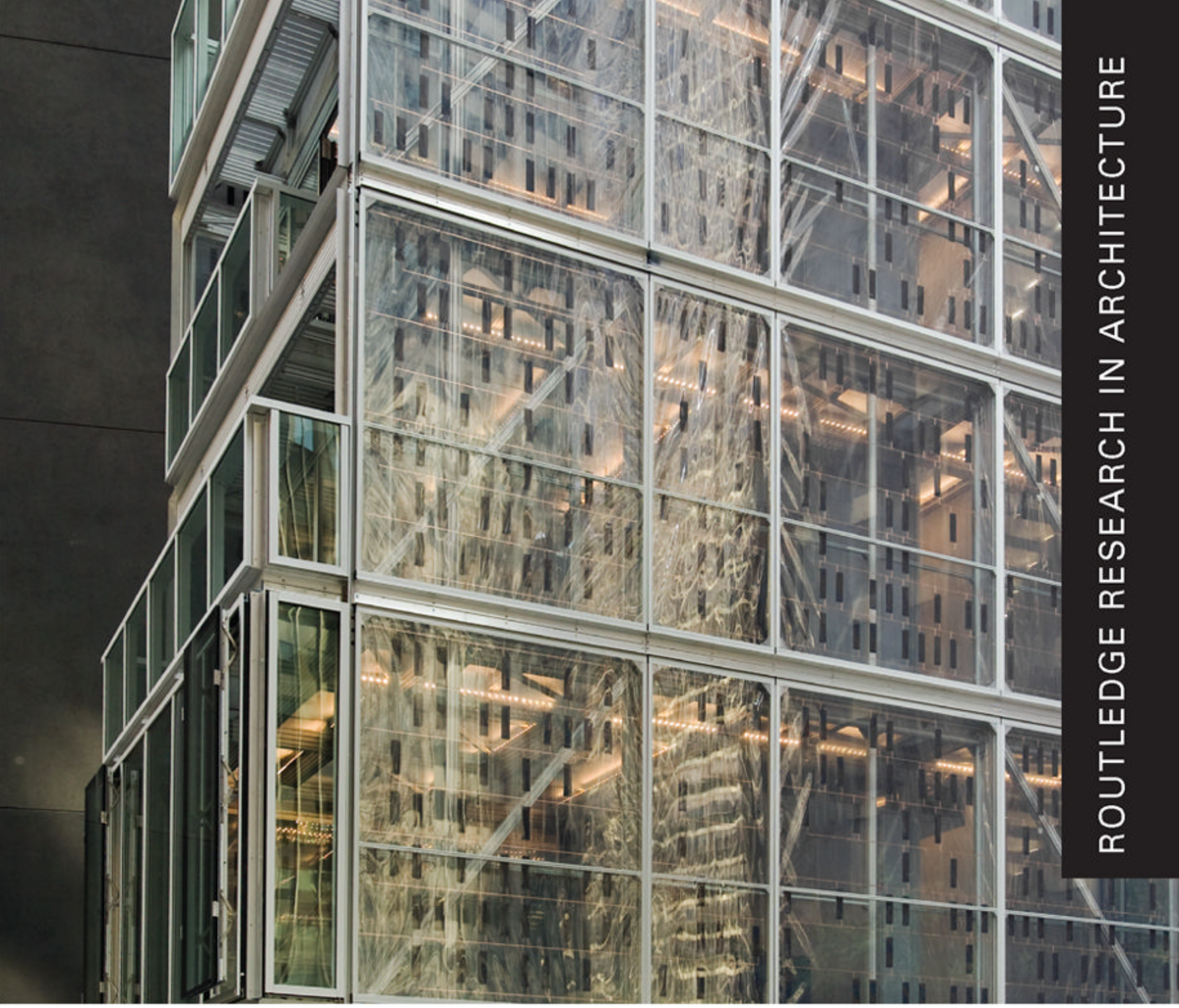

ROUTLEDGE RESEARCH IN ARCHITECTURE

ARCHITECTURAL SYSTEM STRUCTURES

Integrating design complexity in industrialised construction

KASPER SÁNCHEZ VIBÆK

ROUTLEDGE

Architectural System Structures

This book proposes a system structure in architectural design that conceptualises 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 model 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 architectural design. Kasper Sánchez Vibæk's ambition is to bridge an apparent and increasing gap between architectural ideation and the way these ideas are brought to life as real physical manifestations of our built environment.

In line with the so-called systems sciences the book rejects the prevalent scientific view that the degree of detail 'automatically' enhances understanding and explanative power of complex phenomena. It establishes the idea of a systems view on buildings and architectural design that through the use of flexible constituent elements facilitates discussion and decision making about how architectural wholes are appropriately put together as assemblages of what the current and future building industry is capable of producing.

Based on several years of detailed research into the architectural consequences of construction when exposed to industrialised production techniques and systems, *Architectural System Structures* represents a new way to look at what is already there and is useful for all those interested in the processes of architectural creation and realisation specifically attached to time, place and cultural context.

Kasper Sánchez Vibæk is former Associate Professor at CINARK, the Royal Danish Academy of Fine Arts, School of Architecture, Copenhagen, Denmark. Presently working with system architecture, quality, and sustainability in Kvadrat Soft Cells, who develop, produce and sell acoustic solutions with high design content for construction projects worldwide.

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Architectural System Structures
Integrating design complexity in industrialised construction
Kasper Sánchez Vibæk

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Integrating design complexity in industrialised construction

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Note

1 Realdania is a major private Danish 'strategic foundation created with the objective of initiating and supporting projects that improve the built environment.' http://www.realdania.dk/English.aspx accessed on September 3, 2011.

Introduction

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 and Alexander 1965: 161)

Industrialised architecture

The concept 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! While industrialised architecture as field of research still has the architectural result as object, it quickly also involves the *organisation* and *production processes*, *and* their industrialisation that leads to this result. Architecture is generally about creating the best possible physical surroundings for human life, and decisive for the architectural solution space and final result of all creation is not only the material but also the tools, the related techniques and the organisation of people around these.[1] Rather than dealing with a specific result, industrialised architecture is a particular way to construct or assemble buildings – and a way to *think* about architecture and construction – that, however, has significance for the 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 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 off-site 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. An important question here becomes: 'What is then industrialisation of *construction*?'

Division of labour and the modularisation of construction[2]

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 described the division of labour as one of the most efficient ways to improve the productivity performance of companies hence increasing the wealth of nations.[3] His best known example is a pin-manufacturing company. After splitting up the process of making pins into different subtasks – thus specialising the workers – productivity rose by a factor of 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 1960s, 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.[4] Construction specifications, i.e. drawings, had a substantial set of conventions, allowing a few instructions (as e.g. lines and signs) to 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, are 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, 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 premise 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.[5] 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

The present monograph claims that the architect has a special integrative role among and in relation to the stakeholders involved in construction.[6] *Etymologically* speaking architect means *master builder* or *supreme carpenter* (Becker-Christensen 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 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 and a new, more complex, division of labour is a *condition* – not just an option – that architects and other stakeholders in construction have to respond to but simultaneously also stress that, architecturally speaking, industrialisation is a *means* not a goal in itself, then perhaps the discussion is less controversial and can become more fruitful. Thus the discussion of industrialisation of 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 an alternative to traditional mass production. A present parallel tendency is found within the construction sector with reference to and as an alternative to the first wave of industrialisation in construction in the 1960s (Beim, Vibæk and Jørgensen 2007: 25; Jørgensen 2007). While the first industrialisation wave in construction was heavily standardised in its architectural expression and almost became an architectural style in itself, the present industrialisation of construction and architecture points towards a systematisation of project-specific and context sensitive solutions.

Product architecture

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 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, a system level is established that sustains 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 gap between how architecture is conceived and how it can be produced is enhanced due to both technical as well as economical causes. A way to identify and work systematically with 'the product architecture of contemporary 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!

Scope

The research behind this book has had the overall purpose of examining what role system design, systems thinking and systemic building concepts play in relation to modern industrialised construction with a focus on how this world of ideas is expressed in architecture.

Main question

How can systems thinking help bridge 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?

Goal

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.

Work packages

The research, the main question and the goal was operationalised into three main 'work packages':

1 a theoretical study;
2 an empirical study;
3 model generation.

Although overlapping in practice, the work packages are expressed in the sequencing of the following parts (I to III) of this book.

The elaborated model presented in Part III – ‘Model’ represents the *analytical structure for clarifying the potential of industrialised construction*. The model is used for generating theoretical scenarios as well as for analysing empirical evidence. These exercises contribute to the qualification of the model and its possible explanative power and application within both architectural research and practice.

Non-scope

The model is not – at first – developed as a software tool. The core of this initial model development is the *content* and its *explanative power* rather than its technical functionality and performance. Focus on the two latter aspects would move a lot of effort (work) into *programming* which needs to be preceded by a proper *understanding* of what should actually be programmed. What need the model is supposed to cover and in what way comes first! This does, however, pose certain limits to the complexity and the contained data layers of this preliminary version of the developed model in order to make it manually applicable.

The model is not a production planning tool and (intentionally) omits aspects like time and economy. Again this is in the first place to keep coding parameters and the visual result of a coding relatively simple. Although later, possibly software based, versions could include such (and more aspects) it is so far an open question whether these *should* actually be integrated. A risk could be that too many and too specific parameters reduce the flexibility of the model and thus possibly its applicability to *early* architectural design phases where many aspects (should?) remain on an abstract level in order to keep the architectural solution space sufficiently open. A stance here is that the field of production planning and cost control is much better managed through the wide range of existing techniques, tools and software programs already available that integrate many technical aspects that cannot be included within the framework of this research.

The model does not deal directly with the question of architectural quality. However, in the hands of the right person (e.g. a qualified architect) it can support the architectural design work by, for example, *reducing complexity in focus* as an intermediate model. This can, it is assumed, enhance the probability of architectural quality in the final result. In other words: it is a tool to create a better overview and facilitate the process by *clarifying the potential of industrialised construction* scenarios within architectural design.

