SYSTEM STRUCTURES IN ARCHITECTURE

- CONSTITUENT ELEMENTS OF A CONTEMPORARY INDUSTRIALISED ARCHITECTURE

KASPER SÁNCHEZ VIBÆK
PHD-THESIS
CINARK - CENTRE FOR INDUSTRIALISED ARCHITECTURE
THE ROYAL DANISH ACADEMY OF FINE ARTS
SCHOOLS OF ARCHITECTURE, DESIGN AND CONSERVATION
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ELABORATED AT CINARK - CENTRE FOR INDUSTRIALISED ARCHITECTURE

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I.1 PREFACE

ORGANISATIONAL LOCATION, FINANCING AND GENESIS

The present thesis is the result of 30 months of study and research conducted at CINARK – Centre of Industrialised Architecture from 2009-2011. Organisationally located under the Institute of Architectural Technology at The Royal Danish Academy of Fine Arts, School of Architecture (RASA), CINARK *'develops, accumulates and co-ordinates research and education activities concerning the production of industrialised architecture from a sustainable point of view.'*[1] Through several earlier and ongoing research projects – a considerable part of them conducted as PhD-projects – CINARK has since 2004 developed knowledge around the processes as well as the products – or physical results – of architecture and architectural creation exposed to modern industrialised means of production.

The PhD-project has been made possible through cofinancing between the RASA and Realdania – a major private Danish *'strategic foundation created with the objective of initiating and supporting projects that improve the built environment.'*[2] The Realdania cofinancing was given on the basis of a grant application without other conditions than proper documentation of progress according to a project specific research plan approved by the RASA and the provision of the related standard half-year evaluations. The stipulated length of 30 months – slightly shorter than a normal PhD-project – has its origin in an earlier project by another candidate that was abandoned. Due to earlier research work and experience within the field, the candidate of present project was considered qualified to complete the project within the available amount of time.

The incentive to engage in present project is rooted in the candidate's earlier research work at CINARK that started in 2004 with a project concerned with the goals and strategies in the process of architectural design. A subsequent project from 2006 was more focussed on the outcome of these strategies and processes and dealt with industrialised structural building systems. Finally an international collaboration between CINARK, Chalmers University of Technology in Sweden and Paris-Belleville Ecole Nationale Supérieure d'Architecture in France from 2007 looked into user requirements and mass customization

[1] http://www.karch.dk/cinark_uk/table/Profile accessed on September 3, 2011

[2] http://www.realdania.dk/English.aspx accessed on September 3, 2011

in industrial building systems.[3] All projects have had a special focus on the consequences of the industrialised means of production and construction for the architectural quality of our built environment. Architectural quality is a holistic concept than can not easily be reduced or atomised into clear, quantifiable sub parameters characterising an industrialised logic. It is this tension between the constituent parts and the whole that continuously has driven my interest towards present examination of systems and systems thinking in architecture. While the main part of the research has been conducted at CINARK, supplementary supervising was also received during a six month stay as visiting scholar at University of Pennsylvania, Department of Architecture.

STRUCTURE OF THE THESIS – A READER'S GUIDE

Apart from disseminating some kind of final result or findings, the ambition has also been to express some of the processes and the different steps that led to these results and findings. This is sought reflected in the format of the thesis in the sense that it is structured around a number of parts that express a development from a theoretical exploration over a practical to the proposal and application of an analytical model. Several papers and articles have been published during the course of the project. These have in several cases served as the basis for chapters or parts of these in the final thesis but have however been considerably restructured for the purpose in order to get a coherent result and avoid too much repetition. All related abstracts, papers and articles produced during the project are enclosed in the appendix that however mainly is located on a CD in order to keep the format and the focus on the main thesis.

The thesis is divided into five main parts and an appendix. Each main part comprises several sections gathered around a common main theme such as framework, theoretical exploration, practical exploration, model and case studies, and final discussion and methodological reflection.

Part I is called FRAME. This part describes the overall framework for the research i.e. how the project was made possible, what the thematic and organisational background is and how the scope and research problem is defined. A last section of this part describes the methodological approach and tries to relate this approach to a general discussion of scientific approach and knowledge production.

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[3] See (Jensen & Beim 2006, Beim, Vibæk & Jørgensen 2007, and Beim, Nielsen & Vibæk 2010)

Part II is called SYSTEM. This part is the theoretical exploration of the thesis. Here different theoretical paths of systems thinking are examined with reference to the research problem defined in part I. A first section is a historical view on systematic thought in architectural theory. A second section deals with different applied classification systems and taxonomies in construction as opposed to architectural creation. Next follows two sections on other kinds of systems theory outside the field architectural construction such as industrial production theory and general systems theory. A final section seeks to define central concepts as they are used in this thesis.

Part III – PRODUCT is an exploration of the practical reality within architectural construction and its current level of industrialisation and systemic elements. *Commoditisation* is proposed as a useful concept in this context. Subsequently a section deals with the emergence of system products within the field of construction seen as combinations of matter, process, and thought. A final section deals with the specific development of integrated products in construction and seeks to establish an initial product catalogue.

PART IV called MODEL is the presentation of a model as the primary outcome of the thesis. The elaborated model represents an analytical structure or a supportive tool applicable to contemporary and/or future architectural construction. A first section presents the model its current state. Subsequently the model is applied as an analytical tool to a series of cases (case studies).

Part V – REFLECTION is a discussion of the most important findings from the case analyses and the general applicability of the proposed model. Subsequently follows an after the fact methodological critique and reflection on the methods applied, the experience gained and the lessons learned throughout the process of the current PhD-research. A last section draws up the main conclusions in a short form related to the main problem and hypotheses and points out further development perspectives and future research needs.

The last part VI is an APPENDIX containing e.g. illustration credits, bibliography and references, and a keyword index for the thesis. Furthermore, supplementary documentation and material produced during the course of the project is located on an indexed CD to be found inside the cover of the thesis.

I.3 INTRODUCTION TO THE PROBLEM AREA

- Handling complexity in architecture and construction

> *'Design today has reached the stage where sheer inventiveness can no longer sustain it. To make adequate forms, one must be able to explore the relations between circumstances more fully than is done at present, so that the decision as to just where to apply precious and limited inventive power can be made'*
>
> (Chermayeff & Alexander 1965:161)

Industrialised Architecture

Organisationally located at CINARK, Centre for Industrialised Architecture, this thesis takes its starting point and naturally continues the line of earlier research within the field of *industrialised architecture* – a term that CINARK among others have contributed to the definition of. Industrialised architecture does not in itself point towards a specific architectural expression or the appearance of a specific (new) architectural style. Neither can one talk about a distinctly identifiable building typology; it is not about industrial architecture![4] While industrialised architecture as field of research still has the architectural result as object of research, it quickly also involves the *organisation* and *production processes*, their industrialisation, and the perspectives and consequences for the architectural result of this industrialisation. Architecture is generally about creating the best possible physical surroundings for human life, and decisive for the final result of all creation is not only the material but also the tools and the related techniques. Organisation and production processes are equally important when it comes to the definition of the architectural solution space given for each architectural project.[5] Rather than dealing with a specific result, industrialised architecture is a particular way to construct or assemble buildings – a way to *think* about architecture and construction – that however has significance for this result: the finished work or building.

To deal with industrialised architecture as field of research here should not be seen as a direct promotion of organisation, processes and results falling within this category as being something particularly conducive for the architectural result. Rather, it should be seen as a critical discussion of and taking a stance on

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[4] In Danish, (Center for) *Industrial* Architecture is used in the meaning of *industrialised* as a parallel to *industrial design*. Consequently, *industrial* architecture is normally termed *industry* architecture in Danish.

[5] For a discussion of *architectural solution space* – the set of all possible solutions for a given set conditions or parameters – seen in an architectural context see e.g. (Vibæk 2007).

a range of tangible tendencies that is observed concerning the way we presently build. This, on the one hand in relation to architects and other consultants that are contributing to the project basis of building projects as well as on the other hand in relation to stakeholders involved in the practical realisation of building projects. The latter group of stakeholders is increasingly becoming a mix of industrial manufacturers producing parts in offsite factory environments and the more traditional builders as contractors and their subcontractors that process and adapt building materials and components directly on the building site. Countless times construction has been compared with the product industry and its mass produced standard goods for large markets. Although much within the construction sector can be regarded as production there are reasons to believe that construction seen as *architecture* has – and probably always will comprise – elements that cannot be produced as finished goods in a true industrial sense. This is partly due to the fact that architecture is fundamentally bound to time, place and culture in a different way by constituting the framework of rather than the tools for human action and development.[6] An important question here becomes: How does this industrialisation of *construction* look?

Division of labour and the modularisation of construction[7]

Although in some primitive form it has always existed in human communities, the division of labour is one of the most significant characteristics of modern society. In 1776 the British economist Adam Smith describes the division of labour as one of the most efficient ways to improve the productivity performance of companies hence increasing the wealth of nations.[8] His best known example is a pin manufacturing company. After splitting up the process of making pins in different subtasks – thus specialising the workers – productivity raised by factor 240 (Smith 1776). Since the time of Smith, a pronounced division of labour has spread to all areas of society that partly due to this fact have become increasingly complex. Construction and architecture is not an exception.

