SYSTEM STRUCTURES IN ARCHITECTURE: TOWARDS A THEORY OF INDUSTRIALISED ARCHITECTURE

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INTRODUCTION

The present paper and the research behind it is not dealing directly with architecture in the sense of an artistic or a poetic practice. Rather, it is preoccupied with the means for facilitating such architectural creation when exposed to a contemporary industrialised context.

The paper suggests the introduction of the notion of *system structure* in architectural design as a way to conceptualise a systemic level in architecture and construction that lies between general construction techniques and specific architectural results. In order to make such a system structure operational, the elaboration of a system structure model has been attempted that seeks on the one hand to analytically grasp and on the other hand to make it possible to actively work with system structures as part of the architectural design process.

Such endeavour has roots in the apparent and continuously increasing gap between architectural ideation and the way these ideas are brought to life as real physical manifestations of our built environment. Architectural design and construction have – not the least through increased industrialisation – become a hugely complex matter involving a considerable number of different fields of expertise and fragmentation of the knowledge needed to comply with the task produces risk of incoherent results.

In line with the so-called systems sciences present paper rejects the prevalent scientific view that the degree of detail 'automatically' enhances understanding and explanative power. The notion and the model of system structure seek to establish the idea of a systems view on buildings and architectural design that through the use of flexible constituent elements with varying degrees of *integrated complexity* – as another central concept – facilitates discussion about how architectural wholes are appropriately put together as assemblages of what the current and future building industry is capable of producing.

This is not about reinventing architecture and architectural creation but does represent a new way to look at what is already there – an industrially produced architecture. The paper argues that this new view can help facilitating a more active and strategic use of the present and future building industry in order to create architecture – not just construction – specifically attached to time, place and cultural context – not just expression of smooth processes or cost efficient solutions.

Initially, the paper introduces and substantiates the underlying research question concerning the apparent gap between architectural ideation and execution and clarifies the pursued goal or aim of the research. Subsequently, the central notion of system structure and its application through a model that can visualise such structure is introduced and explained. This leads to the introduction of *integrated product deliveries* as new emerging elements in construction with the potential of integrating design complexity thus contributing to a better controlled overall design process and end result. Drawing on examples from a case study, the specific application of systems structures are then further illustrated while a concluding paragraph sums up and points towards future research and development needs.

THE GAP BETWEEN IDEATION AND EXECUTION

The main question of the research behind this paper has been to examine how systems thinking can help bridging the apparent gap between architectural ideation and its subsequent realisation as process and result in contemporary industrialised construction while simultaneously handling the increased complexity of specialisation and technical development.

That this division of the classical Greek *techne* – the art of making as one single entity – historically appears from the Renaissance and on and that the latter part – the realisation – later becomes consolidated in the separate discipline of engineering is among others pointed out by Gevork Hartoonian and by Kenneth Frampton. The classical conception of technology was encompassed in one single concept, *techne*, including on the one hand the architectural meaning or idea and on the other hand the work or construction needed to realise it as a physical form. The idea of an architectural form in Antiquity intrinsically implied the tools, techniques and materials to bring it to life as a unity of thinking and doing or of theory and practice (Hartoonian 1994:6). This unity contained in *techne* is, theoretically broken up in the early renaissance by e.g. Leone Battista Alberti who distinguishes between lineaments and matter/structure (ibid:7). Lineaments are the abstract lines and angles that define and enclose the form and that are derived from thought whereas the physical result is realised in materials retrieved from nature (Alberti 1992:7). Alberti expressly states that '*lineaments remains independent of structure and have nothing to do with materials and that they also remain indifferent to purpose and form*'

(Hartoonian 1994:7). The act of (architectural) design becomes exclusively to produce the correct configuration of lines and angles. The architect is here dissociated from the workman. This conceptual split is clearly visible in renaissance architecture where architectural elements in e.g. façade composition often become merely ornamental and detached from the structural logic of the building. Inspired by Hannah Arendt, Frampton describes this as the separation of the '*what'* and the '*how'* (Frampton IN:Hays 2000). The '*what'* is concerned with representation – or meaning – whereas the '*how'* is about utility and process.

