technology