Industrialisation within construction starts later than the general industrialisation of society. Up until the massive industrialisation of building processes and products in the 1960's, the division between the crafts and professions on the one hand and the modularisation of architectural construction on the other was always identical. The building crafts could be seen as independent modules – or systems of coherent expert knowledge - with clearly defined interfaces to adjacent modules.[9] Construction specifications, i.e. drawings, had a substantial set of conventions, allowing a few instructions (as e.g. lines and signs) to

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[6] A discussion of fundamental differences between industrial and architectural design can be found under *Commoditisation of architectural construction*, III.1

[7] This paragraph is partly taken from (Beim, Nielsen og Vibæk 2010:77f)

[8] Wealth of *nations* is not necessarily coincident with general wealth of the individual citizens

[9] The British sociologist Anthony Giddens use the notion of expert systems to explain how people in their everyday life draw on large amounts of embedded knowledge when e.g. taking the bus or using the telephone. (Kaspersen 2005:439 and Giddens 1990)

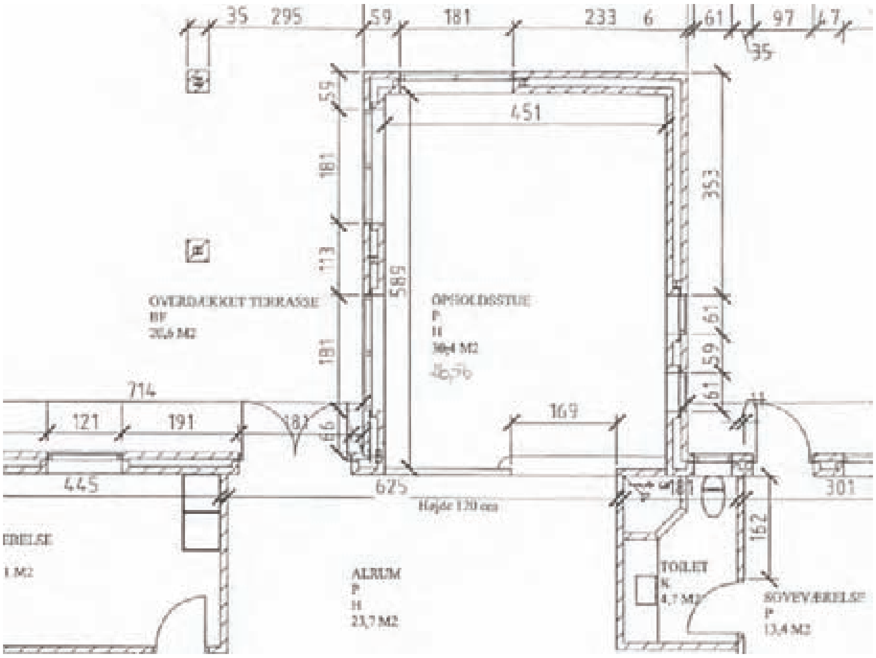

FIGURE I.1.1
CONSTRUCTION SPECIFICATIONS AS CONVENTIONAL PLAN DRAWINGS INCLUDE LARGE AMOUNTS OF EMBEDDED KNOWLEDGE

be clearly comprehended due to a large amount of implicit – or *embedded* – knowledge. The dimensions of the windows on the plan of a masonry building, for instance, is known to refer to the window sills, not to the sides of the actual carpentry. The carpenter knows that he has to subtract the size of the joint (for which he has responsibility). It is thus not necessary for the architect as a 'specifier' to design this specific interface, only to define where it is. If the architect wants to control the appearance of the detail, he can supply a drawing. If he does not, the craftsman's default solution will be used, still with a high-quality result, as this detail will seem coherent in the particular building. The *complexity* of the design task is reduced by making use of this embedded knowledge of the implicit building tradition applied by the craftsman.

Today, the crafts and construction skills have almost disappeared from the construction industry in their traditional form due to increased technical and economical demands in architecture. Large standardised quantities, extreme precision on the technical side and a need for increased productivity with less manpower on the economic side, dissolve the essentials of the traditional manually based workshop production and on-site adaptation. At the same time, the explosion in the number of choices within the building material industry has made it impossible for anyone to cope with all possible combinations in a traditional non-explicit (tacit) manner. Although the fundamental architectural challenge is relatively unchanged and still generally is about creating the best possible physical surroundings for human life (in all aspects), the premises for solving this task as specific buildings has changed considerably – building has become much more complex both as object (material) and design task (process). Simultaneously, the possibility for the architect of drawing on coherent knowledge from the crafts has been reduced. It is not that expert knowledge in construction has decreased – quite the contrary – but this knowledge no longer relates to and is no longer automatically embedded into a coherent way of building. Local vernacular architectures are expressions of such traditionally coherent knowledge systems with the crafts as subsystems. However, although the crafts still exist to some extent, they no longer cover construction as a whole. More and new areas of specialisation have emerged as crystallisations or fusions of earlier trades as e.g. foundation work, flooring, ventilation, alarm, and BMS systems etc.[10] A next question then becomes: How can this increased complexity and knowledge fragmentation in construction be handled in order to facilitate a focus on the architectural core instead of getting lost in technical and economical details that however still needs consideration and control?

Architecture as (industrialised) production

In this context, the present thesis claims that the architect has a special integrative role among and in relation to the stakeholders involved in construction.[11] *Etymologically* speaking architect means *master builder* or *supreme carpenter* (Becker-Christensen ed., 2001) and the architectural profession deals (to a great extent) with the conception and the creation of physical wholes. It is the task of the architect to bring the different knowledge systems and their physical outcome or products together in order to create these wholes – or coherent systems – that become more than the sum of their constituent elements: They become architectural works. However, it seems that the architect's tools for creating this integration or synthesis has not evolved parallel to the described development and specialisation within the construction sector in general and the building component industry in particular. The architect is trained with and still widely works from a 'craft based' approach that through use of a range of materials transforms an architectural concept into a true physical form. The modules or *systems* used for architectural thinking, it is argued here, still predominantly correspond to the traditional crafts rather than to the specialised and partly industrialised building industry that is supposed to produce them. That this is *also* the case for the processes of most of the traditional contracting companies does not necessarily reduce the problem in relation to the handling of complexity. There is apparently a growing gap between how on the one hand architecture is conceived and, on the other hand, how it is or can be produced. Just the mere expression of architecture as *production* probably 'grates on the ear' of many architects.

If however, we assume that industrialisation is a *condition* – not just an option – that architects and other stakeholders in construction have to respond to but simultaneously also stress that that architecturally speaking industrialisation is a *means* not a goal in itself, then perhaps the discussion is less controversial and can become more fruitful. This way the discussion of industrialisation of

[10] BMS = Building Management System is a computer based control system that controls and monitors the building's mechanical and electrical equipment (http://en.wikipedia.org/wiki/Building_management_system) accessed on August 8, 2011

[11] For a similar assertion, see e.g. (Bachman 2003:6)

construction and industrialised architecture can be diverted from a dialectic perspective of pros and cons towards a focus on potentials and perspectives of a conscious and critically well-balanced application of industrial logic in construction and architecture. Industry and industrialised production methods draw on strict methodologies and systems in order reduce or handle complexity. While these methodologies and systems earlier inherently meant standardisation of the product, modern information technology has gradually facilitated the standardisation of even complex *processes* that on the contrary can lead to huge variety when it comes to the resulting products. This phenomenon is often termed *mass customisation* with direct reference to and as alternative to traditional mass production. The term *new industrialisation* covers, as pointed out in earlier CINARK-research, a current parallel tendency within the Danish construction sector with reference to and as alternative to the first wave of industrialisation in construction in the 1960's (Beim, Vibæk og Jørgensen 2007:25 and Jørgensen 2007).[12] While the first industrialisation wave in construction was heavily standardised in its architectural expression and almost became an architectural style in itself, the new industrialisation of construction and architecture points towards a systematisation of project specific and context sensitive solutions. This leads to the question: How can architecture and construction be seen - and possibly conceived - as a system of processes and/or products that better match the means of production that currently produces our built environment while *simultaneously* taking into account architecture's specific attachment to time, place and cultural context? – and: What (kind of) knowledge can possibly be transferred to a general system level thus reducing the complexity to be handled within each building project seen as a single and context specific design task?

Product architecture and integrated product deliveries

Within the product industry when designing e.g. cars, computers, washing machines or bags, the notion of product architecture is used to describe, analyse, and optimise how production and product in the most adequate way can be divided into a number of constituent elements of processes and/or physical modules. Product architecture is not about architecture in the sense that architectural designers usually apply it but simply refers to organisational and product structural issues. The product architecture defines how different subsystems form part of a complete supply chain and production line, and how these subsystems are assembled in the final product without this structure necessarily being perceivable to the end user. Through the product architecture,

[12] The Danish Technological Institute has lately initiated a network of companies and research institutions co-ordinated by a so-called *Centre for New Industrialisation* (CNI). http://www.cni.teknologisk.dk/ accessed on July 15, 2011

a system level is established that sustain the whole while simultaneously splitting up this whole into meaningful elements that subsequently as more or less interdependent entities can be treated (designed and produced) separately – as processes and/or physical elements that perhaps even are performed by different independent suppliers. The product architecture as a design and production tool reduces the complexity of the design task without necessarily reducing the complexity of the product itself. This is particularly the case, when subsystems or elements of the product architecture are based on standardised solutions or well-known principles and/or processes.