Contribution to a wider knowledge context

In general the subject of industrialisation within construction seems more prevalent in Western industrialised countries, such as those in Northern Europe or similar climates where the weather factor combined with high labour costs encourages the development of more automated and off-site dominated production techniques. However, the current project points out that this *can never* *be an either/or*. Architectural creation and construction will always be a combination of on the one hand on-site and perhaps more labour intensive craft based work and, on the other hand, off-site prefabrication of varying degrees of automation and of integration of the final product delivered.

The ambition is – although this project still mainly stays on the theoretical level – to bring the theoretical conceptualisation of this special field of knowledge closer to implementation in architectural and construction practice. The main problem as stated in the introduction is an apparent gap between how architecture is conceived and how it is or can actually be produced. The model developed is intended as an analytical tool for enhanced understanding and potentially as a proactive design tool for early design phases. Through early visualisation of industrialised production scenarios within architecture, it becomes more probable that architects or other professionals can influence or make active demands to an industry that often (and perhaps logically) seem dominated by technical and economic aspects of production rather than visionary architectural thought.

In a context where the creation of architectural artefacts changes rapidly partly driven by new technological possibilities (pull), partly forced by external factors[7] (push) the model is proposed as a tool to help describe and handle the structural complexity of any building through the procedural and material organisation behind their immediate appearance.

Organisational location and genesis

The present monograph is the result of research conducted at CINARK – Centre for Industrialised Architecture. Organisationally located under the Institute of Architectural Technology at the Royal Danish Academy of Fine Arts, School of Architecture. Since start-up in 2004 CINARK has 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. Architectural quality is a holistic concept than cannot easily be reduced or atomised into clear, quantifiable sub-parameters that normally characterise an industrialised logic. This tension between on the one hand the constituent (industrialised) parts and processes and on the other hand the architectural whole has been a central research focus and has led to the present examination of systems and systems thinking in architecture.

Structure of the book

The book is structured around four parts that express a logical progression in time and knowledge development from a theoretical exploration over a practical exploration to the proposal and application of an analytical model ending in a final discussion of the findings.

Part I is called ‘System’. This part is the theoretical exploration of the book. Here different theoretical paths of systems thinking are examined with reference to the research problem defined in the Introduction. Chapter 1 is a historical view of systematic thought in architectural theory. Chapter 2 deals with different applied classification systems and taxonomies in construction as opposed to architectural creation. Next follow two chapters on other kinds of systems theory outside the field architectural construction such as industrial production theory and general systems theory. Chapter 5 seeks to draw out and define central concepts as they are subsequently used in this book as well as to establish a particular taxonomy of integrated complexity.

Part II – 'Product' – is an exploration of the practical reality within architectural construction and its current level of industrialisation and systemic elements. Chapter 6 deals with the emergence of system products within the field of construction seen as combinations of matter, process, and thought and seeks through specific examples to show how a movement from construction of projects to production in projects can possibly enhance industrialisation of construction. Chapter 7 deals with the application of the taxonomy established in Chapter 5 to such system products in a kind of initial product catalogue. Finally, Chapter 8 introduces industrial ecology as a strategy for discrete controlled products.

Part III – called 'Model' – is the presentation of a model as the primary theoretical outcome of the research. The elaborated model represents an analytical structure or a supportive tool applicable to contemporary and/or future architectural construction. Chapter 9 presents the model its current state as a way of visualising system structures in architectural construction. Subsequently the model is applied as an analytical tool to a series of cases (case studies).

Part IV – 'Reflection' – is a discussion of the most important findings from the case analyses and the general applicability of the proposed model. The final chapter 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.

Notes

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

2 This paragraph is partly taken from Beim, Nielsen and Vibæk (2010: 77f.).

3 Wealth of *nations* is not necessarily coincident with general wealth of the individual citizens.

4 The British sociologist Anthony Giddens uses 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; Giddens 1990).

5 BMS = Building Management System is a computer-based control system that controls and monitors the building's mechanical and electrical equipment. Available online at http://en.wikipedia.org/wiki/Building_management_system (accessed 8 August 2011).

6 For a similar assertion, see Bachman (2003: 6).

7 Economic, ecological, organisational factors, power relations, decline of the old crafts, etc.

Part I

System

The introduction and the scope of this book point towards 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 first a theoretical and then a practical exploration. These explorations correspond to respectively Part I – 'System' and Part II – 'Product' and will be addressed through a number of sub-questions. Finally, the main question is addressed through the introduction of the *system structure model* found in Part III – 'Model'.

The present Part I, 'System', forms the theoretical backdrop of the book. Through five chapters it examines and evaluates on systems theory and systematic thought applicable within the scope of the book in the form of a scanning within different fields of knowledge and a concluding attempt, on basis of the findings in these (system) fields in order to establish a consistent terminology for the book as well as for use in the general discussion of systems thinking in architecture and construction. The chapters of this part are the following: 1. Systems in architectural theory; 2. Classification systems in construction; 3. Industrial production theory; 4. General systems theory; and finally 5. Systems terminology for architecture and construction.

The five chapters do not form an exhaustive evaluation of systemic 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 in systematic ways or as being systems. This is meant to work as a short ideographic contribution within each field of knowledge as well as a source of inspiration for how the present book 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 chapter advances a hypothesis derived from the main question and goal of the book that subsequently leads to one or two research questions examined within the particular fields.

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1 Systems in architectural theory

Introduction

First of all, it is evidently important to have a look at how architectural theory historically has dealt with architecture and architectural creation as a system or a compound of subsystems. What has been subject to classification and categorisation, why or with what purpose, and finally, how has it been approached? The following chapter looks into how architectural theory has treated the theme of systems and systems thinking. Through a number of examples from architectural theory a collection of points will be extracted in order to be used in the later parts of the monograph – or (perhaps) avoided as apparent blind alleys.

Hypothesis and questions addressed

A gradually growing division has appeared between on the one hand how architecture is conceived as design (conceptual idea and form) and, on the other hand, how it can actually be produced (construction).

The hypothesis is addressed through the following two research questions:

1. What are the main constituent 'elements' of architecture as expressed in architectural theory?
2. How can the apparent division between design and production/construction be substantiated and explained through architectural theory?

The constituent elements of architecture

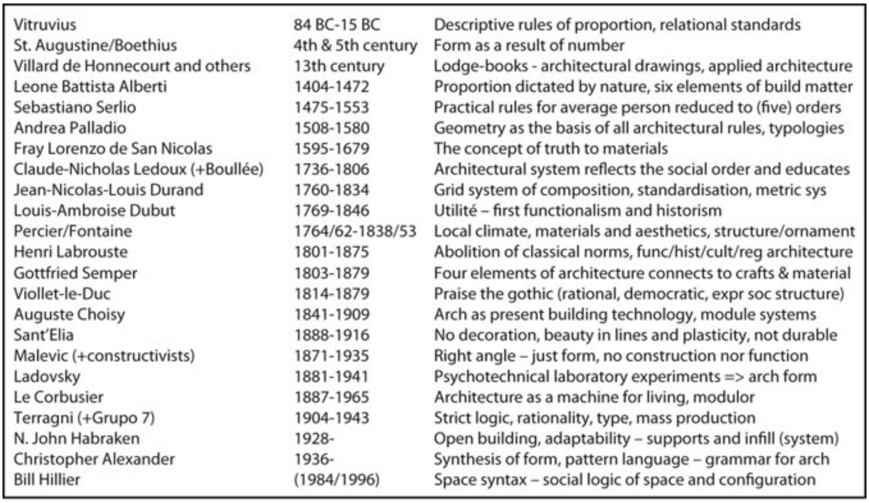
Any theory can be seen as a systemisation or a structure of thought. However, it is not just a systematisation of architectural thought we are looking into here. The object of systemising the theoretical categories should furthermore address some kind of basic elements of the architecture it seeks to describe. These theoretical categories, or basic elements, can present considerable variation in nature according to the different theories or systems they circumscribe. These can be about aesthetics/proportion, form/geometry,[1] function, material, construction, technology, typology, psychophysical laws,[2] social, cultural or economic issues or combinations of these into a coherent whole. The selected examples represent several kinds of these basic elements. It could be said that the *character* of the constituent elements of architecture within the different systems varies and that this variation to some degree reflects the *purpose* of the theoretical system in question.[3] The historical context equally has importance for the individual theoretical systems and their basic elements and they consequently have to be related to this context. A strongly religiously dominated society such as present day India or central Europe during the Middle Ages probably produce other architectural systems and appurtenant elements compared to a distinctly secularised or technocratic society such as present day Germany or the former Soviet Union. Theories and elements have cultural foundation. The theoretical system and its constituent elements make up a 'language' or syntax that makes it possible to talk about (or create!) architecture and buildings in a particular way. However, this also means that a theoretical system of elements cannot be neutrally descriptive even if this is initially the intention. This is pointed out by *Critical Theory* that claims that all science has a normative standpoint. Consequently, the knowledge it produces must be held critically up against this standpoint. This on the other hand makes it possible to pose the same general demands of clarity of argumentation, coherence of the argument and documentation for all sciences – natural, humanistic and social.[4] The particular architectural systems or theories must be seen both as supporting as well as supported by and originated through architectural practice and the cultural setting it forms part of. Architectural theory always oscillates between being reactive and proactive:

> . . . there is a certain ambiguity in the influence on theory on built architecture. It can lay down norms which make it almost impossible to produce really bad architecture; at the same time, making aesthetic conventions normative can stifle, or at least hamper creativity.
>
> (Kruft 1994: 17)

The scanning of architectural theories has been limited to a Western perspective while being conscious that Asian architecture and architectural philosophy deal extensively with the same questions.[5] Located in and primarily dealing with a Western and northern European cultural environment the choice has been to concentrate on architectural theory embedded in this context. The presentation does not, as mentioned, partly limited by the scope of the current research, form an exhaustive overview of systems in architectural theory but rather looks for inspiration that nurtures the specific goal of the book which is to propose an analytical structure or a model.[6] The selected examples can subsequently not be considered as a historical presentation describing an evolution step by step. The risk of some fragmentation or arbitrariness in the selection of examples is accepted as a condition within the current scope and extent of the task.