Both Frampton and Hartoonian locates the next step as the formal separation of design from construction activity at the end of the seventeenth century where the traditional guilds in Paris were replaced by the academies and the institution of '*Corps des Ponts et Chaussées*' the later '*Ecole des Ponts et Chaussées*' (School of Bridges and Pavements). This marked the establishment of the two from then on clearly separated disciplines of architecture and engineering with roots respectively in liberal and mechanical arts. '*A sharp differentiation thus came about between ideative techniques – activities of thinking and translation into precise projects – and the work of execution, whose sole task was to put such plans into effect was so determined*' (Hartoonian 1994:5). For Frampton architecture (and the '*what*') was led into ideological distraction removing it from the task of realisation. This was found either through a reformulation of antiquity as in the Beaux-Arts tradition or through utopian ideas as in the conceptual and dematerialised works of Boullée or Ledoux. Architectural ideals separated from construction could only wither in their specific physical manifestation. Engineering on the other hand continued to develop its mechanical understanding of nature and its superior technical performance based on the scientific '*how'* and produced a formal language of its own as expressed in '*the viaducts, bridges, and dams of a universal system of distribution*' (Frampton IN:Hays 2000:369).

Today, architectural design and construction have become a hugely complex matter involving a considerable number of different fields of expertise and fragmentation of the knowledge needed to comply with the task produces, as mentioned, risk of incoherent results. Syntheses can no longer be grasped intuitively by one or few. Although sophisticated IT-tools have been developed to handle the complexity, these tools rather support a specialisation than the integration of the design process. This solidifies a linear progression and enhances the gap(s) between the different stages of the process from idea to result thus preventing loops and feedback where e.g. a more product based building industry could inform initial conceptual design.

The goal pursued in the research has with reference to the main question been '*to propose an analytical structure (interpreted as a tool or a model) for clarifying the potential of industrialised construction as positively enabling rather than limiting the architectural solution space*' (Vibæk 2012:18). The primary outcome is a so-called *system structure model* that as an analytical structure supported by a conceptual framework has been tested, reiterated and substantiated through the application on a number of case studies. The system structure model represents a systemic level in architecture and construction that lies between general construction techniques and specific architectural results – a general level of/in specific projects.

SYSTEM STRUCTURES

So, what *are* these so-called system structures in architecture and why are they needed or useful? System structures should be understood as abstract (system) representations of buildings focussing on the way these are put together as combinations of thought (ideas), process and matter (materials/products). A pivotal point with reference to the classical conception of *techne* is exactly that the elements of architectural creation are (or should be?) *combinations* of thought, process and matter rather than following the Post Renaissance conception of discrete categories or stages of creation.

System structures are meant as a *supplementary* view on buildings and architectural construction that are particularly – but not exclusively – suited for industrially produced architecture with varying degrees of off-site processes or prefabrication. This has to do with the fact that such solutions often 'outsources' considerable parts of both design and construction work and thus further problematizes the Post Renaissance division and bilateral relation between a designer and a builder. A system structural view on any building – industrialised or not – is concerned with the constituent elements and how they come together to form a complete whole.

The basic system entity or element in a system structure is the *delivery* which closely relates to, while simultaneously seeking to merge, the two concepts from the product industry of *product architecture* and *supply chain*. While product architecture indicates a static (actual or thought) physical structure (or organisation) of the constituent elements of a product, a supply chain is concerned with the structure of the flow of processes, materials and operators in order to reach this final physical structure. The system structure is meant specifically for architectural construction providing a structural and organisational view combining idea (whole) with process and result (matter).