In contemporary architecture and construction there is no self-evident product structure as it earlier was provided by the crafts – although in a non-conscious manner. The coherence between how architecture is conceived and how it can be produced has, as mentioned, been broken due to both technical as well as economical causes. A way to view 'the product architecture of construction' could become a useful tool – not just in construction phases but equally during the earlier architectural design phases. Precision, strict methodology and control can also be used in a creative manner! In the first case, such a tool (as analytical) could increase the understanding of how buildings are and can be put together from different industrial scenarios understood as a combination of production (prefabrication) and on-site construction. In the long run, the tool could potentially also be developed into a design supportive tool that, apart from reducing the complexity of the architectural design process, could increase incentives for true product development of architectural subsystems in the form of more and new types of integrated product deliveries. Earlier research at CINARK, described in the publication *Three Ways of Assembling a House*, points out the emergence of such integrated product deliveries as a product level between traditional onsite construction and the turnkey solutions of the conventional offsite building manufacturers (Beim, Nielsen & Vibæk 2010). The present thesis seeks to go one step further both concerning development and clarification of concepts as well as regarding the tool development. Inspired by the industry, it seeks to examine how different systems approaches can be used to bridge the gap between conception and realisation in the most appropriate way. The underlying research thus deals with a question of commoditisation of construction. This is not the same as a commoditisation of buildings as products or of architecture itself. As pointed out, this commoditisation can take place (and already does so) on a subsystem level in the form of integrated product deliveries that are used as elements of a building. I will return to a formal definition of systems and integrated product deliveries as central notions of this thesis.

PART II – 'SYSTEM'

The problem area and the scope of present thesis point out some circumstances formulated as a general hypothesis of a gap between architectural ideation and contemporary industrialised building production and construction. In the following two parts this hypothesis is examined, substantiated and discussed through both a theoretical and a practical exploration. These explorations correspond to respectively Part II – 'System' and part III – 'Product' of the thesis and will be addressed through a number of sub-questions. Finally the main hypothesis is (partly) sought met in the *system structure model* found in part IV – 'Model' of this thesis.

The present part, part II – 'System', forms the theoretical backdrop of the thesis. Through five sections it examines and evaluates on systems theory and systematic thought applicable in the thesis in the form of a scanning within different fields of knowledge and a concluding attempt, on basis of the findings in these (system) fields, to establish a consistent terminology for the thesis as well as in the general discussion of systems thinking in architecture and construction. With outset in existing knowledge and theory, the overall objective of the thesis is to look into the empirical reality of building construction from a systematic frame of reference – to look upon architecture and architectural creation as a system of constituent parts, elements or subsystems. The sections are the following: 1. Systems in architectural theory (II.1), 2. Classification systems in construction (II.2), 3. Industrial production theory (II.3), 4. General systems theory (II.4), and finally 5. Systems terminology for architecture and construction (II.5).

The five sections do not form an exhaustive evaluation of systematic elements found within the different fields. They rather offer a number of examples through a selection of different ways of approaching architecture and other complex fields from a systematic frame of reference. This is meant to work as a short ideographic contribution within each field as well as a source of inspiration for how the present thesis may contribute to a more systematic approach to architecture and architectural creation in particular – or less pretentious: contribute to a clarification of the *perspectives* of such a systematic approach to architecture. Each section advances a hypothesis derived from the main question and goal of the thesis that subsequently leads to one or two research questions examined within the particular fields.

II.5 SYSTEMS TERMINOLOGY FOR ARCHITECTURE AND CONSTRUCTION

INTRODUCTION

The previous sections of the present Part II – 'System' have, with reference to the topic of this thesis introduced key theoretical themes from related fields of knowledge i.e. architectural theory, classification systems in construction, industrial production theory, and general systems theory. The idea is that these themes form the theoretical and conceptual framework or backdrop used for the rest of the thesis. This both in the sense of underlining and further clarifying the problems that the thesis sets out to treat as well as introducing useful concepts for use in the subsequent practical exploration in Part III – 'Product' and for the case analyses and model presentation found in part IV – 'Model'. The current section seeks to distil key concepts and other findings into a more condensed form in a so-called *systems terminology for (industrialised) architecture and construction* that furthermore tentatively establishes a taxonomy relating some of these key concepts to each other.

KEY CONCEPTS AND CONCEPTUAL UNIVERSES

A considerable amount of the vocabulary introduced above can seem unfamiliar for use in architectural design. Many terms are closely connected in small 'conceptual universes' of subsidiary concepts gathering around a central key concept or theme. Below, such key concepts and their subsidiary concepts are defined as to how they will be used throughout the rest of the thesis. A hope is that they will also be useful within the more general conceptual universe of architecture and construction as a contribution to a province of it under development – *industrialised architecture*.

System

System as used in this thesis refers principally to the interconnected whole of materials, processes, and information that constitutes the intentional human creation of a building or a similar discrete and fixed physical entity of our

FIGURE II.5.1
INTEGRATION OF DIFFERENT SUBSYSTEMS SERVE FUNCTIONS THAT CANNOT BE REDUCED THE SUM OF THE CONSTITUENT PARTS

everyday physical environment (i.e. urban space, bridge, tunnel etc.). Materials refer to physical matter put into the building or consumed during its creation, processes refer to the manipulation of these materials by use of tools, machinery and personnel, whereas information represents immaterial resources i.e. knowledge and ideas. Although conceptually these systems of *matter, process* and *thought* can be separated, in practice they are always integrated when it comes to a building and cannot independently lead neither to a building nor to elements of it.[112] Matter without processing and knowledge about this processing yields no result. Equally, intentional processes as building construction originate from knowledge and ideas and are only expressed through the application to matter.[113] Finally knowledge and ideas about buildings stay immaterial if not directed towards processes that manipulates material.[114] A building in the definition above is furthermore, as argued previously, a *complex system* where many of its constituent elements or subsystems can be characterised as *systems* in their own right (e.g. the structural system, the heating system or the building envelope). As with other complex systems a building is more than the sum of its constituent elements: A structural system carrying a heating system and enclosed by a building envelope provides shelter from the natural elements even in cold climates or seasons. The combination of subsystems contributes to the provision of a liveable space serving many functions that are not inherent in its subsystems seen as isolated (See figure II.5.1). The building as system can also be regarded as a subsystem of other *supra-systems* such as blocks, cities, cultures and social systems with more or less tangible physical substance. This is here termed *levelled complexity*. The choice of focus or system scale defines the primary and subsidiary system elements and their complexity level.

[112] Peter Checkland uses a similar division of *designed physical systems* (matter), *human activity systems* (processes) and *designed abstract systems* (thought). See explanation and reference in *General systems* theory, II.4

[113] Natural processes and systems as opposed to human processes and systems are not governed by external intention but creates and reproduce themselves. In systems theory such systems are termed *autopoietic* (self creative) as opposed to *allopoietic* systems where ‘producer’ and ‘product’ are separate entities. A building can be seen as the product – or subsystem of an allopoietic system. The building itself is then called a heteropoietic system which means that it is created by something or somebody exterior to the system itself. See e.g. http://en.wikipedia.org/wiki/Autopoiesis accessed on July 22, 2011

[114] A drawing or a description of a building is still only a representation – not a building it itself.

Again, focus here (in present thesis) is the building as the primary (complex) system with appurtenant subsystems. Furthermore, the focus of the subsystems is exclusively delimited to elements that integrate some physical matter to be inserted in the primary system (the final building). Such (physical) subsystems form hierarchies spanning from simple materials to complex integrated systems and can be integrated into each other.[115] This is here termed *nesting*. Present system definition also operates with what is termed as different *dimensions* of the system and its subsystems. A *preparation dimension* expresses different levels of preparation of the physical (sub-)system (upon delivery), a *standardisation dimension* expresses different levels of standardisation (of product and/or process) upon delivery, and a *service dimension* displays different levels of service (in the delivery process).[116] Below, the dimensions will be used in an attempt to establish a taxonomy for classification of integrated product deliveries and their degree of integration. As an overall consideration, it can be said that the notions of *system* and *network* are closely related in the present system definition stressing interconnectedness and interdependency rather than separation and classification.