Concerning the first paragraphs of this chapter, Hanno-Walter Kruft's *A History of Architectural Theory from Vitruvius to the Present* has been examined, and his definition of architectural theory approached as a historical review has been adopted (Kruft 1994). For practical reasons Kruft restrains his review on architectural theory to written sources thus excluding highly ambiguous analysis and interpretations of buildings themselves or unrecorded practice.[7] Pattern books primarily based on illustrations with some text are also included in his review.

All built architecture is based on principles of some kind – a systematic level of thought that could be generalised into a theory or a philosophy of the architecture in question. This does not, however, mean that these principles are articulated or can be reconstructed (in a written or build form) as they were conceived. Buildings do not necessarily, and only rarely in an unambiguous form, reveal the *architectural* systems behind their physical manifestations (ibid.: 13). Hence, the focus on the written sources. Kruft states that: 'The majority of programmes that purport to be theories of architecture seek to combine aesthetic, social and practical considerations in an integrated whole' (ibid.: 14) and he then proceeds to a definition of architectural theory as 'compris[ing] any written system of architecture, whether comprehensive or partial, that is based on aesthetic categories. This definition still holds even if the aesthetic content is reduced to the functional [categories]' (ibid.: 15). From the slightly different and enhanced view that will be used in this book the same could be the case even for architectural systems based on other types of basic elements, as exemplified above. Figure 1.1 shows an initial scanning of system elements in architectural theories, each with a couple of keywords.



Vitruvius	84 BC-15 BC	Descriptive rules of proportion, relational standards
St. Augustine/Boethius	4th & 5th century	Form as a result of number
Villard de Honnecourt and others	13th century	Lodge-books - architectural drawings, applied architecture
Leone Battista Alberti	1404-1472	Proportion dictated by nature, six elements of build matter
Sebastiano Serlio	1475-1553	Practical rules for average person reduced to (five) orders
Andrea Palladio	1508-1580	Geometry as the basis of all architectural rules, typologies
Fray Lorenzo de San Nicolas	1595-1679	The concept of truth to materials
Claude-Nicholas Ledoux (+Boullée)	1736-1806	Architectural system reflects the social order and educates
Jean-Nicolas-Louis Durand	1760-1834	Grid system of composition, standardisation, metric sys
Louis-Ambroise Dubut	1769-1846	Utilité – first functionalism and historism
Percier/Fontaine	1764/62-1838/53	Local climate, materials and aesthetics, structure/ornament
Henri Labrouste	1801-1875	Abolition of classical norms, func/hist/cult/reg architecture
Gottfried Semper	1803-1879	Four elements of architecture connects to crafts & material
Viollet-le-Duc	1814-1879	Praise the gothic (rational, democratic, expr soc structure)
Auguste Choisy	1841-1909	Arch as present building technology, module systems
Sant'Elia	1888-1916	No decoration, beauty in lines and plasticity, not durable
Malevic (+constructivists)	1871-1935	Right angle – just form, no construction nor function
Ladovsky	1881-1941	Psychotechnical laboratory experiments => arch form
Le Corbusier	1887-1965	Architecture as a machine for living, modulor
Terragni (+Grupo 7)	1904-1943	Strict logic, rationality, type, mass production
N. John Habraken	1928-	Open building, adaptability – supports and infill (system)
Christopher Alexander	1936-	Synthesis of form, pattern language – grammar for arch
Bill Hillier	(1984/1996)	Space syntax – social logic of space and configuration

Figure 1.1 Timeline of constituent elements of architecture in architectural theory [Author's scheme]

Much of the classical architectural theory deals with the search for universal laws or guidelines concerning what is considered to be 'true' physical form. The logic of the system prescribes or suggests a certain combination of its constituent elements for a given situation. In modern architectural theory the content in some cases become more political or critical of the society it forms part of. Suddenly it deals less with controlling the built form and its aesthetics and is more about the role of architecture as a forming and *trans*forming force in society. Through a kind of transcoding or rewriting of systems of thought from other (philosophical) fields and disciplines into architectural code, architectural theory and architecture itself participate in the general cultural and political debate of society. The *modernist* movement, for example, seeks to reconcile or mirror architectural design with the rapid technological advancement in society as expressed in Le Corbusier's architecture as a 'machine for living'. In the case of, for example, *postmodernism*, the parallel philosophical 'fall' of the big ideologies on the other hand produces an interest in purely abstract form or eclecticism, where the coherence of the work is created as unique narratives that draw simultaneously on many different theories or historical references without any coherent system – or as the American architect and theorist who consolidated the term, Charles Jencks, writes:

> It can include ugliness, decay, banality, austerity, without becoming depressing. It can confront harsh realities of climate, or politics without suppression. It can articulate a bleak metaphysical view of man – Greek architecture or that of Le Corbusier – without either evasion or bleakness. The extraordinary power of tragedy when it is really tragic, or inclusive architecture when it really unifies disparate material, is its disinterested fulfilment.
>
> (Jencks in Hays 2000: 309)

In short, systems in an architectural context are to some extent always representing a certain time, societal situation and stage of technology.

Vitruvius and antique architectural theory

Vitruvius' (84–15 BC) ten books represent the first preserved architectural theory. Others are known to have existed but have been lost. However, Vitruvius was the first to cover the entire field of architecture in a systematic form (Kruft 1994: 21). About the aim of his effort Vitruvius writes:

> I have drawn up *clearly defined rules*, so that by studying them closely you will be able to judge for yourself the quality of the buildings you already created and of those to come, for in these books I have laid down *the principles of architecture*.
>
> (Vitruvius cited in Kruft 1994: 23 – author's emphasis).

Building principles

Vitruvius introduces the famous concepts of *firmitas, utilitas* and *venustas* – durability, convenience and beauty (Vitruvius, Book I, ch. 3). This triad roughly divides architecture into aspects of respectively construction (i.e. good foundations and materials), spatial distribution (i.e. proper arrangement and type), and aesthetic qualities (i.e. good taste and correct proportions). This is to be reached through the fulfilment of six fundamental principles (not necessarily presented in the most logical order!):

Order	gives measure and detailed proportioning of each separate part of a building and relate this to the general proportioning of the building as a whole (= symmetry, below).
Arrangement/ disposition	is dealing with the overall layout and the positioning of the different parts in their proper place (in plan, elevation and perspective) according to the character (type) of the work.
Eurhythmy	is the resulting beauty and fitness of the order and symmetry.
Symmetry	treats the interrelation between the different parts of the building and their relation to whole by reference to a (chosen) standard unit of measure.
Propriety/décor	is the correct appearance based on approved elements or principles from precedent. The use of orders comes under this heading and points beyond mere aesthetic rules to (cultural) conventions of different types and their use.
Distribution/ economy	is about the construction management i.e. selection of materials and cost control as well as choosing a level appropriate to the class of the client and the type of the building.

Vitruvius' six principles are primarily addressing the concept of beauty from the triad above and centres particularly around the principle of symmetry and the subordinate concept of proportion as the heart of his treatise: 'There is nothing to which an architect should devote more thought than to the exact proportions of his building with reference to a certain part selected as standard' (Vitruvius, Book VI, ch. 2). Through symmetry and proportion Vitruvius establishes relational standards as opposed to *absolute* standards. As an analogy of symmetrical proportions that are to be found in the design of temples Vitruvius uses the body, where each element or member according to him has its specific proportional relations to other parts and to the body as a whole.

For temples however, the specific proportions specified also depend on what style or class they are to be. Most known are what would later become the established orders of columns but other details such as the doorways are equally specified in relation to the whole and concerning its internal proportions (order and symmetry = eurhythmy):

> In the Doric [doorway], the symmetrical proportions are distinguished by the following rules. Let the top of the corona, which is laid above the casing, be on a level with the tops of the capitals of the columns in the pronaos. The aperture of the doorway should be determined by dividing the height of the temple, from floor to coffered ceiling, into three and one half parts and letting two and one half thereof constitute the height of the aperture of the folding doors. Let this in turn be divided into twelve parts . . .
>
> (Vitruvius Book IV, ch. 6)

Much of Vitruvius' theory was based on (rough) generalisations of empirical evidence. Even though he explains the emergence of rules as evolving from man's 'vague and uncertain judgements to fixed rules of symmetry' he also gives them absolute validity (Kruft 1994: 24). The British historian John Ward-Perkins relates the nature of Vitruvius' concept of symmetry and proportion directly to an architecture of the time based on modular thinking such as the Pantheon in Rome:

> The type of rules about the application of proportions that fills the pages of Vitruvius' [ten books] arise naturally in an architecture that depends, for its execution, on the use of multiple fundamental units, or modules, or its simple derivations.
>
> (Author's translation of Perkins in Spanish edition 1989: 88)

Building types

Vitruvius also establishes *functional* categories or standards of building types. Apart from clock making and construction of machinery which Vitruvius considered as separate branches of construction, buildings are divided into two general types: public facilities and private buildings. Public buildings are then subdivided into three functional classes: defensive, religious and utilitarian. The latter includes harbours, markets, colonnades, baths, theatres, promenades (Book I, ch. 3). In his detailed treatment of the individual building types Vitruvius does not strictly follow the fundamental concepts or relational standards that he claims to be universally binding (Kruft 1994: 28). There is no systematic connection between the *relational* standards and the *functional* standards established. However, from the renaissance and on interpretations of his work he has exerted enormous influence on built architecture.