By focussing strictly on structural/ organisational aspects while intentionally omitting the specific formal, material, contextual and other qualities of a project the system structure potentially introduces a systemic level in specific projects that lies between general construction techniques and the specific architectural results. This provides for the possibility of working with what in the general systems theory is termed *isomorphism* and *equifinality*. The former – isomorphism – expresses situations where equal system structures leads to different buildings (e.g. with different functionality, architectural expression or style etc. based on equal constituent elements). Isomorphism in system structured occurs when similar ways of conception/production are used to reach different architectural results. The latter – equifinality – expresses situations where different system structures leads to essentially equal buildings (e.g.

Figure 1. System structural isomorphism (left) and equifinality (right)

equal formal expression and/or functional scheme based on different structural organisation of the constituent elements). Equifinality in system structures occurs when different ways of conception/production leads to similar results. (see figure 1)[1]

Isomorphism and equifinality point towards systemic strategies for handling some of the present complexity of architectural construction in individual projects moving it to a more general level looking at wholes (structures) of constituent elements without getting lost in detail thus counteracting the fragmentation produced by widespread specialisation. Both isomorphism and equifinality can conceptually be used either project internally as different project scenarios well as for identifying common denominators across individual projects.

SYSTEM STRUCTURE MODEL AND INTEGRATED PRODUCT DELIVERIES

But, how does the system structure model look and what does it show at the present stage of development? The model visualises system structures as chains of several deliveries as the basic system entity or element (cf. above) with different degrees of *integrated complexity*. This concept can at first perhaps be understood intuitively through the denomination of a number of delivery tiers spanning from *raw materials* (tier 5), over *building materials and standard components* (tier 4), to *sub-assemblies and system components* (tier 3), *assemblies* (tier 2), and *building chunks* (tier 1), ending in the *building* (tier 0). Lower tier # means higher integration in complex deliveries, while higher tier # means lower integration and more simple deliveries. (see figure 2)

Simpler deliveries as e.g. raw materials or building materials and standard components can be nested into more integrated (and complex) deliveries as e.g. sub-assemblies and system components, assemblies or even entire building chunks before reaching the final building. A building thus becomes (or essentially always is) a combination of more or less integrated deliveries ultimately nested on-site in the final building. Integrated and discretely produced sub deliveries that form part of a larger more complex product are widely known in the product industry that is often considered more industrialised than construction. Drawing on such (existing) industrialised deliveries represents an efficient means of reducing complexity in focus for a given design task. As pointed out by several sources, similar deliveries are beginning to emerge as new more or less industrialised systems in construction and architecture – see e.g. Kieran & Timberlake (2004) and Mikkelsen et al. (2005). Following the latter, an integrated product (in construction) can be defined as '*a multi-technological complex part of a building*' that can '*be configured and customised*' to a specific construction project. It is furthermore '*developed in a separate product development process based on the principles in integrated product development*'. In its actually produced and specifically customised state and when delivered to a customer this building assembly becomes an integrated product delivery (IPD) that – as a kind of supra level – also can include '*marketing, shipment and servicing*' (Ibid:3).[2] IPDs in this definition should not be mistaken for the concept of integrated *project* delivery as used elsewhere. Here they introduce a more nuanced picture of the system structure of a building. As well as a building conceptually can be decomposed into its spaces – i.e. living space, kitchen, entrance – or its architectural elements – wall, opening, roof, floor – it can also be decomposed into its (more or less integrated) systems as they are actually produced and delivered. Industrialisation of architecture and construction is not just a question of off-site or prefabrication production vs. on-site construction. The theoretical as well as practical graduation of different deliveries and their different degrees of integration as expressed in the system structure model gives a more nuanced view – and the model provides a means to visualise and discuss this view – a view of (potential) construction scenarios.