Model

The notion of *model* is in the present thesis used as referring to a visually perceivable coded structure that as an intermediate tool displays a focussed view of a system seen on a specific abstraction or complexity level (cf. system and levelled complexity as defined above). Such a model is always modelled for a *context specific* purpose and this purpose defines the right level of abstraction for each of the elements contained in the model.[117] Models are in the present thesis used to represent and display *structural organisation* or specific *configurations* of subsystems in a main system (a building) in the form of a specific pattern. However, as focus and complexity level can change according to the context specific purpose of coding, the model should enable *flexible structuration* of both elements and their interrelations.[118] Although thus being a purely mental (or epistemological) construct with no claimed ontological categories, the model still represents a tool for understanding complex reality through a simplified but flexible lens. It is a way to deal with the world. This is not the same as simplifying reality itself.[119] The systems view inherent in the model aims at focusing on relations between rather than on specific content of each of the elements (as patterns) thus reducing the amount of information needed for keeping track of each element and its position in the system structure. In this way the model can potentially reveal *isomorphisms* (equal form or here:

[115] Systems organised hierarchically within other systems are called *holons* – simultaneously constituting wholes and parts. See *General systems theory*, II.4

[116] The notion of *dimension* is inspired by the Danish DBK and the Swedish BSAB classification systems respectively working with *aspect* (aspekt) and *view* (vy) as different ways to look at an object or a building. See *Classification systems in construction*, II.2

[117] Both Meadows and Bertallanfy point out the need to model specifically according to the purpose of the model. See II.4

[118] For a definition of flexible structuration, see *General systems theory* II.4

[119] This quality of the model is pointed out by e.g. Odum and Bertallanfy. See *General systems theory* II.4

structural patterns) between various systems (buildings) coded within the model even if these from a formal design point of view are completely different. Equally, systems or buildings that from a formal design point of view are equal or similar can have different configurations of subsystems and thus result in different coding of the model (equifinality). Structural patterns expressed visually through the model can potentially by manipulated through the model as a tool. Again, following the system definition above, the model focuses on elements with some kind of material presence in the overall system being the final building. Different codings of the model represent different *system structures* – a main concept coming out of this thesis which will be formally defined below.

Delivery

In order to formally define the *system structure*, a clearer definition of the elements – or *system entities* – of such a structure initially needs to be done. Using the idea from *supply chain management* that each link in the (supply) chain encompasses both the operator, the operation and the product or material as it advances through the chain, the basic element or subsystem of the system, of the model, as well as of the resulting system structure is here defined as a *delivery*.[120] This delivery has, as the simple supply chain link, physical substance (material), represents a process (operation), and is provided by a supplier or a manufacturer (the operator) and thus overcomes the traditional product/process dichotomy.[121] This integration helps to reduce complexity of structures comprised of such system entities. The physical substance of a delivery needs, in present definition, to become part of the final building. The process of a delivery comprises as a minimum the possibility of buying or acquiring and transferring the physical substance from the supplier for integration in the building or for nesting it into another delivery that ultimately is equally integrated in the building. However, processes can equally include higher levels of the service dimension of a subsystem[122] meaning that the supplier (or manufacturer) can supply, process, and/or install the delivery in the building or nested into other deliveries. Deliveries, as used in this thesis, become physical subsystems and their related processes as they are delivered and nested (inserted) into a building or a subsystem of a building. Deliveries nested into other deliveries can generally speaking – and with reference again to supply chains – be characterised as *upstream deliveries* while if inserted into the building itself they are *downstream deliveries*. The notions of upstream and downstream are also used as relative to a certain viewpoint and will be more consistently elaborated in the description of the model in part IV – 'Model'.

[120] See *Industrial production* theory, II.3

[121] The integration of process and product is, as earlier pointed out, substantiated by Bertallanfy. See *General systems theory,* II.4 p5/6. Also advanced DSM-techniques tends towards juxtaposing processes, products and operators (organisational DSM's) See *Industrial production* theory ,II.3

[122] On *dimension*, See system definition above

FIGURE II.5.2
THE DASHBOARD OF A CAR IS TODAY DELIVERED TO THE CAR ASSEMBLY LINE AS A FINISHED INTEGRATED PRODUCT DELIVERY COMPRISING SEVERAL SUB-SYSTEMS IN ITSELF.

Integrated product delivery

Being concerned with the possibilities of knowledge transfer about systems and systems application from other fields into the fields of architecture and construction makes *integrated product deliveries* a central concept and a type of delivery to be dedicated special attention in this thesis. Integrated product deliveries, as used in the product industry, are complex systems in their own right and represent an efficient means of reducing complexity in focus for a given design task – in particular if these integrated product deliveries are well established as commoditised products. While (building) materials and (building) components are perhaps easy to understand as deliveries, the integrated product delivery as a subsystem requires a little more introduction. Following Mikkelsen et al., 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'* (Mikkelsen et al 2005:3)*[123]. The definition of an IPD as (sub)system goes clearly beyond the division between product and process – between physical and non-physical – thus again acknowledging the difficulty of a consistent distinction between what, as Bertalanffy suggested, *'may be the very same thing'*.[124] As an example a service can be seen as a system but whether it is mostly a product or a process depends on the specific service in question and on how you look at it. Following the definitions of *system* and *delivery* above, this thesis concentrates on IPD's containing several kinds of physical substance that become nested into the final building. Although configurable for specific building projects, IPD's exceed as systems the project and context specific purpose. IPD's exist with different degrees of complexity and together with materials and components they can be integrated – or *nested* – into each other so that a more complex and integrated system contains one or several less complex systems. A prefabricated bathroom pod as a subsystem to a building contains several nested subsystems as electrical wiring, plumbing and structure that themselves can be seen as systems. Whether these are relevant in a given system structure depends on the focus of attention. *Integration* and *nesting* are almost aligned in present definition and become conceptually the opposite of *modularisation*.[125] However, to integrate or nest a delivery

[123] Authors own translation from Danish. See Vibæk (2009) – the last part of the definition points towards the service dimension of the system structure model – See *Model presentation*, IV.1

[124] See *General systems theory*, II.4

[125] See Baldwin & Clark's destinction explained in *Industrial product theory*, II.3

does not exclude a subsequent disintegration or *disassembly* for replacement or conversion purposes. Modularisation and integration/nesting are like opposite sides of the same coin. Whereas integrated products and their separate production and delivery are common within other larger designed and engineered products such as cars, ships and aeroplanes, it is still a relatively new system entity in construction.[126] (See figure II.5.2)

Present thesis works with two main types of IPD's in construction that are both of them upstream in relation to the final building that they are nested into and downstream in relation to the simpler building materials and components that they are integrations of. In some cases IPD's can also be nested into each other.[127] The two main types are *chunks* that are volumetric (spatial) units that can integrate a wide range of sub-systems (or parts of these if these subsystems are distributed in the building) and *assemblies* that are defined as system based deliveries by having a narrower more specific scope often encompassing fewer systems but in their entirety. Where chunks in this definition are concerned more with overall spatial performance, the assemblies are rather concerned with system performance of one or few specific systems. This distinction is in other contexts referred to as *'by zone'* and *'by system'*. Chunks are deliveries 'by-zone' whereas assemblies are deliveries 'by system'. Assemblies or parts of these (modular assemblies) can be nested into chunks, and in some cases chunks can be nested into other chunks (e.g. a bathpod into a large volumetric element). Both main types are predominantly off-site produced before final delivery. A final special type of IPD is onsite processing and delivery of a clearly delimited and finished integrated solution that can have touch of both assembly and chunk. This type, although delivered on-site with low preparation still works as integrated through the high degree of service that lies in the finished installation.[128]

System structure

The notion and the underlying concept of *system structure* is central to and a main contribution of the present thesis. Conceptually, system structure fusions the closely related concepts of *product architecture* and *supply chain*. While within the product industry a product architecture indicates a static (actual or thought) physical structure (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. Another way to put this distinction could be a *product breakdown structure*

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[126] The sections of Part III – 'Product' introduce and discuss several different kinds of these integrated product deliveries in construction.

[127] This primarily illustrates the difficulty in making a completely consistent hierarchical graduation of complexity and integration of different deliveries in construction.

[128] In the case studies of Part IV – 'Model' this kind of integrated product delivery is referred to as parallel deliveries as opposed to serial nesting. A discussion of this distinction and the different kinds of integrated product deliveries can furthermore be found in *Findings*, V.1

as opposed to a *work breakdown structure*.[129] The system structure seeks to encompass both these aspects of structure thus, as mentioned earlier, overcoming the dichotomy of process and product. The system structure in present definition is exclusively concerned with architectural design and construction of buildings as complex systems assembled by a number of subsystems. The adaptation of the term from the more production related 'predecessors' reflects this fact. Leaving out the notion of architecture as in product *architecture* furthermore avoids confusion of this term within the context of architectural design as a distinct profession and discipline.[130]

Corresponding to the definition of *model* above, a system structure is not an ontological entity – it is so to say not inherent in any building seen as a complex system. A system structure is an epistemological (artificial, immaterial) entity that makes it possible to articulate and interpret certain characteristics of buildings related to the way they are produced and constructed. Particularly concerned with the ways in which a building can be divided into constituent elements that matches the way buildings are actually produced, the *overall purpose* of a system structure is to bring closer on the one hand architectural ideation and on the other hand contemporary processes of construction and building production. The distance between architectural ideation and the way buildings come into being is the main problem set out to be treated in this thesis. The idea of a system structure is the main contribution in this regard.