The Renaissance and Alberti

According to Kruft the Middle Ages produced no architectural theory on its own (ibid.: 40). Neither did Vitruvius' system have any significance in this period. Some, as St Augustine (AD 354–430) and Boethius (AD 480–525) promoted with outset in Pythgorean, Platonic and Neoplatonic philosophy '[t]he importance of number as the principle underlying cosmic order . . . (ibid.: 36) and developed aesthetic systems based on numerical proportion that also influenced architectural expression.

The writings of Leone Battista Alberti (1404–1472) are considered one of the most significant contributions to architectural theory ever (ibid.: 49). Vitruvius, although claiming absolute validity, de facto was mostly *descriptive* about how buildings up to his time *had been* built. Alberti further develops the antique tradition and is *prescriptive* about how buildings *should be* built (Alberti/Rykwert 1992: x; Kruft 1994: 44). Heavily drawing on ideas and concepts by Vitruvius, Alberti also presents his work *De re aedificatoria* – on the art of building – in ten books. About his aim Alberti writes:

> We have undertaken . . . to inquire more fully into his (the architect's, ed.) art and his business, as to the principles from which they are derived, and the parts of which they are composed and defined.
>
> (Alberti 1992: 5)

Building principles

Alberti adopts Vitruvius' basic triad of *firmitas, utilitas* and *venustas*[8] but further develops their underlying principles in separate books (of the ten) – still, as his predecessor, giving primacy to beauty over function and durability. *No better way can a building be protected and preserved as through the beauty of its appearance* (ibid.: 156). Ornament, however, is only a complement to his definition of beauty which is a much broader concept dictated by *concinnitas* – the absolute and fundamental rule (of beauty) in Nature. A building is conceived as a body of lineaments and matter. The former (as lines and angles) being product of thought whereas the latter (in form of building materials) is obtained from nature. Lines and angles define and enclose the surfaces (of material) in order 'to prescribe an appropriate place, exact numbers, a proper scale and a graceful order for whole buildings and for each of their constituent parts . . . ' (ibid.: 7) The form and the beauty of it is in Alberti's definition detached from the material and its properties which – in some cases – apart from ensuring *firmitas* becomes a supplementary ornamental layer (ibid.: 163). The analogy to mathematical values as found in nature and natural organisms in the definition of beauty as sets of relational standards of proportion is similar to Vitruvius' theory.

Alberti, however, through *concinnitas* introduces an overruling principle that as innate capacity enables man to correct relational standards according to the specific application:

> The shapes and sizes for the setting out of columns, of which the ancients distinguished three kinds according to the variations of the human body, are well worth understanding . . . Having taken the measurement of a man they discovered that the width, from one side to the other, was

> a sixth of the height, while the depth, from navel to kidneys, was a tenth . . . The ancients may have built their columns to such dimensions, making some six times the base, others ten times. But that natural sense, innate in the spirit, which allows us as we have mentioned, to detect concinnitas suggested them that neither the thickness of the one nor the slenderness of the other was suitable. They concluded that what they sought lay between those two extremes . . . and they made a column eight times the width of the base, and called it Ionic.
>
> (Alberti 1992: 309)

In general both Vitruvius' and Alberti's inductive attempts to or explanations of moving from empirical to general relational standards seem as overstated generalisations.

Building types and elements

Alberti does mention the existence of various building types that has developed from the original shelter as specialisation of functions. Generally he, as Vitruvius, divides buildings into two types: public buildings with several functions, sacred as well as profane, and private buildings divided into two groups – those for foremost citizens and those for common citizens. Many of the building types are described in detail. However, he stays within antique types and does not deal with the specialisations of his own époque. More interesting than his building types is, in the context of this book his statement that the whole matter of building is composed of six general elements:

Locality	The land or region surrounding the building including its climate.
Area	The particular plot of land enclosed by the building.
Compartition	The division of the area (the building) into its different spaces – the floor plan – like the different members of a body.
Wall	All vertical structure that supports the roof or screen off interior volumes.
Roof	Uppermost part protecting against the rain as well as any horizontal element '*above the head of anyone walking below such as ceilings, vaults, arches and so forth*' (ibid.: 8) The roof is the most fundamental (and archaic) element of the building.
Opening	Anything that offers entry or exit for man or thing including as well as light and air. Generally divided into these two purposes as doors and windows. Stairs are included as a vertical door/opening (ibid.: 28) as well as openings (in and out) for water, smoke, etc.

All six general elements relate to and should each be endowed with the attributes of *firmitas*, *utilitas* and *venustas*. Albertis Book III on construction is a detailed description of how the building (and its elements) are put together. Here, a similar distinction of the fundamental physical elements is found with various subcategories or elements:

Foundation and plinth	Stones and rubble from solid ground to the level of *area*.
Structure	*Walls* subdivided into (structural) *bones* including columns, beams and arches where openings and *panelling* consisting of (inner and outer) skin, binders between these and infill. Finally a *cornice* closes off.
Roof	of wood or stone and distinguishing between the *horizontal division* (ceiling and floor beams) and the *covering* (the outer roof membrane).
Pavement	All flooring inside and outside the building.

Important to note is Alberti's conscious attempt to avoid a dogmatic and closed architectural system. His directions are prescriptive rather than an expression of fixed rules and set out the possibilities of building while variety (*varietas*) is also a demand. Architectural alternatives should (to some extent) be kept open:

> I mean that a certain variety possessed by both angles and lines, as well as by individual parts, which is neither too much nor too little, but so disposed in terms of use and grace, that whole may correspond to whole, and equal to equal.
>
> (Alberti 1992: 426)

Durand and the grid system[9]

Jean-Nicholas-Louis Durand (1760–1834) was a French architect educated at the Academie Royale d'Architecture. From its start and for 35 years he held the Chair of Architecture at the Ecole Polytechnique – the new engineering school founded 1794. Durand's rational principles represent some of the first traces of functionalism in architectural theory. Kruft states that his simplified architectural schematism partly must be explained in the fact that he taught engineering students, not architects (Kruft 1994: 273). As part of his teaching he worked out a typological atlas of architecture aiming at presenting 'the most important monuments of all ages of all nations' (ibid.).

Architectural principles

The fundamental principles of architecture are by Durand reduced to only two being 'proprietary' and 'economy'– architecture as a combination and weighing of the most fitting and the most economic. The former embraces solidity, soundness and commodity, while the latter includes symmetry, regularity and simplicity. The aesthetic categories classically included in the principle of *venustas* here become subordinated to the two others and take the form of '*grandeur*', '*magnificence*', '*varieté*', '*effet*' and '*caractère*' (ibid.: 274) that put considerable distance to Vitruvius' eurhythmy/symmetry and Alberti's *concinnitas* that were based on proportional rules using analogies to nature. Durand, furthermore, considered architectural ornament superfluous.

Grid system

Durand's rationalist and functional approach demanded codification into a systematic theory of architectural composition of which he claimed universal validity and which took the form of a grid system. The building volume was not thought of as a (three-dimensional) architectural space but was produced as a combination of plans and elevations (and sections) that were subordinated to the grid. The introduction of this abstract metric system augurs the abandonment of Classical theories of (anthropometric) proportion. Through the neutral grid systems architectural features (i.e. colonnades, walls, arches, windows, roofs, etc.) were, as separate elements, combined into individual buildings and building types. Although Durand did not consciously draw his work to this consequence Kruft states that Durand here 'reached the theoretical point of standardisation enabling prefabricated construction' (ibid.: 274) and draws direct parallels to Crystal Palace built in 1851. Buildings are conceived as individual configuration and the addition of a sample of standardised architectural elements.

Semper and the four elements of architecture

One of the leading architectural theorists of the mid-nineteenth century was Gottfried Semper (1803–1879). While starting studies as a mathematician in Germany, Semper quickly moved to Paris and followed an architectural programme in the spirit of Durand whose functional '*schematic procedures*' he, however, vehemently rejected. His main inspiration as architect and theorist came rather from the German-French Jaques Ignaz Hittorff and his treatise on architectural polychromy in Antiquity that was published in 1824 (Kruft 1994: 311). Semper sees polychromy in architecture – the use of colours (of materials and paints) – as an expression of a free democratic society that was broken with the (monochromatic) architecture of the Renaissance as an erroneous interpretation of its Classical Greek predecessor. Materials and their colour, texture and structural characteristics were important to architecture and should be used by the architect to express the social and historical structure of society and its current technological stage:

> Let the materials speak for themselves and appear undisguised, in whatever form and whatever conditions have been shown by experience and knowledge to be best suited to them. Let brick appear as brick, wood as wood, iron as iron, each according to the structural laws that apply to it.
>
> (Semper in Kruft 1994: 311)

This could be misunderstood as exactly the functionalism he sought to distance himself from, but the material and the structure are not the only aspects that have to be considered. The connection to the specific society and cultural, regional and climatic setting is also important and modifies this dimension. Semper elaborates a conceptual formula for the relationship between the (architectural) work of art, its style and all its constituent elements. The work of art is thus determined by a *constant* – constituted by the function(s) – and a number of *variables* which are: (1) materials, (2) regional, ethnological, climatic, religious and political conditions, and (3) the influence of the artist (the architect) or the patron (the client) (ibid.: 312f.). The specific combination produces different styles. Interesting here, in relation to this book, is both the insistence on the *contextuality* of architectural creation in a broad sense as well as the connection between *idea* and *realisation*: architecture is a context specific translation of an architectural idea and specific human needs into the materials and their related tools and technical skills available in a given society at a given time.