Through deduction a number of theoretical construction scenarios can be created from the model i.e. traditional construction, prefabrication (as construction under roof!) and the vision for a future industrialised architecture – the latter based widely on the use of IPDs. The IPDs (expressed as tier 1 and 2 in the model) have, it is asserted, particular potentials for introducing the mentioned system level between project specific and general by enhancing the *integrated complexity* of a building project. (see figure 3)

INTEGRATED COMPLEXITY

Although it is perhaps intuitively possible to understand integration as some kind of enhanced complexity of a product or a process, it is harder to put into words what exactly contributes to this complexity. Is it e.g. the size, the number of components, the trades involved, or the price? An integration taxonomy elaborated through the research seeks to grasp *some* of the important dimensions in this sense. The

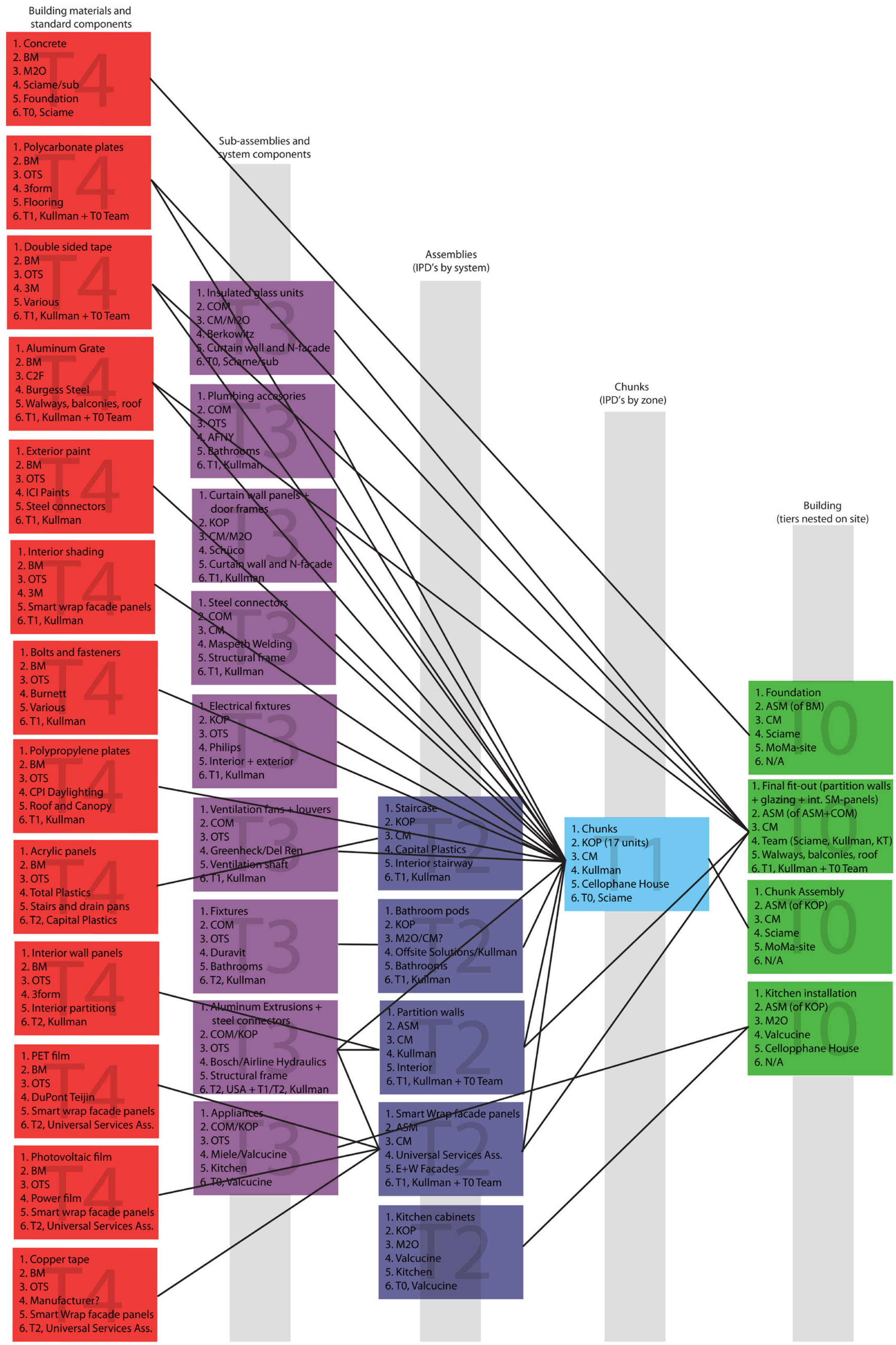

Figure 2. System structure model of the Cellophane House™. Each coloured box is a separate delivery. Lines illustrates integration or nesting into other deliveries while the different tiers are expressed as T4 to T0

taxonomy works with three dimensions and should be seen as non-exclusive meaning that other dimensions could be added. The dimensions are *'preparation'*, '*standardisation'*, and '*service'* and each one is expressed through four different levels or degrees (See figure 4). Although essentially being a qualitative assessment, this (semi-numerical) multidimensional approach can, when the dimensions are put together combined with their different levels, to a certain

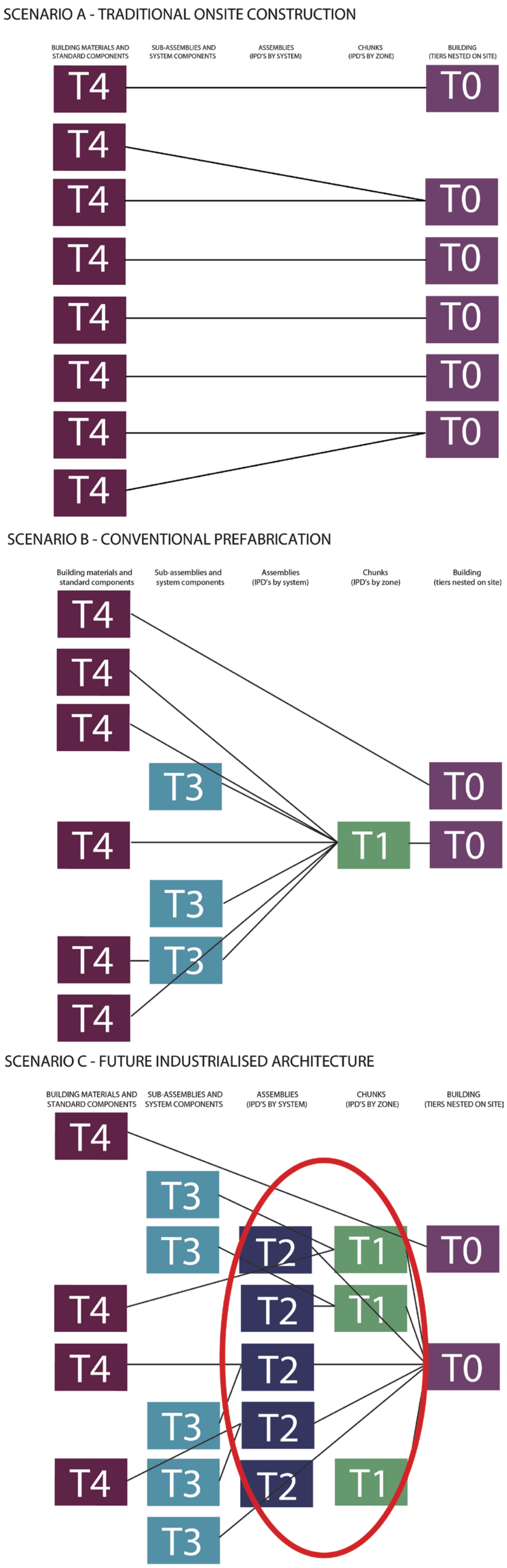

Figure 3. Theoretical construction scenarios expressed as simplified system structures