The introduction of the notion of system structure should not only be understood as a 'technical' tool to look at a building. Inherent in this particular view is also a certain *architectural interpretation* of buildings in general – and industrially produced buildings in particular. The definition above of buildings as complex systems of subsystems points towards an epistemological split of the architectural (art)work into on the one hand the whole as an indivisible entity that is more than its constituent elements and, other the other hand, the work as an *assemblage* of relatively independent elements created outside the work that together form a coherent whole – that is equally more than its constituent elements. Technically, assemblage means the (simple) act or result of assembling elements. However, assemblage within the arts also refers to three dimensional (sculptural) compositions or 'collages' of miscellaneous objects or materials or as defined in Webster's: '*an artistic composition made from scraps, junk and odds and ends [i.e. miscellaneous articles, ed.]*'. The assemblage has connections to the artistic technique of *montage*.[131] In such works of arts the

[129] Se e.g. Armistead et al (1996)

[130] Ulrich & Eppinger uses the term system level design for products as e.g. printers, photocopiers and scooters. *'The system-level design phase includes the definition of the product architecture and the decomposition of the product into subsystems and components.'* (Ulrich & Eppinger 2008:15). See also *Industrial production theory*, II.3

[131] As described in *Systems in architectural theory*, II.1, Gottfried Semper in the mid-nineteenth century anticipates montage as an architectural and tectonic strategy.

constituent elements both point inwards towards the internal composition but also outwards towards their origin outside the work. The architectural and artistic implication of the notion of system structure as applied in this thesis tends towards the notion of the architectural whole seen as an assemblage of its relatively independent subsystems.[132] The assemblage is the entire system – the building as whole – as both physical object and architectural work.

The system structure is modelled by use of a visually perceivable model (see above) and displays a given structure (actual, thought or simplified theoretical) of deliveries of different complexity and their interrelation as they become nested into each other and/or ultimately into a finished building. In other words: It expresses a certain *configuration* of the constituent elements (deliveries) of the system (the building).[133] The delimitation of each delivery is not clear-cut and universal but project specific and depends furthermore on the specific focus and purpose of modelling the system structure. Where each delivery – apart from comprising some kind of physical substance – often additionally would imply a contractual relation (between a supplier and a receiver), this is not a definite criteria. Company internal or partly company internal system structures can in some cases make sense – particularly if the company is a manufacturer producing highly complex integrated product deliveries or perhaps even all encompassing building solutions either as prefabrication or as on-site construction or combinations hereof.[134] On the other hand, a delivery can also comprise various nested subcontracts that are opaque (not visible) in the system structure, if this detailed subdivision is considered irrelevant for the specific purpose of the modelling. Such opaque subsystems are actually one of the means to reduce unnecessary complexity of the design process. Apart from aiming at a consistent subdivision according to the complexity and integration of each delivery, the system structure promotes the distinction between offsite and on-site deliveries in regard to where/when the delivery is produced and to what degree it is prepared for nesting on-site or into other off-site deliveries. Apart from the point that the model through this *flexible structuration* is project and purpose specific, one of the major arguments for its utility is that the balance between off-site production and on-site construction always is project specific. Through use of the coded model the system structure can act as analytical tool (retrospectively and potentially proactively) that gives an overview over different system structure scenarios, read: different ways to produce a given system (i.e. a specific building).[135] Important here is to note that offsite production or prefabrication is not necessarily the same as industrialisation in the sense of

[132] For an elaborated discussion of the *assemblage* as a three dimensional version of the montage or collage in art and architecture) see (Bundgaard 2006:39-47)

[133] Configuration is here used in a sense similar to the way it is used in Space Syntax as explained in II.4

[134] Most if not all building solutions are a mix of different degrees of off-site production and on-site construction.

[135] This ressembles the notion of *equifinality* as described in II.4

automation. Often off-site production is merely construction under roof. Still, the choice of a certain off-site production (or prefabrication) can have other justifications – economy- or quality-wise.

Equal to the capacity of, through the model, facilitating a visual display of possible production and assembly structures, and inspired by Nagurneys definition of supply chains,[136] system structures can also be used to indicate a possible afterlife of the different sub-systems due to the quality of integrating process and product. By displaying possible disintegration or *disassembly* scenarios the system structure extend, its utility to facility management for modelling scenarios for after the end of a building's useful life. This will be further elaborated in part IV, 'model'. The system structure underlines a building's quality of being an open system with partly interchangeable constituent parts that can be put together in different configurations.

INTEGRATION TAXONOMY

Based on the notion of *dimensions* and the definition above of the three different dimensions of a given delivery or subsystem (being integrated or not), this paragraph seeks to draw up a taxonomy that can be used for classification of the different deliveries in a system structure. The overall purpose of the system structure in the first place is to handle complexity by focussing (the limited capacity of) design attention where it is most needed during the architectural design process while simultaneously better integrating issues about how the architectural idea is transformed into physical matter in the final building. Reducing the complexity of the design process does, as pointed out, not necessarily reduce the actual complexity of the final outcome (i.e. the building – or main system). Through the coded model of the system structure a chosen abstraction level is established according to the specific purpose in question while less relevant detail are left out of focus.

The three dimensions of *preparation, standardisation*, and *service* can all be seen as expressing different aspects of complexity concerning a delivery (subsystem) in a building. Each of the three dimensions is here detailed as divided into four levels that generally can be said to span from low to high integration of complexity. Integration of complexity (in a delivery) means that the complexity is handled by the supplier e.g. through production system or delivery

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[136] See *Industrial production theory*, II.3

FIGURE II.5.3
EXAMPLES OF THE DIFFERENT PREPARATION LEVELS

service. Potentially, *integrated complexity* reduces the complexity to be handled by the (architectural) designer/client or whoever is receiving a given delivery.

Due to the qualitative character of the subject (of complexity), the graduation of each dimension into four levels is arbitrary in the way that the categories seek to theoretically cover the possible range within each dimension while the specific subdivision is fixed to four intuitively meaningful categories. The categories attempt to avoid too much overlap and at the same time provide a comparable graduation between the dimensions that makes it easier to understand and use. Below, the three different dimensions and their corresponding values or levels are listed.

Preparation level

The preparation dimension describes the level of preparation of the delivery when it leaves one (production) location in order to be inserted into another, being a building or subsystem of a building. This *in between* state of a delivery is independent of the processes needed to install the delivery at its destination point in the system structure. The following four levels are defined corresponding to the definition of deliveries and integrated product deliveries above:

0. MAT = Building material (manufactured raw material as one single or a composite material).[137]
1. COM = Building component (assembled component as a simple custom made component of one or few materials or a standard (industrial) technical device.)
2. ASM = Assembly (integrated assembly of materials and/or components often encompassing one or few subsystems in their entirety – an assembly by system)
3. CHK = Chunk (large volumetric element that can integrate a wide range of subsystems or parts of them if these subsystems are integrated in the building as a whole)

Some deliveries leaves one location as kit-of-parts (earlier KOP-category) of prepared materials, components and or assemblies that when installed at the destination point constitute assemblies (ASM) or chunks (CHK). Whether these are coded as assemblies, chunks or as their constituent components and materials is defined by the primary place of processing. If a considerable amount of

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[137] Raw materials are seldom if ever used in a non-processed manner in a *building* as e.g. directly from the mine. The category refers to building materials – materials on a level that is relevant in architectural construction. In another context with another focus, materials could even be treated on the molecular or atom-level. It is the focus on buildings and architectural constructions that defines the relevant range.

FIGURE II.5.4
EXAMPLES OF THE DIFFERENT STANDARDISATION LEVELS

FIGURE II.5.5
EXAMPLES OF THE DIFFERENT SERVICE LEVELS

processing and adaptation is needed at the destination point, the delivery is classified as its constituent (upstream) sub-elements. If only simple assembly or a minor amount of processing and adaptation is needed then the delivery is classified as the assembly or chunk.[138]

Standardisation level

The standardisation dimension describes the level of standardisation of the delivery when it leaves one (production) location in order to be inserted into another, being a building or subsystem of a building. The following four levels are defined:

0. BSP = Bespoke (custom product/custom delivery – non-standard solution made specifically for a project)
1. M2O = Made-to-order (custom product/standard delivery – customised product version within existing system – often called mass customisation.
2. C2F = Cut-to-fit (standard product/custom delivery – cut and delivered in customized dimensions for known customers)
3. OTS = Off-the-shelf (standard product/standard delivery – delivered in standard dimensions produced for unknown customers

Service level

The service dimension describes the supplier's level of direct involvement in the handover of the delivery to the point of destination. The following four levels are defined:

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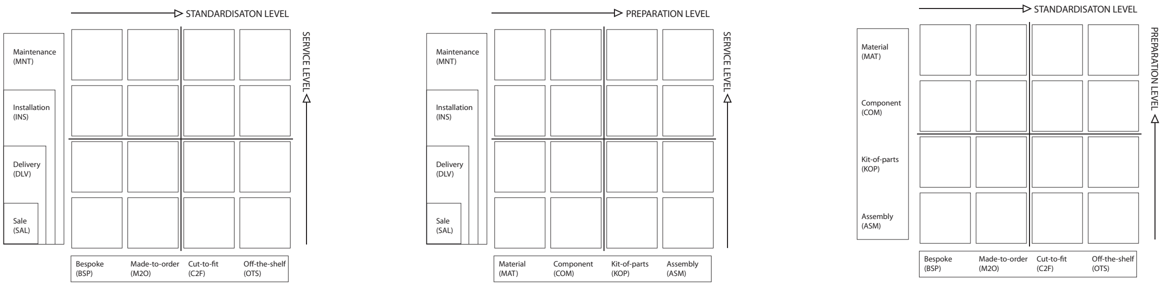
[138] Earlier iterations of the taxonomy had a kit-of-parts category (KOP) that however showed difficult for consistent coding and has been omitted.