In *The Four Elements of Architecture* (Semper 1989), Semper locates the *hearth* – or fireplace – as the first and most archaic architectural element satisfying basic human needs by providing warmth and a 'food-preparing flame'. Furthermore: 'Throughout all phases of society the hearth formed that sacred focus around which the whole took order and shape' (ibid.: 102) and thus equally gained moral value. In order to protect the flame and its holders against the hostile elements of nature, three supplementary basic elements crystallised around the hearth: the *roof*, the *enclosure*, and the *mound* – or terrace. Semper relates each of these four basic architectural elements to a material and the gradually evolving techniques or *crafts* to manipulate them. The creation of the hearth was related to ceramics (and later metal works), the roof and its accessories to wood and carpentry, the enclosure to the weaving and the wall fitter, while construction of the mound was related to the water (regulation) and masonry work (in stone) (ibid.: 103).

Special attention is paid to the enclosure that becomes part of Semper's – rather forced – argument for a nascent polychromatic culture and the development of the ornament finding its (temporary) culmination in Greek Antiquity. This will not be followed here. What is more interesting in relation to the present exploration of systems in architectural theory is that the four elements and their related materials and techniques, according to Semper, developed into different context specific combinations and emphasis depending on the cultural setting where they were unfolded. Different architectural systems or 'characteristic configuration[s] of spatial relations' were established (ibid.: 115):

> According to how different human societies developed under the various influences of climate, natural surroundings, social relations, and different racial dispositions, the combinations in which the four elements of architecture were arranged also had to change, with some elements becoming more developed while others receded into the background.
>
> (ibid.: 103)

The four elements of architecture in Semper's theory should thus be understood as flexible entities that can even infringe the domains of each other exemplified by Roman architecture where heavy (stone) material and construction techniques that originally were tied to the mound or terrace, now through walls, arches and vaults, began to influence the enclosure and the roof elements.[10] Semper's insistence on the enclosure or wall as rooted in the weaving of (colourful) carpets rather than the stacking of stones can be a little hard to follow and is probably tied to his early argumentation concerning polychrome Antiquity. However, the variables of his formula for the architectural work (see above) and the flexible domains of the four elements represent interesting arguments for the (partial) emancipation of the material in architecture from pure functionalism into an object for architectural ideation – as, for example, the selection of decorative forms and colours (ibid.: 128). A contemporary architecture should not imitate Greek or Roman Antiquity and their architectural systems but, as mentioned above, constitute a context specific translation of the architectural idea and the basic human needs. This can only be done through application of the four elements as they are founded in present day production techniques.

Contemporary theories

From the mid-twentieth century onwards, architectural theory become a plethora of different competing schools of more or less stable character and historical impact. The continuation of the modern movement and postmodernism, have already been mentioned as major examples. The relatively short historical distance to these theories makes it more difficult to keep them at arm's length and value their true impact on systems thinking in architecture. However, two recent theories elaborated by architects – or rather the resulting *models* – will be introduced in connection with the general systems theory presented in a following chapter. These are Christopher Alexander's *pattern diagrams* and Bill Hillier's *Space Syntax* that both represent more true systems approaches, as this is defined in the general systems theory.[11]

The division between idea and process

In the following paragraph the intention is to trace some of the possible historical explanations for the alleged division between on the one hand how the architectural idea is conceived and on the other hand the physical processes that through the crafts or other forms of production lead to the realisation of the final architectural work. In order to comply with this, help is mainly found in two texts respectively by Gevork Hartoonian on *montage* and by Kenneth Frampton on *critical regionalism*. Both texts give a kind of historical sectional view of the development or emergence of this division from Classical theory and architecture up to modernity and present time (Hartoonian 1994; Hays 2000). Some supplementary references will be used to substantiate their claims as a general perception.

Hartoonian and the fragmentation of techne

According to Hartoonian the Classical conception of technology expressed in the Greek term *techne* – the art of making – encompassed in one single concept 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). Vitruvius' three basic categories of *venustas*, *utilitas* and *firmitas* articulate an integration of the style, the rules of gravity and the property of materials into one single body of architectural knowledge (ibid.: 7). '[C]lassical architects' conceptualizations of the different functions of architectural elements were integrated with their technical knowledge' (ibid.: 11). Through examples from Palladio's prescriptions for the design of villas Hartoonian shows how symmetry (in the modern sense of the word) as an organising principle in architecture is not only about aesthetics but equally has useful structural implications in the construction of buildings.

The unity contained in *techne* is, as Hartoonian points out, theoretically broken up in the early renaissance by, for example, Leone Battista Alberti who distinguishes between lineaments and matter/structure. Lineaments are, as mentioned above, 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 expressly states that 'lineaments remain independent of structure and have nothing to do with materials. They also remain indifferent to purpose and form' (ibid.: 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.

Hartoonian locates the next step in the 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' (ibid.: 5). The Classical *techne* was now fragmented into different fields of knowledge. In the nineteenth century in line with the breakthrough in the mechanical sciences the seeds were sown for the cult of the machine that culminated in the modernists of the early twentieth century. The emergence of industrialised materials and techniques were praised to such extent that the status of architecture, according to Hartoonian, was reduced to that of a mere technical discipline focusing on production. Architecture and its elements had lost its metaphoric significance and *technology* with its focus on production had replaced *techne* (ibid.: 13):

> [T]he status of architecture was either reduced to that of an utensil, as was the case in the Werkbund and Bauhaus schools, or the field was wrongly assumed by some disciples of the Russian Constructivists to be equivalent to engineering.
>
> (Hartoonian 1994: 6)

From the architectural province Hartoonian introduces Durand's architectural types based on configurations of 'standardised' architectural elements as an example of an autonomous architectural language that was separated from the exigencies of its construction/production (ibid.: 13). Boullées architecture based on pure geometrical forms is another clear example. The search for meaning in architecture was relegated to the realms of pure form and/or function. The Classical conception of architecture as defined by universal laws of beauty had been substituted by architecture as (subjective) expression.

By introducing the concept of *tectonic* Hartoonian suggests a possible closing of the gap between architecture and construction without returning to *techne* in the Classical sense. Through Viollet-le-Duc's statements on the ornament as 'the structure of the architectural features' or 'the best architecture is that whose ornaments cannot be divorced from the structure' (ibid.: 18) he hints that an expressive architectural language freed from the laws of divine Classical orders can (re)integrate the element of construction even when adapted to new forms of production. In Gottfried Semper's integration of urforms with new techniques and materials he finds an even clearer pointer. Architecture is, as also described above, rooted in four industrial arts with direct connection to four basic elements of architecture (ibid.: 20). Tectonic form for Semper is neither about expressing the structure (the construction) nor the formal intentions of the architect. Rather it reveals a symbolic intention through the material and the related techniques (skills) embedded:

> Tectonics deals with the product of human artistic skills, not with its utilitarian aspect but solely with that part that reveals a conscious attempt by the artisan to express cosmic laws and cosmic order when molding the material.
>
> (ibid.: 23)

Interesting in the present context is also Semper's interest in 'How to change old forms, consecrated by necessity and tradition, according to our new means of fabrication' that according to Hartoonian becomes Semper's motto on the tectonic (ibid.: 24). Through the acknowledgement of the rooting in materials and their related techniques stemming from other industries as a primary condition of architecture Semper anticipates, according to Hartoonian, montage as an architectural (and tectonic) strategy of the modern era (ibid.: 1). In montage the relation between the whole and its parts is altered from organic (as in *techne* and the analogy to natural proportions) to cultural (ibid.: 26) where the whole instead become a juxtaposition of fragments in the act of montage. The 'dis-joint' or seam becomes the tectonic form of montage. Montage (apparently?) introduces a new culturally based autonomy of architecture that is neither based on classic myth nor on the subjective expression or idea of the architect by, in Hartoonian's words, 'problematizing the event of its [architecture's, ed.] inception' (ibid.: 27):

> Montage is a technique that drains the metaphysics of the tectonic and unfolds a new way of being in the world.
>
> (ibid.: 28)

The architectural idea seems, according to Hartoonian, potentially to recover its connection to construction – or rather to fabrication – through its cultural roots in the contemporary means of production.

Frampton and critical regionalism as meaning

In Frampton's reading of Hannah Arendt's *The Human Condition* he equally describes a historical origin of the division between the architectural invention and its subsequent fabrication. As with Hartoonian, the renaissance is seen as a decisive turning point where the split between the liberal and the mechanical arts produced a change in the hierarchical organisation of construction work. From a lodge organisation where a master builder/mason coordinated the specialised work of different masters in charge of various aspects of a construction job the master builder/mason now 'rose to the status of sole planner' while the rest were degraded to merely manual labourers – *Animal Laborans*. The master builder had become an architect – a man of invention and speculation (Frampton in Hays 2000: 367).

With reference to Arendt, Frampton distinguishes between *work* and *labour* as a principle duality of *Homo Faber* – 'man-the-maker'. Man is both capable of producing useless things such as works of art which are ends in themselves and of inventing and producing useful objects that serves for predetermined ends. The fundamental difference in these two forms of production can be described in the words *what* and *how*. The first one is concerned with representation – or meaning – whereas the second is about utility and process. In architecture this ambiguity is, according to Frampton, reflected in its status as both *edification* (i.e. moral instruction) and as *building* (construction work). Man or *Homo Faber* is 'neither pure artist nor pure technician': he is both at the time. Both modes of production, he continues, resulted in the ancient world in physical manifest results (art or tools). However, through the emergence of the empirical sciences, production shifted towards equally including the invention of 'abstract instruments of cognition' – or systems of thought – as they are tentatively termed in the present monograph. Apart from widening the division between thought and fabrication (the latter expressed in *Animal Laborans*) this scientific approach on the other hand also changed the emphasis or esteem of *Homo Faber* from the *what* to the *how*:

> Fabrication which had hitherto disappeared into the product, now became an end in itself since pure science was not interested in the appearance of objects, but in the capacity of objects to reveal the intrinsic structure lying behind all appearance.
>
> (Ibid.: 367)

Homo Faber, according to Frampton, instrumentalised by himself promoting the process before the result – the architect or master builder seen primarily as technician – as a means to an end or as action before contemplation (ibid.: 368). During the Enlightenment (eighteenth century) this change resulted (as Hartoonian also points out – see above) in the formal separation of architecture and engineering. 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' (ibid.: 369). According to Frampton, production and process in their own right dominate the man-made world and influence from then on and still today back on how architectural form can be conceived:

> Increasingly buildings come to be designed in response to the mechanics of their erection or, alternatively, processual elements such as tower cranes, elevators, escalators, stairs, refuse chutes, gangways, service cores, and automobiles determine the configuration of built form to a far greater extent than the hierarchic and more public criteria of place.
>
> (ibid.: 370)

Buildings (not architecture) become determined by the processes they accommodate rather than being actual architectural (and symbolic) expressions or intentions of a culture to sustain itself. Utility as an end has replaced utility as a tool to reach an end – reach the *what* or the meaning of architecture. As he cites Arendt for: ' . . . utility established as meaning generates meaninglessness' (ibid.: 372). The non-functional aspects of architecture – the meaning – are left without connection to society and its cultural foundation being either inaccessible as 'introspective abstraction' or reduced to a mere commodity as 'ideosyncratic vagaries of kitch'. This is probably also the main problem of a petrified and dogmatic functionalist architecture as expressed in the industrialised mega blocks from the late 1960s.