Figure 4. Three dimensions of integrated complexity - each with four different levels from low to high

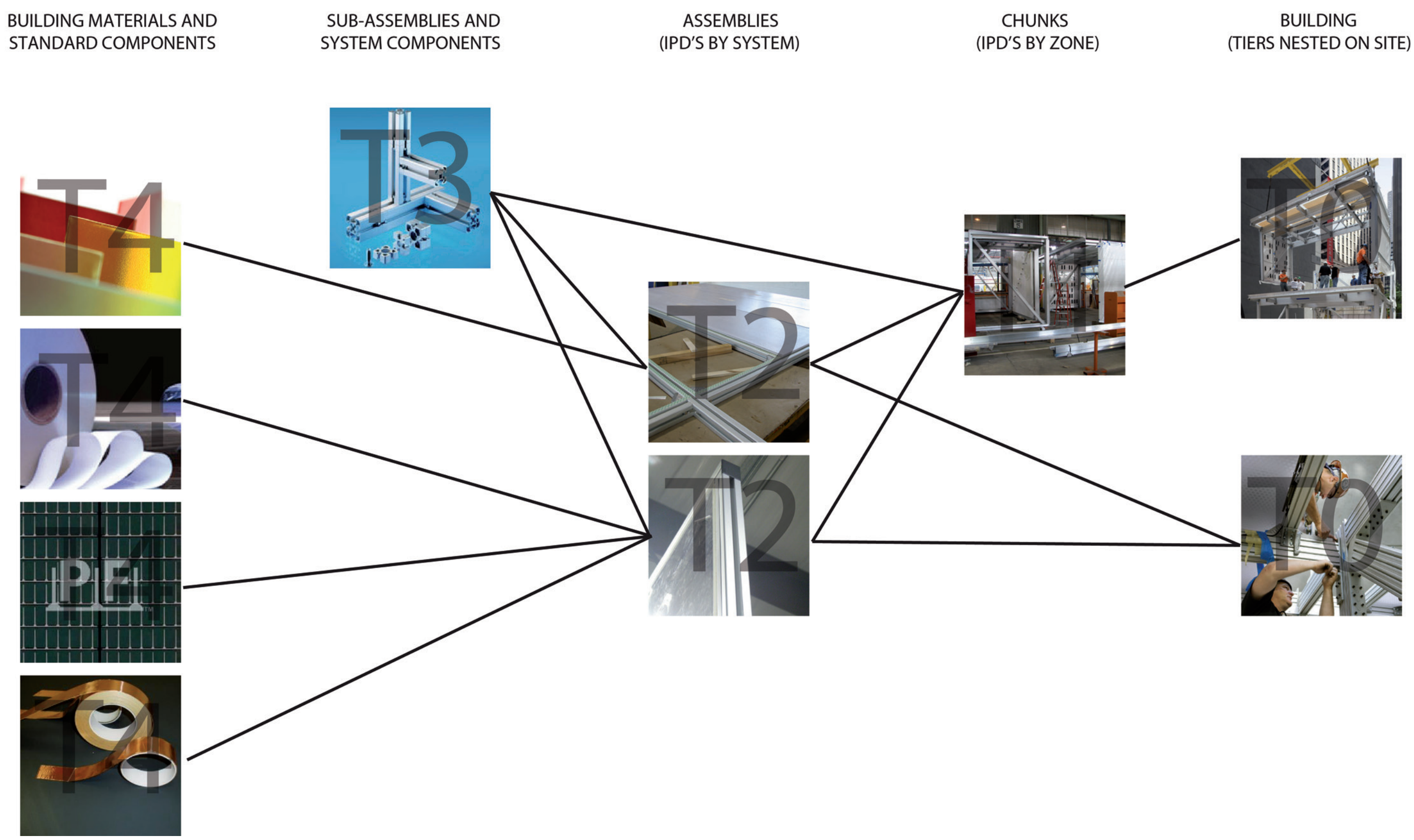

Figure 5. Detail of serially nested sub-chains of the Cellophane House™ system structure