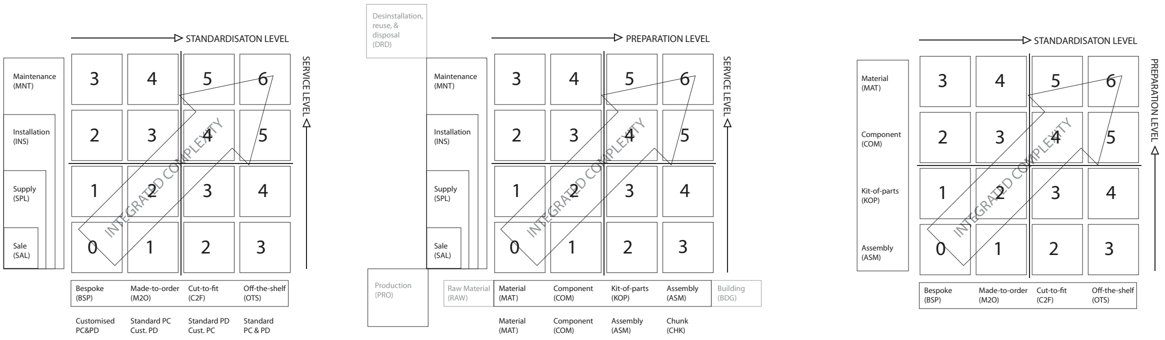


FIGURE II.5.6
2D-GRAPHS WITHOUT VALUES

FIGURE II.5.7
2D-GRAPHS OF DIMENSION PAIRS WITH THEIR RESPECTIVE VALUES

0. SAL = Sale (delivery pick-up arranged by purchaser/receiver)
1. SPL = Supply (supplier delivers to purchaser/receiver at point of destination (integration location i.e. factory or building site))
2. INS = Installation (supplier installs at point of destination (integration location i.e. factory or building site))
3. MNT = Maintenance (supplier maintains delivery after delivery and installation)

Remark that the levels of the service dimension are inclusive in the way that a higher service level automatically also includes the lower levels (e.g. delivery (SPL) always includes sale (SAL). Likewise maintenance (MNT) always includes sale, delivery and installation (INS). Although maintenance can perfectly be (and often is) a separate (service) delivery applied to a building after its construction, the focus of the system structure (cf. above) is exclusively delimited to deliveries that contain physical matter to be inserted in the building up until its completion. Such deliveries that include maintenance after completion will consequently automatically encompass the other service levels.

Integrated Complexity Value

Theoretically, every delivery can be classified along each of the three dimensions defined above. The different dimension values of each delivery can then be crossed and plotted into simple diagrams showing the relations between pairs of dimensions. Figure II.5.6 shows how such diagrams could look. Intuitively it can be understood that deliveries located in the lower left corner of the graph will have a low integrated complexity whereas, on the contrary, deliveries located in the upper right corner will have high integrated complexity.[139] By moving rightwards or upwards, integrated complexity of deliveries increases while moving leftward or downward means that integrated complexity decreases. It is thus argued that also high standardisation values point towards some kind of integrated complexity of the delivery. Although standards perhaps are defined completely outside a product through e.g. legislation or public regula-

[139] As mentioned above all three aspects and their related levels express something about the complexity integrated in a delivery or product. Integrated complexity means complexity handled by the supplier and thus – at least theoretically – is beyond the attention of the purchaser/receiver of the delivery – representing the next link in the ‘supply chain’.

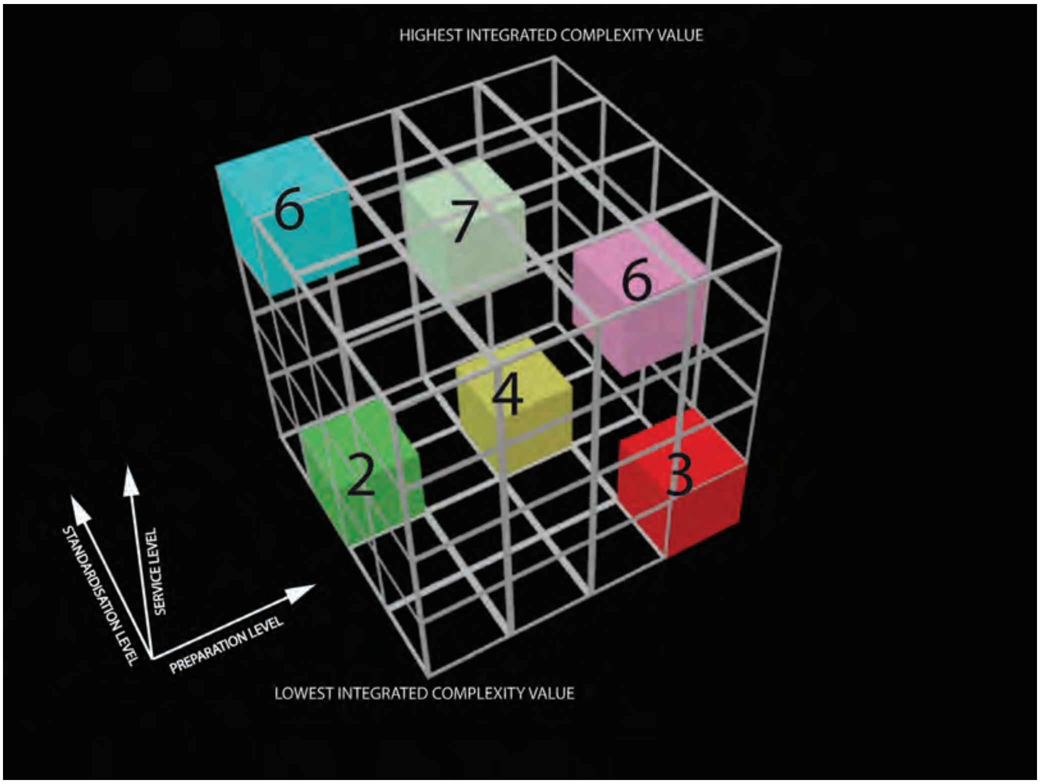


FIGURE II.5.8
EXAMPLES OF DIFFERENT TOTAL INTEGRATED COMPLEXITY VALUES AS COLOUR CODED CUBES IN A THREE-DIMENSIONAL GRAPH

tion, these exteriorly defined standards make it possible to deliver a 'simpler' product by constraining the solution space. The complexity integration lies in this case prior to the product itself that subsequently can draw on it as an established standard.

By applying numerical values to the levels of the different dimensions it is tentatively sought to arrive at a simple (and simplified) mathematical expression of the integrated complexity seen as combinations of the different dimensions. By using values between zero (0) and three (3) for each of the dimensions of a given delivery the values can subsequently be added to a sum. Figure II.5.7 shows how values of two dimensions are added.

If the values of all three dimensions of a given delivery are added it gives what is here defined as a *total value of integrated complexity.* In order to express this in a diagram one needs three dimensions. In figure II.5.8 this is expressed like a three dimensional graph. In the first case such a value is only a local measure in the sense that it can (theoretically) be used to compare different versions of the same physical element in a building. By having three dimensions it can, again intuitively, be understood that if one dimension value goes one down and another one up or if one dimension value goes two down and each of the two other goes one up each, then the total value of integrated complexity will stay constant. Working with numerical values of qualitative parameters (as the dimension) is of course not correct in a strictly mathematical sense and the values are – at least not at the current stage of research – meant to be taken as exact. It does however give an impression of different levers that can be used to adjust the amount of integrated complexity in a delivery – and perhaps of the total amount of deliveries that constitutes a building (seen as a complex system).[140]

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[140] Conceptually a *relative integrated complexity value* could be calculated by adding all total values of the deliveries in a system and dividing it by the number of deliveries. A relative integrated complexity value would – at least theoretically – be comparable between systems (different buildings or different system structures for the same building)

Such levers could be including installation (INS) to a supply (SPL) or using an off-the-shelf (OTS) product instead of a bespoke (BSP) solution.

Examples

The highest possible value of integrated complexity would be a completely standardised (OTS) chunk (CHK) that is delivered, installed, and subsequently maintained (MNT) by one single supplier or at least with this single supplier as responsible for the entire service.[141] On the contrary, the lowest possible integration of complexity would be the – perhaps slightly unusual – situation where a completely bespoke (BSP) material (MAT) would be sold for pick-up (SAL) to be arranged separately by the receiver (manufacturer, client, or main contractor) who would also be in charge of it's later installation in the building or as nested into another delivery. However, most deliveries would be located in between these two extremes as e.g. a standardised (OTS) ventilation device (COM) delivered (DLV) for subsequent installation by a plumber or a cut-to-fit (C2F) delivery of simple façade cladding panels (MAT) installed onsite by supplier (INS).

The above examples do, as general (theoretical) examples, perhaps seem evident. However, applied in a design process with specific deliveries or as an overall design strategy they can potentially contribute to a more conscious selection of where design effort is located (read: where complexity is kept open) and where the effort is rather 'outsourced' to other (upstream) suppliers (read: where complexity is integrated). The following part III - 'Product' looks into specific examples of what integrated product deliveries are and can be and how they can be described using the terminology as defined in this part.