Frampton seems, compared to Hartoonian, more pessimistic concerning a contemporary reintegration of construction into a unified architectural system of thought. The *work* and *labour* duality of *Homo Faber* is broken and man generally reduced to an *Animal Laborans* in the service of (re)production of commodity and not the creation of meaning and culture. Modern life and means of production efficiently destroy the durability of the world through a 'ruthless cultural reduction' and 'the celebration of technique as an end in itself' (ibid.: 370/371). According to Hays – introducing Frampton's text – architectural practice is however seen by Frampton as a 'potentially resistant practice' (ibid.: 259) that can mediate between work and labour: 'It affords, above all, a hybrid situation in which rationalised production (even partially industrialized production) may be combined with the time-honored craft practices . . . '. We will not go deeper into Frampton's argumentation here but will return in the end of this monograph to this idea of a hybrid situation in present architecture as a possible way of pointing towards an *industrialised* architecture.[12]

Kruft and architectural theories

In order to substantiate the idea of a *general* perception of the historical emergence of a division between architectural idea and construction work a couple of references from Hanno-Walter Kruft's book on architectural theory will here be summarised shortly. Kruft equally cites Alberti for, in his definition of the architect, making a sharp differentiation between the architect and the craftsman (Kruft 1994):

> For it is not a Carpenter or a Joiner that I thus rank with the greatest Masters in other Sciences; the manual Operator being no more than an Instrument to the Architect. Him I call an Architect, who, by sure and wonderful Art and Method is able both with Thought and Invention, to devise, and, with Execution, to compleat all these Works . . .
>
> (Alberti in Kruft 1994: 43)

The terms of *thought*, *invention* and to *devise* are specific to the architect and opposed to the craftsman which are reduced to merely being *an instrument to the architect*.

In Kruft's description of J.N.L Durand's (1760–1834) architectural thought he equally grants Durand for drawing 'particular attention to the increasing divergence of architecture and civil engineering, recognising that the latter will eventually become a discipline in its own right' (ibid.: 273). This break into two disciplines – one of idea and invention and another of process and realisation is equally found in both Hartoonian's and Frampton's descriptions (above). However, Hartoonian and Frampton locate the break already from the seventeenth century and during the Enlightenment. Durand wrote his theories in the early nineteenth century. Durand's architectural types and elements, however, accentuates architecture's disruption from the exigencies of its construction.

Further discussion

Several recent sources outside architectural theory underpin the separation of design and coordination from construction as a fundamental characteristic of the construction sector as opposed to design and production within other industries.[13] It has not fallen within the scope and extent of this monograph to follow this track further, but there seems to be good indication for a general and historically substantiated division between on the one hand how architecture and construction is conceived and on the other hand how it is produced.

The first part of this chapter dealt with examples of classification of the constituent elements of architecture. If the historical split between the architectural idea and the physical realisation of it is so pronounced; if from the seventeenth century they have even belonged to separate established disciplines then it is equally possible that there will be a considerable difference between these constituent elements of architecture and the constituent elements of *construction*. The consequence of such differences would in very general terms be the need for some kind of translation from the language of one discipline to the language of the other. The next chapter looks into the question of classification systems in construction – or the constituent elements of *construction* as opposed to the constituent elements of *architecture*.

Notes

1 In Boullée's and Palladio's theories form can be seen as the main subject of an autonomous architecture (see e.g. Hartoonian: 1996: 15).

2 Ladowsky (in Kruft 1994) has this angle – it will, however, not be followed further in this book.

3 *Purpose* refers to in what context, from what worldview and with what aim the theory has emerged.

4 Critical Theory has roots in the 'Frankfurt School' of social sciences. See Andersen et al. (1998).

5 The broad term *Asian* primarily refers to Chinese and Japanese systems of architectural thought.

6 See ‘Scope and methodolgy’, Introduction.
7 Unrecorded practice is evidently not retrospectively accessible.
8 ‘What we construct should be appropriate to its use, lasting in structure and graceful and pleasing in appearance’ (Alberti 1992: 155).
9 Kruft (1994: 273ff.).
10 In Greek (polychrome) antiquity, Semper claims, masonry or stone walls, were ‘subordinate features hidden behind a partition wall’ or cladding of weaved textile or painted decoration (Semper 1989).
11 See ‘General systems theory’, Ch. 4.
12 See ‘Findings’, Ch. 14.
13 The separation of design and coordination from production: Bowley (1966), Nam and Tatum (1988), Groák (1994), Flanagan et al. (1998), Miozzo and Ivory (2000), González-Díaz et al. (2000) – citation from Thomassen (2003).

2 Classification systems in construction

Introduction

The previous chapter concentrated on the historically emerging split between architectural idea and its execution as construction and showed examples of how the elements of architecture have been defined in architectural theory. This chapter concentrates on classification systems used for this second leg – the execution of building projects. These systems both concern the processes and the physical elements in construction and can be legal systems, systems developed within the construction business, IT standards or looser recommendations for a smoother or better controlled building process. However, they all have in common that they are elaborated as attempts to handle the *increasing complexity and fragmentation* of knowledge in construction by establishing clearer interfaces between a number of stages (process) or a system of physical elements (matter). As mentioned in the introduction to this book, the construction sector can no longer draw on the traditional crafts as subsystems together forming a clear and coherent system of knowledge.[1] Through industrialisation these crafts have dissolved, specialised and cross-merged into niches that cannot simply be delimited in terms of material, tool and process. Furthermore, they have become detached from the architectural conception of the work and its elements and instead focused on the realisation of it. This chapter looks into examples of recent attempts to classify processes and elements of buildings in the construction sector.

Taken from mostly a Danish/Scandinavian context the examples below are primarily introduced as a way to point out the diversity and perhaps the arbitrariness and common problems of such classifications. It is also discussed how they contribute to how and what we build.

Hypothesis and questions addressed

The growing complexity of construction both as processes and as objects has produced a variety of classification systems that either split up or transcend the traditional crafts.

The hypothesis is addressed through the following two research questions:

1 How has the construction sector conceptually systemised building processes and/or physical elements in order to facilitate clear interfaces of responsibility between a growing number of stakeholders and reduce the complexity of the construction process?
2 Do classification systems used in the construction sector reduce the complexity from the point of view of the architect and what implication does it have for the architectural result?

Project stage models in construction

Despite many historical attempts to turn construction into true industrialised mass production as in the product industry, construction is still predominantly project-based. Projects are unlike standardised products characterised by having a project-specific course. That is what makes them projects! Product *development* in other industrialised sectors can also be seen as projects. Companies in construction that generally deal with projects – as architects, engineers and contractors – tend to follow some kind of system concerning how these projects should progress. Construction projects involve many different stakeholders each one having their internal procedures that need to be coordinated in some kind of common system in order to clarify sequence, communication and responsibility issues.

Different project stage models have been used in construction processes in order to provide this coordination and for clarifying and communicating the project course and status to the client. Each stage in a model is usually completed by some sort of documentation, i.e. descriptions, drawings, models, etc., that can provide the basis for a decision of proceeding to the next stage. Stage models are also important because they lay out the basic structure for contracts between stakeholders in the building process. The specific models used are in some cases national standards in others elaborated by trade organisations. The ISO-standard 12006–2: 2001 – *Organization of information about construction work* – defines a project stage as a ‘period of time in the duration of a construction project identified by the overall character of the construction processes which occur within it’. This definition is, in a short introduction to Danish project stage models, also adapted by the Danish organisation *Det Digitale Byggeri* (Danish Digital Construction).[2] This introduction and a couple of other sources will be used as the basis for the short introduction below (DBK 2006).

In Denmark a general project stage model applicable for all stakeholders in the construction process, ABR89, was made in collaboration between the major construction consulting organisations and the public authorities and was introduced in 1989 replacing a range of earlier models. The model has been widely applied in the construction sector and divides the process into five general stages:[3]

1 programme
2 proposal/conceptual design
3 design development
4 construction
5 use.

A later revision of the model, partly caused by EU-imposed procurement rules partly by enhanced industrialisation, added two more stages – *procurement and bidding* and *production planning* before the *construction* stage. In 1996 the consulting organisations (architects and engineers) made their own five-stage model exclusively for consultancy services:

1 pre-design consultancy
2 design management consultancy
3 design consultancy
4 construction consultancy
5 operation consultancy.

The design stage (including the earlier programming and proposal stages) is further divided into five substages – *outline proposal, project proposal, preliminary project, main project* and *project follow-up*.[4] This model is now generally used among Danish consultants but is too trade-specific for general use in the sector as a whole. Instead a simplification of the first ABR89-model into a four-stage model (4 *fase-modellen*) has been adopted by other parties.