extent be said to express how much the use of a certain delivery in a building project potentially could reduce the complexity of a given design task. This 'measure' is termed the *total integrated complexity value* for a given delivery and should be seen as local (delivery specific). It can as such *not* be summed up for an entire building and even less be used for comparing values between buildings. It does however give an idea of the different possible levers in existing and (future) potential building products (deliveries) that can be used to reduce complexity of the overall design task by outsourcing – thus integrating – preparation processes, standardisation decisions, and/or service elements to project external parties.

PARALLEL AND SERIALLY NESTED DELIVERIES

In some cases or for some parts of a building the different integration levels of deliveries (expressed in the tiers of the model) cannot be distinguished in any meaningful way or are not in focus – e.g. traditional trade based site work delivery as e.g. carpentry work or joinery. This can in the model be expressed as an *opaque parallel delivery* spanning from material delivery to site installation (tier 4 to tier 0). More industrialised deliveries are often serially nested thus integrating various clearly distinguishable sub deliveries on various tiers – e.g. glass in IGU's inserted into a window frame or hinges on a door inserted into a wall assembly. However, the particular coding and detail of a system structure is always a question of focus and relevance. Different viewpoints can result in different relevance of detail of a chain of deliveries in the system structure. This quality of *levelled complexity* and *flexible structuration* inherent in the model is inspired by the so-called soft system approach as introduced by Checkland (1981): '*[A] system is in itself always an abstraction chosen with the emphasis on either structural or functional aspects, This abstraction may be associated with, but must not be identified with, a physical embodiment*' (ibid:57). The system structures and their coding are epistemological rather than ontological and serve as intermediate conceptual models or tools for human understanding.

CASE EXAMPLE – THE CELLOPHANE HOUSE™

In the following some points from a case study will be used to further illustrate the application of system structures.

The limited extent of the present paper does not allow for an exhaustive presentation of the results and the examples do not go into detail architecturally and project-wise but focus strictly on system structural aspects.[3] It should also be mentioned that the case(s) represents an after-the-fact analysis of a recently built project(s). Although the system structure potentially is meant to work as a pro-active design supportive tool it has still mainly been applied as an analytical and educational tool for enhanced understanding of modern building production and construction scenarios.

One of the case studies forming part of the research was the *Cellophane House™* designed and erected as a 5-storey prototype building for the MoMA exhibition Home Delivery in 2008 by the Philadelphia based architectural office KieranTimberlake. The office has both build and published several works with a special focus on industrialised construction and the use of integrated products in architectural creation (Kieran & Timberlake 2004 and 2008). They explicitly state to '*believe in process as the first art*' which alludes to their interest in bridging the architectural ideation with way things are actually produced.[4]

In a system structural view, the Cellophane House™ represents a serially nested system structure where several sub-chains of off-site produced deliveries express a gradual integration (or nesting) from the more simple building materials, standard components or subassemblies into assemblies and building chunks that are ultimately integrated (or nested) into the final building on-site (See figure 5). Not all sub-chains have equal length meaning that in some cases building materials go directly to chunk assembly (on tier 1) or to the building site (tier 0) whereas in other cases there are several intermediate tier steps. Equally, some deliveries have destinations on various tiers meaning that they e.g. are both integrated (nested) into more complex deliveries and are installed directly on-site. The analysis is made from the perspective of the architectural office but even then, and due to their specific focus on and interest in using industrialised and integrated solutions, the sub-chains of the system structure reveal considerable detail. However, when choosing already existing industrialised products – as e.g. the applied bathpod system – some of the design complexity has already been integrated further upstream (read: have been defined by others into a *product*) and is subsequently not a specific *project* concern in focus for the architect thus remaining opaque in the particular coding of the system structure. Such integrated complexity (see above) could e.g. be the definition of and consequently also the restriction to one or few materials, a specific construction method and detailing, or predefined component choices and colour schemes. In the extreme it results in a completely standardised product.