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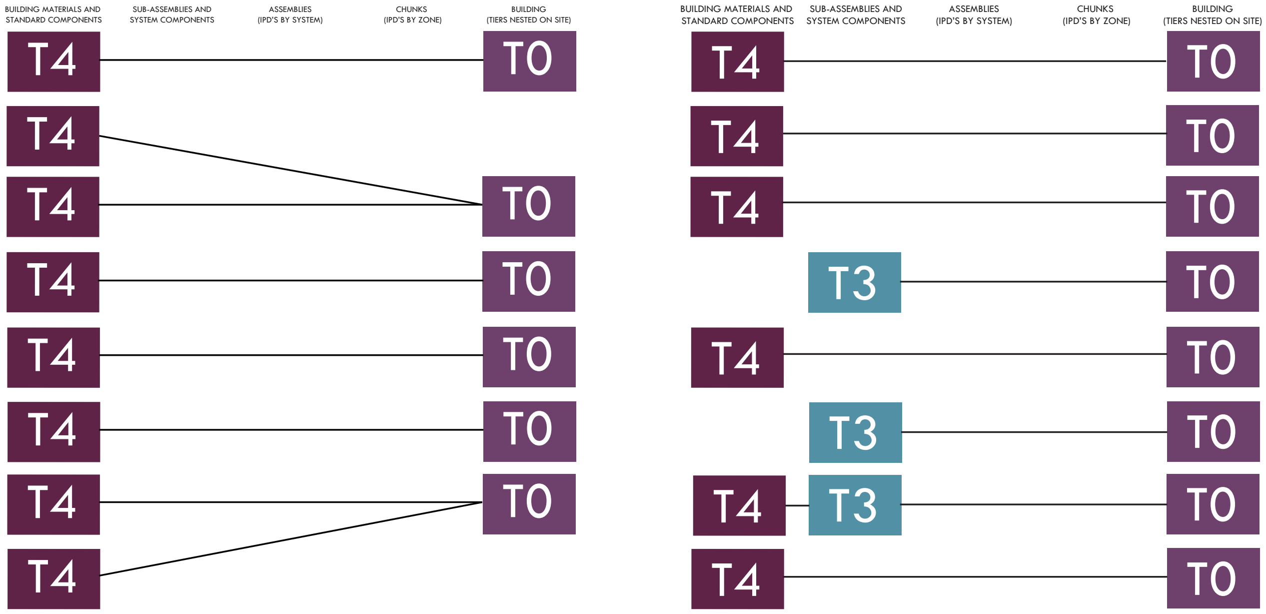
[141] Whether the actual installation and/or maintenance is done by a sub-supplier has little importance as long as the contractual relation is between supplier and manufacturer, client, main contractor or whoever is receiving.

PART III – PRODUCT

As opposed to the previous part II – ‘System’ being a theoretical exploration, the present part III – ‘Product’ represents a practical exploration and discussion of the building industry and its products as they are available on the market today – or perhaps will become available through discernable tendencies or development initiatives. A particular focus is the integrated product delivery as a new or emerging kind of building product. Through three chapters different aspects of products and integrated product deliveries in construction are examined. In *Commoditisation in architectural construction*, commoditisation is proposed as a useful concept for understanding integrated product deliveries as a qualitatively different kind of products compared to other kinds of delivery in construction. The notion of industrial ecology is also introduced as having special parallels to this kind of building products. In *Customisable architectural subsystems*, the delimitation and definition of integrated product deliveries as an entity are challenged through specific examples or types. Finally, *Development and classification of integrated product deliveries* starts with short historical intro to product development in construction leading to the description of a specific recent initiative. In the last part of the section the elaborated taxonomy of integrated complexity from the *Systems terminology* section is tentatively applied to different building products in a short catalogue-like format.

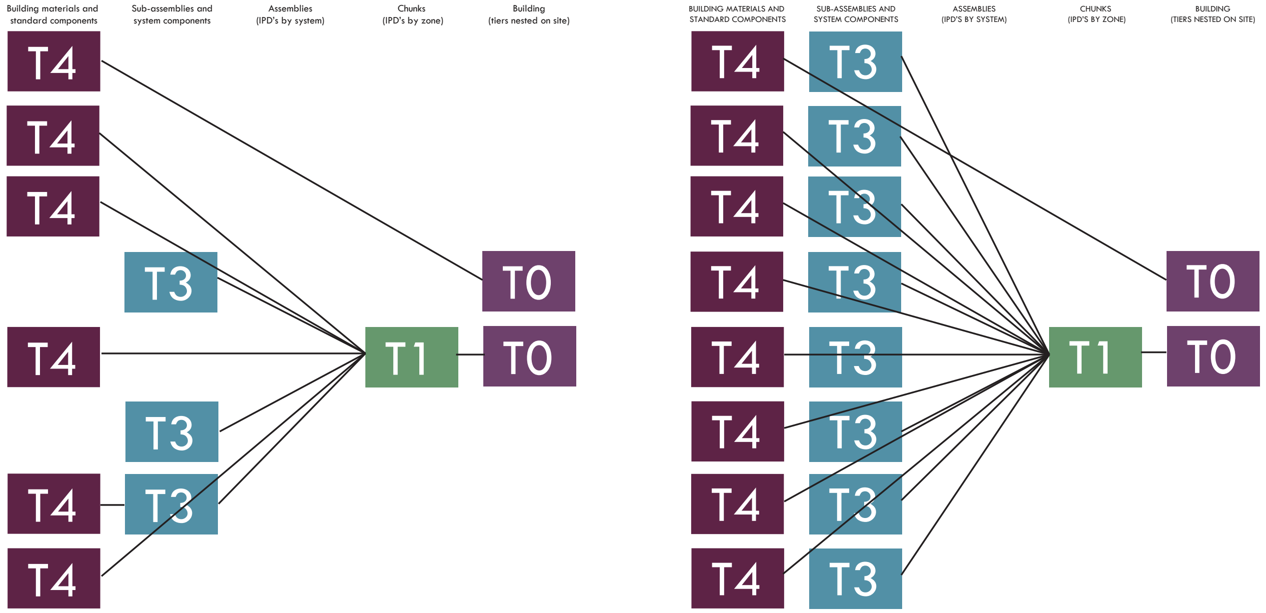
PART IV – MODEL

The two former parts II and III have mainly constituted explorations of theoretical and practical fields in order obtain a better understanding of the problem area and the main problem formulated as the scope of the thesis as well as establishing a terminology for the latter parts and – hopefully – for the field of knowledge in general. The present Part IV – 'Model' introduces the system structure model and the system structural view it provides as the primary outcome or product of the thesis. As described in the section of *Method and scientific approach*, the model has been developed iteratively with initial inspiration in the mentioned explorations and a primary case study conducted at KieranTimberlake. Subsequently, the first model draft has, as a hypothesis of a generally applicable model, been tested back on the primary case material as well as on three other secondary case studies as an analytical tool. This has worked partly as a discussion of the explanative power of the model partly as four separate analyses and discussions of the four different cases. The case-studies – particularly the primary – are fairly detailed and should consequently be seen as relevant in themselves as a way of further folding out aspects of the field of contemporary industrialised construction as well as giving valuable feedback for the evaluation and modification of the model.



SCENARIO A - TRADITIONAL ONSITE CONSTRUCTION

SCENARIO B - CONTEMPORARY ONSITE CONSTRUCTION



SCENARIO C - CONVENTIONAL PREFABRICATION

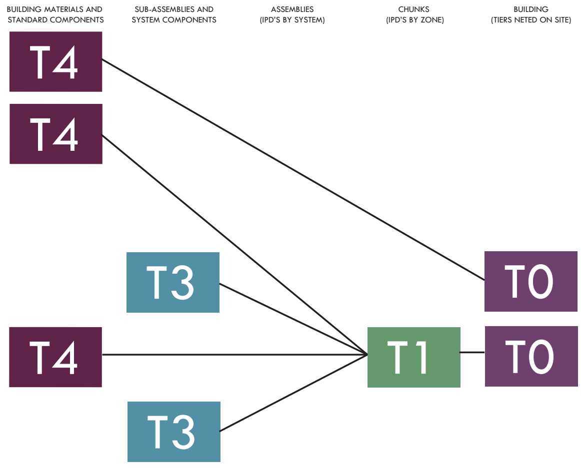
SCENARIO D - CONVENTIONAL BESPOKE PREFAB

FIGURE IV.1.6 A-F
DIFFERENT THEORETICAL CONSTRUCTION SCENARIOS EXPRESSED AS SIMPLE SYSTEM STRUCTURES

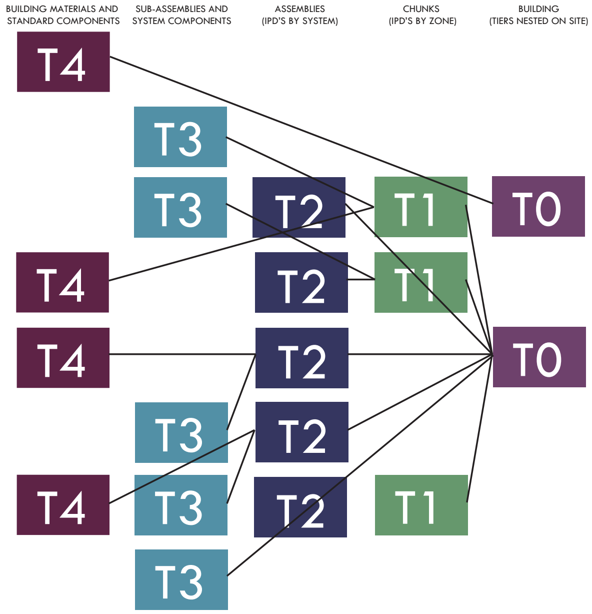
The total *integrated complexity value* expresses to what extent the architect (or other ‘customer’) can draw on knowledge and processes already embedded and nested into the delivery further upstream. It could also be explained as the degree of commoditisation of a delivery.*[6] The dimensions nuance the coding of the deliveries that each of them is graphically represented by a simple box in the system structure model.