1 programming
2 design
3 execution
4 operation.

This model is widely used among contractors. All stage models above – as stage models in general – have the drawback that they have a tendency of freezing a specific way of organising construction works that obstruct new or project-specific organisation that may be more adequate in certain cases.[5] An alternative, the '7K-model', was introduced as a way to facilitate early procurement, where contractors are brought in already in the (early) design phases (all starting with a 'k' in Danish = 7K):[6]

1 contact
2 contract
3 performance (specification)
4 concept
5 construction
6 control
7 consumption.

This model was later simplified into a three-stage model by the interest group Lean Construction Denmark: *value and concept, construction, consumption*.

In practice, such models are often used with 'loose edges' between the stages, for example, buildings are never completely designed before construction begins. The development sketched above shows that while there are evidently advantages in following a common structure it is very difficult – and probably impossible – to come up with an ideal or definitive model that everybody can agree on even on a national level. Internationally this would become even more complex. Organisation of construction is culturally founded and changes furthermore over time and therefore needs to some extent to be project-specific. In addition, industrialisation and more integrated building products have moved part of the design work to sub-consultants, suppliers or manufacturers. This also blurs the stage boundaries and makes difficult the linear logic of a sequential number of phases. Robust (stage) models need to be open for some degree of project-specific adaptation by offering what we will later term as *flexible structuration*.[7] General Systems Theory (GST) offers a way to conceptualise such models and will be treated in a following chapter.

Building classification systems

As described in the previous chapter, in Classical architecture the construction elements and the architectural elements were convergent. Equally, the building techniques that were related to these elements were embedded in such a way that each particular element was always made in the same way. The architectural idea unambiguously led to the transformation of specific materials by specific techniques into specific results. Today this coherence is no longer present and this has from the 1950s onwards led to the emergence of different classification systems as attempts to make it possible to specify building data as processes and elements in a precise way thus enabling consistent communication among different stakeholders. These systems, however, have emerged rather from a contractor perspective than from an architectural context and thus largely lacks correspondence with how the buildings are conceived and designed in the first place. Architectural projects need (subsequently) to be translated into these codifications; they do not naturally lead to them, neither do they (initially) support the architect's way of working. This, in combination with the fact that they are often quite complex, has limited their spreading, implementation and success considerably – particularly for use in early design stages. Although there are obvious advantages in being able to communicate clearly between stakeholders, the architect still seems to have very little direct incentive to use these systems.

The SfB-system

One of the first attempts to make a complete building classification system common for all involved parties was the *SfB*-system published in the

1950s by the Swedish *Samarbetskomitén för Byggnadfrågor* (Collaboration Committee for Construction Issues). The system was originally intended to be used for standardised Swedish construction work descriptions but was adopted in various construction related fields, for example, for registration of building materials. In 1972 the SfB-system was recognised by the CIB (Commission Internationale du Bâtiment) and became widely applied internationally although often in adapted national versions and – again – with limited practical success. The format and structure of the system have equally to some extent been found adequate for later IT-adaptation.[8] The system is based on a three-layered coding based on values from three separate tables:

1 a building component table
2 a construction type table
3 a resource table.

By *building components* the system refers to the function of the component as outer wall, roof, exterior surfaces, pavement, etc. By *construction type* is meant techniques as masonry construction, in situ casting, pipework installation, etc. and finally the *resource* describes the material and also includes 'immaterial' resources as administration and different kinds of work or service. An example of a coding could be:

> (22) G q4 = '(interior walls)' 'prefabricated base building' 'concrete' = prefabricated structural concrete walls.

In Denmark the SfB-system has been adapted and updated several times and the latest complete revision is from 1978 with a later update of the building component table in 1986 (SC/SfB). However, the complete system and its structure has only sparsely if ever been used in a consequent way that crosses all involved stakeholders in one or several building projects. Insufficient updating according to new construction techniques and application of materials in new ways have complicated a consistent coding and mostly limited the use to building product catalogues, rather than the building processes.[9]

DBK – Danish building classification[10]

A Danish governmental initiative *Det Digitale Byggeri* (Danish Digital Construction) ran from 2003 to 2006 and was then handed over to the building sector itself led by its central organisations.[11] *Det digitale byggeri* developed the basis for ICT-demands of public clients in construction projects and was supposed to work as a driver for the construction sector in general. The demands encompassed four fields:

1 Procurement and (competitive) bidding via the Internet
2 Application of 3D-models

3 Use of a common project-web
4 Digital delivery of building data relevant for operation and facility management.

In order to comply with these demands several tools and guides have been developed. The most important of these is the DBK-system (Danish Building Classification). The standards are based on the international ISO 12006–2 for *Organization of information about construction work*. DBK form the most coherent and at the same time digitally supported information structure that has been made for the built environment in Denmark so far. It encompasses the entire construction industry and the entire life cycle of construction from planning over construction to operation. The overall structure of the system is that certain resources are applied in certain processes in order to create certain results. To each of these separate *domains* properties are associated from a domain of properties.[12] Apart from classifying building complexes, single buildings, spaces and building parts DBK equally encompasses processes, stakeholders, documents and other construction information. The DBK-system and the associated structure for construction descriptions (B100/B1.000) are meant to substitute the use of the SfB-system and all its different trade-led or company based modifications or adaptations.

Ekholm describes DBK as a *reference system* – a combination of a classification and an identification system. Classification is based on a 'type-of'-principle while identification is based on a 'part-of'-principle. (Ekholm 2011: 3). DBK is object oriented and more complex than the SfB-system by enabling different views (called *aspects*) upon each object as, for example, a building component depending on the purpose. Four aspects are defined: a *product aspect* (what an object consists of), a *form aspect* (what it looks like), a *functional aspect* (how it is used) and a *location aspect* (how it is integrated/installed). An example of the coding of a building component (a window) in the DBK-system following the product aspect (coded as preceded by '-') looks like this:

-205	Wall system
-205.02	Window section inserted into wall system
-205.02.01	Window in window section inserted into wall system
-205.02.08	Seam/joint in window section inserted into wall system

The different levels of the coding make it possible to describe elements that are integrated – or *nested* – into other larger and more complex elements and facilitate different 'zooms' of complexity in focus. In a following chapter on *general systems theory* this issue of *nested system integration* and *levelled complexity* will be further explored. Coding, alternatively, along the functional aspect (preceded by '=') the coding =20.01 refers to 'illuminating with daylight' while under the location aspect (preceded by '+') the coding

+1.002 would refer to first floor, room 002. The form aspect (preceded by '#') refers to the geometry. Coding in different aspects can be joined into an integrated description as –205.02.01/+1.002/=20.01 thus referring to a 'window in window section inserted into wall system placed on first floor room two providing illumination in the form of daylight'. A building component can also have various functional aspects simultaneously.

The idea with the *aspect* dimension is that while objects i.e. building components (as simple, combined or nested) are defined in an unambiguous way as classified objects, the relation – or the system – they form part of can be seen in different ways – as systems of parts, systems of functions, systems of locations or systems of forms. The different aspects are used one by one according to which is the most appropriate for different parts of the building life cycle processes in question. The production aspect points out the combination of elements into a larger assembly; the functional aspect describes functional relations or interfaces between elements while the location aspect brings out spatial relations between the elements of an object (e.g. a building).

The vision of classifying and identifying any resources, processes and results of the entire life cycle of buildings in a consistent way seems very ambitious. This book does not leave time or space to comment on this in a nuanced way and the scope of the subsequent model building is much more confined. However, the *aspect* dimension is interesting within the current project frame because of its potential capacity to establish *different views* on what is still basically considered the same object – being a building complex, a single building or simply parts of a building. The *system structure* of a building is – as it will be described later – somehow an alternative (fifth) aspect of a building project.[13]

Other classification systems

BSAB (96)

In Sweden the original SfB-standard (see above) was from 1972 and developed into a new classification system called BSAB by Bygandets Samordning AB (Coordination in Construction Ldt.) The incentive for the development lay in the enhanced importance and sophistication of installation systems in construction that could not be properly classified within the SfB-system. Later the development in information technology has resulted in further modifications in the latest version BSAB 96 finished in 1998. As the DBK-system this version to some extent follows the international ISO-12006–2 but with modifications and adaptation to Swedish circumstances and experience using the system.

The BSAB system works with a concept of *views* (in Swedish: '*vyer*') that to some extent resembles the concept of aspects in the DBK-system. Accordingly, it includes an *activity* view, a *functional* view, a *construction* view, a *production* view, a *resource* view and a *management* view.[14]

Classification tables have been elaborated within eight main classes: activity, infrastructural unit, building, space, building parts/components, building component type, production result, resources, management result and geometrical form. The different views (or aspects in DBK-terminology) refer to one or several of these classes and tables (Ekholm 2011: 87ff.)

IFC and STEP[15]

The IFC standard – Industry Foundation Classes (today officially the Buildingsmart data model) was originally developed by IAI (International Alliance of Interoperability). IFC is a data model and file format used to exchange CAD-data like BIM-models and drawings between the different software programs used in the construction industry. The standard is not written to a specific piece of software and is in this sense an open international standard. It is not a classification system in itself but can support classification coding as e.g. DBK applied to a BIM-model. IFC objects constitute in this sense a subset of the total number objects or elements in construction focusing on a model oriented work approach. The IFC is originally based on the more general ISO-standard 10303 informally known as the STEP (Standard for the Exchange of Product model data). STEP describes how to represent and exchange digital product information.

Related to this book, IFC and STEP are interesting in the way that they are in their basic idea created in order to reduce 'translation' work between systems and thus also reducing the possible faults of such translation. The apparent distance pointed out between architectural ideation and its subsequent construction and/or production has been accentuated by increased division of labour of the latter where many different stakeholders use their own tools and procedures:

> In design and manufacturing, many systems are used to manage technical product data. Each system has its own data formats so the same information has to be entered multiple times into multiple systems leading to redundancy and errors. The problem is not unique to manufacturing but more acute because design data is complex and 3D leading to increased scope for errors and misunderstandings between operators. The National Institute of Standards has estimated that data incompatibility is a 90 billion dollar problem for manufacturing industry.[16]

Several earlier national data exchange standards mainly focusing on geometrical data have been used including SET in France, VDAFS in Germany and IGES in the USA.