Another interesting feature of the Cellophane House™ seen from a system structural view is that the project explicitly addressed the issue of *design-for-disassembly* as part of the original design concept. As the prototype had to come down by the end of the MoMA-exhibition, KieranTimberlake used the occasion to focus not only on how it was put together but equally how it could come apart and potentially also be reused; in that sense it even became an exercise in *design-for-reuse* or *design-for-reassembly*. This fact served in the present research to illustrate how system structures equally can be used for showing and/or planning the afterlife of a building and its constituent elements. A building need not necessarily be wasted nor completely brought back to its constituent raw materials at the end of its useful life. Thoroughly designed, elements on various integration levels (read: tiers) can be reused as e.g. relocating the entire building in another setting, using building chunks in a reconfigured retrofitted version, reapplying assemblies in other buildings, or simply by reusing building components as e.g. structural members, flooring or windows. This is perhaps the heaviest single argument for introducing the use of system structural analysis as an integrated part of the architectural design process which in the future increasingly will need to include the later disassembly and recycling design. The system structure provides a means of visualising and articulating such aspects.

KEY CONCLUSIONS AND FURTHER RESEARCH

The notion of system structure and the system structure model represent the author's proposal for an analytical structure – or tool – that can help clarifying the potential of industrialised construction as positively enabling for architecture thus bringing architectural ideation in closer contact with the way buildings are constructed. The aim is to contribute to bridging the apparent gap between architectural wholes (of thought/idea) and subsequent realisation (in terms of process and matter) that was pointed out as the main problem of the research. The model proposal is substantiated by the meaningful results of applying the model in its present state to different case studies – examples from one of the cases has been presented above.

The system structure model draws on several sources of systems thinking and introduces an epistemological system level that lies between general construction techniques and specific architectural results. The use of flexible constituent elements termed deliveries of varying degrees of integrated complexity in several dimensions introduces a new more nuanced way of looking at the issue of on-site/off-site construction and industrialised architecture. Although prefabrication has often been forwarded as *the* solution for a better controlled construction process and for better quality in the end result maximised prefabrication does not always equal optimisation neither from an architectural nor from an economical point of view. The best possible balance between off-site and on-site processes and the best combination of existing products (integrating complexity) and project specific solutions is always project specific in itself. Architecture – even industrialised – will never become completely standardised solutions.

The current sustainability agenda and the demand for environmentally sustainable solutions make it of outmost importance to control resource use and material cycles. This is perhaps, as pointed out above, the heaviest single argument for introducing the use of systems structures or similar conceptual tools as an integrated part of the architectural design process which in the future will need to include the later disassembly and recycling design of buildings and their constituent elements. Both architectural practice and research need, it is here argued, systems thinking and related tools to handle this complexity – and preferably used as an integrated part – a *system of thought* – already from the early design phases of architectural design.

However, there is still a need for a considerable amount of future research, development and refinement both concerning the model as analytical tool for general understanding, as well as its practical applicability as a proactive design tool. One path could be also to include entirely non-physical deliveries into the model, as e.g. design and technical consultancy services. This in order to further enhance a holistic and systemic design view where thought, process and matter merge thus equally embracing the concept of integrated *project* delivery and other organisational issues of the construction sector. The model so far mainly stays with the physical dimensions and on an analytical level although here it does introduce a new way of thinking about – or viewing upon architecture and construction.

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ENDNOTES

1. For a detailed introduction to the concepts of isomorphism and equifinality see e.g. (Bertalanffy 1968)
2. Author's translation from Danish
3. For a more elaborated presentation including several other case studies, please refer to (Vibæk 2012)
4. See http://www.kierantimberlake.com/profile/ profile_1.html, accessed on July 10, 2012