[6] Ibid

SCENARIO E - CONVENTIONAL STANDARDISED PREFAB



SCENARIO F - FUTURE INDUSTRIALISED ARCHITECTURE



System structure scenarios

The system structure model has a generic character that potentially can be applied to any building project – industrialised or not – as a way of analysing and visualising the system structure in question.

As mentioned earlier, it expresses a *focussed* view representing a specific viewpoint i.e. the architect's, the contractor's, the manufacturer's etc. In each case the details or scale relevant for this view can be expressed in the system structure. Some of the deliveries (in focus) will appear nested as chains of subsystems, systems and supra-systems (from upstream to downstream tiers) with the building itself as the final integration point (T0). Others will be directly nested into the final building. A characteristic of the model is that it combines the idea, the process, and the product into one single system entity circumscribed by the concept of delivery and visually expressed like a box (See figures IV.1.4 and IV.1.5). A way to illustrate where a delivery of a certain integration level is nested into another delivery or into the final building is through the use of simple lines between the boxes. These lines are always directional downstream meaning that simpler deliveries (always) are nested into more complex ones with the building itself (T0) being the most complex of all.[7]

Simplified theoretical scenarios have been put into the generic model for showing (and testing) its explanative power in a simple way (see figure IV.1.6 A-F). Different ways of defining and organising deliveries in construction projects will be reflected differently in the model – read: result in different system structures. As an example traditional and contemporary onsite construction scenarios will have a large amount of the simple T4 and some T3 deliveries that are integrated directly at T0 – the building site. On the contrary standardised and customised prefab scenarios can have virtually the same T4 and T3 deliveries but with the

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[7] An exception to this directional rule is if the model, as it will be introduced later, is used to look at disassembly scenarios. In some cases lines can be found between deliveries on the same tier. This is a question of the 'granulation' of the model rather than an expression of inconsistency

IV.2 SYSTEM STRUCTURE ANALYSES

- introduction to the case analyses

INTRO

The following sections are the result of the application of the model to a number of case studies. As mentioned in the section *Method and scientific approach* in Part I – 'Frame', the primary case study at KieranTimberlake had at first the purpose of generating a draft for the model – a hypothesis about a *generally* applicable analytical model drawn from a *specific* study and analysis of an existing architectural project while simultaneously using the general insight gained from the theoretical and practical explorations as reflected in part II and part III. The choice of the primary case study has already been explained here.

Subsequently the model hypothesis was to be empirically tested on a number of secondary cases as analyses of the system structure of recently finished building projects. The selection of these secondary cases was chosen as to have supposed similarity with the theoretical (and simplified) scenarios developed from the first model draft. Furthermore cases were for supplementary variation tentatively chosen to represent different stakeholder perspectives concerning the building projects in focus i.e. the architect, the manufacturer, the contractor, the consultant etc.

SELECTION CRITERIA

As discussed more generally in the section of *Method and scientific approach* the applied qualitative research design with a limited number of cases excludes any claim of representativity in the cases. Furthermore, a *supposed* similarity with the theoretical scenarios is not the same as actual similarity. However, by trying to choose cases with certain similarity with these theoretical scenarios that through the model does express variation in system structure, a preliminary assumption is that these (secondary) cases will equally express the same or at least *some* differences in the system structure expressed through the model. The different stakeholder perspectives should further accentuate this aspect of variation in the system structure. Even if this turn out not to be the case the secondary cases would serve as an attempt to test and possibly *modify* the model as a hypothesis of a generally applicable model as stated earlier. Alternatively the model could be rejected as lacking any or at least significant explanative power within the studied field – industrialised architecture and the transition from a more traditional craft based approach. The exercise of the following analyses is thus *primarily* to test the model and its usefulness and *secondarily* to actually bring out interesting features from the specific case analyses. This prioritisation is due to the explorative stage of the current research and the model development.

The secondary case studies were carried out as shorter compressed versions of the format used in the primary case study. By using the experience from this initial study many of the same advantages of this 'on location' study was transferred to a shorter format. The secondary case studies consist of 2-4 days of field studies in a company and dealing with a specific recently finished building project. The project was chosen as well as key individuals (informants) located before arrival through introductory correspondence. The research format included a) interviews with several key individuals involved in the chosen project b) direct access to full project material (on location) c) flexible timing of appointments with key individuals, concerning access to project material d) check-out session with clearance of proprietary issues and e) supplementary understanding of the work methods and work culture in the company by being physically present in the environment for several days.

CASE SELECTION

The following companies have been selected, each representing their specific perspective or viewpoint and with selected recently built cases as the object of study.

a) Company: KieranTimberlake
  - An American architectural office located in Philadelphia, USA with a special focus on industrialised construction and the use of integrated products in architecture,
  - The architect's perspective
  - Built case(s): Cellophane House™, a prototype house made for an exhibition at the MoMA in New York and Loblolly House, a holiday home made for one of the KieranTimberlake partners

b) Company: Scandibyg
  - A Danish housing manufacturer located in Løgstør, Jutland. Scandibyg is specialised in prefabricated volumetric elements thus representing a high degree of completion,
  - The manufacturer's perspective
  - Built case(s): The day care facility Ellepilen made for the City of Copenhagen and a large number of dwellings within a social housing programme called Almenbolig+

c) Company: NCC Construction
  - A major Danish contractor located in Hellerup, Copenhagen. NCC is specialised in property development and turnkey contracting within construction
  - The contractor's perspective
  - Built case(s): Company House Vallensbæk (office building) and a general office building concept called DK-kontorhuse (DK-office buildings)

d) Company: Arup Associates
  - A British building consultant (subsidiary of Arup) located in London. Arup Associates (always) integrates architecture, structural engineering, environmental engineering, cost consultancy, urban design, and product design within one (multidisciplinary) studio
  - The architect/consultant's perspective (integrated)
  - Built case: Ropemaker Place as a 'shell & core' high end office building development in London

V.3 CONCLUSIONS IN SHORT

- revisiting main problem, hypotheses and research questions

The two previous sections have sought to recapitulate and discuss both the pivotal as well as more secondary findings of the present research on three levels concerning respectively methodological aspects and experience, model development, as well as results from the specific analyses of the case studies in part IV – 'Model'. The attempt to span all three levels in one single thesis produces a large material that, admittedly, can make it difficult to get an overview and draw out explicit and concise conclusions of the work. This last section is intentioned to sum up the findings in a short format by revisiting the main problem and the hypotheses with their respective research questions as they were formulated in part I – 'Frame' and part II – 'System'. A final paragraph touches upon the issue of further development perspectives and the need for future research.

MAIN PROBLEM AND GOAL

The main problem was formulated as:[53]

How can systems thinking 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?

The derived goal then followed as:
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.

The notion of *system structure* and the system structure model, as it has been presented, represent the author's proposal for an analytical structure – or tool – that can, it is asserted, help clarifying the potential of industrialised construction as positively enabling. This assertion is substantiated by the meaningful results of applying the model in its present stage to four different case studies. By integrating inspirational systemic elements from four different theoretical

[53] See *Definition of scope*, I.4, p. 18

fields as well as from a practical exploration of products and commoditisation in architectural construction, the system structure model draws on several sources of systems thinking in order to introduce a systemic level in architecture and construction that lies between general construction techniques and specific architectural results. This level – grasped by the system structure model – seeks to bridge the apparent gap between architectural ideation and its subsequent realisation by establishing a systems view on buildings and architectural design that can facilitate the handling of the increased complexity of both specialisation and technical development. Through the use of flexible constituent elements – termed *deliveries* with varying degrees of *integrated complexity* – the model visualises how architectural wholes (ideas) are appropriately put together as assemblages of what the current and future building industry is capable of producing (realisation as process and matter). A multi dimensional understanding of integrated complexity – an integration taxonomy – has been introduced as a way to nuance what deliveries and in particular integrated product deliveries as an emerging entity in architectural construction are, and how they can contribute to handling complexity in architectural construction through different preparation, standardisation and service levels. The taxonomy does not exclude supplementary dimensions.

Used actively, the notions of system structure, integrated complexity and the system structure model potentially bring idea closer to realisation in architectural construction. However, at its present stage, the model stays mainly analytical on the strategic and theoretical level. Still, it enhances understanding and overview concerning industrialised construction in particular and is thus applicable even on a practical level although it will still need further elaboration in order to become a true and effective operational tool for direct use in architectural practice.

HYPOTHESES

The thesis lines up five hypotheses – one methodological and four theoretical. The latter are derivations of the main question of the thesis but with regard for the respective fields of exploration.

Methodological

The methodological hypothesis was formulated as:[54]

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[54] See *Method and scientific approach*, I.5, p. 23

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