Omniclass/OCCS[17]

In the USA the Omniclass Classification system provides an open and extensible classification system for production, storage and retrieval of all information in the construction industry thus providing a structure for, for example, electronic databases. Omniclass is equally based on the international ISO-standard 12006–2 and strongly inspired by the UK equivalent, Uniclass, but adapted to North American terminology and practice. Construction information is organised around 15 tables each representing different facets of construction fitting and overall structure of construction resources, processes and results. The 15 tables classify *Construction entities* – by function and by form, *Spaces* – by function and by form, *elements, work results, products, phases, services, disciplines, organisational roles, tools, information, materials* and *properties*. Relevant information can be classified within one or as a combination of various *facets* (read: tables) and can be used and reused throughout the life of a building or a similar facility. Particularly interesting in the present context is the difference between table 23 concerned with products and table 22 for classifying work results. Products are defined as:

> . . . components or assemblies of components for permanent incorporation into construction entities. Products are the basic building blocks used for construction. A product may be a single manufactured item, a manufactured assembly of many parts, or a manufactured operational stand-alone system.[18]

Products are applied in work results on-site that 'represent completed entities that exist after all required raw materials, human or machine effort, and processes have been provided to achieve a completed condition'.[19] These two definitions seem to provide a distinction between off-site produced products as being purely physical deliveries (table 23) and on-site produced results as combinations of processes, products and raw materials (table 22). Work results can even be purely procedural involving only labour and equipment as e.g. trenching or foundation work (ibid.: 3).

Discussion

One of the general problems of all classification is that it points towards a static world based on universal and discrete non-ambiguous entities. The systems theorist, Ludwig von Bertalanffy, whose thoughts will be presented further in a following chapter,[20] presents classification as an old-fashioned way of conducting scientific work with roots in Greek Antiquity:

> The Greek conception of the world was static, things being considered to be a mirroring of eternal archetypes or ideas. Therefore classification was the central problem in science, the fundamental organon of which is the definition of subordination and superordination of concepts. In modern science, dynamic interaction appears to be the central problem in all fields of reality. Its general principles are to be defined by system theory.
> (Bertalanffy 1968: 88)

In a complex modern society it is difficult to formulate definitive all-encompassing classifications and although many national and international attempts – some of them described above – have been made, they all seem to face the problem of trying to be both detailed (read: specific) and structural (read: general) at the same time. The main problem of all of these elaborated classification systems seen from an architectural point of view is that they, through mechanistic aggregation of parts, seek to arrive at wholes in a way that is very foreign to the way these wholes are actually conceived as architectural designs. Such designs are rather conceptualised as integrated wholes that subsequently have to be split up in their constituent elements. However, if we are to bridge the gap and avoid troublesome translations between how architecture is conceived and how it is subsequently produced or constructed neither of these strategies represent a plausible path and the consequence is that supposedly universal classification systems are used only in simplified versions.

More sophisticated classification and management systems are sometimes, as will be described in some of the later case studies, developed within large companies for their own internal use – often as modifications of one the national or international standards.[21] Although fairly elaborate, by being local these systems often cause considerable translation work when other parties get involved and produces company internal sub-optimisation rather than real benefits for the construction process and the architectural result as a whole. None of the existing classification systems seems to have root in how architecture is conceived – or at least have taken into consideration this (necessary) aspect. They do not facilitate the translation from architectural concept to ‘project production’. The following chapters take a peek into the product industry to see how industrial production theory seeks to manage complexity of industrial production and sophisticated products.

Notes

1 See Introduction.

2 *Det Digitale Byggeri* is an initiative, publicly funded since 2003, in charge of promoting tools for a coordinated, digitally supported construction process in Denmark. We will get back to this initiative later in this chapter.

3 Available online at http://www.voldgift.dk/regler/abr-89.htm#2 (accessed 8 April 2011).

4 The stages can be found in ‘description of services’ in Danish and English on http://danskeark.dk.

5 In fact this is a general problem in the application of systems. However, the drawback should be weighed against the gains of a clearer structure or process. Meadows (2008) points out that models should always be adapted to the specific purpose. See the chapter ‘General systems theory’, Ch.4, for an introduction to systems thinking.

6 The 7K-model was developed and tested as a part of some major development projects initiated by the former Ministry of Urbanism and Housing (By og Boligministeriet) – ‘PPB’ and ‘Projekt Hus’.

7 See ‘General systems theory’, Ch. 4, and ‘Architectural systems terminology’, Ch. 5.

8 See HFB (1993: 937).

9 Available online at http://www.byggeklassifikation.dk/Rapport/Slutrapport2.pdf (accessed on 5 April 2011).

10 Sources: http://www.ebst.dk/detdigitalebyggeri; http://www.bips.dk; http:// www.hfb.dk; http://www.detdigitalebyggeri.dk/, http://it.civil.aau.dk/it/education/ (accessed on 5 April 2011); Ekholm (2011) and Jørgensen (2010).

11 Bygherreforeningen, Danske Arkitektvirksomheder, Foreningen af Rådgivende Ingeniører, Dansk byggeri, TEKNIQ, ATkartellet and DI-Byggematerialer.

12 The *Resource Domain* (trades, contractors, materials, equipment and documents), the *Process Domain* (the subprocesses of the different stages in construction), the *Result Domain* (building complexes, single buildings, spaces and building parts) and the *Property Domain* (classification of properties).

13 The concept of aspects is adapted from the Danish standard DS/EN 61346 on structuration principles and reference terms in industry. This standard includes the aspects of function, production and location. The form aspect is DBK-specific. However, DS/EN 61346 opens the possibility of working with supplementary aspects (Ekholm 2011: 28).

14 In Swedish: 'Verksamhetsvy, funktionsvy, konstruktionsvy, produktionsvy, resursvy' and 'förvaltningsvy'.

15 Available online at http://standards.eu-innova.org; http://www.buildingsmart.com; http://www.ebst.dk; http://www.steptools.com/ (accessed 10 April 2011).

16 Available online at http://www.steptools.com/library/standard/step_1.html (accessed 10 April 2011).

17 Source: Omniclass, Introduction and Users Guide. Available online at http://www.omniclass.org/ (accessed 18 August 2011).

18 *Omniclass, Table 23*, page 2 – accessed via http://www.omniclass.org/ (18 August 2011.

19 *Omniclass, Table 22*, page 3 – accessed via http://www.omniclass.org/ (18 August 2011).

20 See 'General systems theory', Ch. 4.

21 The cases of *Arup Associates* and *NCC* are both examples of such company internal use of classification systems. See Part III – 'Model'.

3 Industrial production theory

Introduction

The two previous chapters have concentrated on architecture and the construction sector where building projects are mostly regarded as discrete projects rather than as products on a continuous line of production. However, as construction become more industrialised and more processes move from the construction site into factory environments, the links to and the inspiration to draw on from the general production industry become evident. Standardised and industrially produced building materials and components are not a new phenomenon – probably as old as industry itself – but the complexity and sophistication of these deliveries have increased although not to the same extent as within the production industry in general.[1] The link to the industry has lately been further strengthened by the fact that while industry originally was based on the idea of mass production of uniform objects, today new processes, techniques and business models have yielded more individualised and customised products. The one-off projects of construction and the standardised products of production seem to be approaching each other from different sides and intersect, for example, in concepts like mass customisation and configuration.

The current chapter introduces core concepts from industrial production theory that are relevant in the context of industrialised architecture and construction and thus addresses the question of how the industrialisation of building processes and their results – the architecture – can be conceptualised. Based on a literature survey, this chapter mainly draws on Ulrich and Eppinger's *Product Design and Development*, Baldwin and Clark's *Design Rules: The Power of Modularity, The Power of Product Platforms* by Meyer and Lehnerd, and *Essentials of Supply Chain Management* by Hugos. Furthermore several paragraphs from *Arkitektonisk Kvalitet og Industrielle Byggesystemer* (Architectural Quality and Industrialised Structural Building Systems), co-authored by the author, have been adapted for the present use (Ulrich and Eppinger 2008; Baldwin and Clark 2000; Meyer and Lehnerd 1997; Hugos 2006; Beim, Vibæk and Jørgensen 2007).

Hypothesis and question addressed

Industrialisation within the production industry has moved from standardisation of products towards standardisation of processes thus extending the concept of 'the product' to include processes, techniques, and business models that are equally applicable within construction – even when it comes to one-off building projects.

The hypothesis is addressed through the following research question:

1 Which concepts from industrial production theory are applicable within the context of building projects and architectural design?

Concepts from the production industry

Product architecture

A concept widely used within the production industry when discussing design issues is product architecture. According to Ulrich and Eppinger the 'product architecture is the assignment of the functional elements of a product to the physical building blocks of the product' (Ulrich and Eppinger 2008: 164). In order to reduce the complexity of a product (architecture), the different physical elements are assembled into a number of major building blocks that often are referred to as 'chunks' (ibid.: 165). This division into a number of major constituent elements – the chunks – is often called modularisation. The functional elements are the different functions that together constitute the overall performance of the product. For example, a mobile phone some of the usual functions are emitting and receiving sound (i.e. conversation), displaying the status of calls and other information, storing contact information, protecting sensitive electronic parts, etc. whereas the corresponding physical building blocks for these functions are loudspeaker, microphone, LCD-screen, memory unit and casing. The relationship between the two genres of elements, however, is not necessarily one to one: where each building block can encompass various functional elements, the performance of a functional element can equally comprise several building blocks. These are cases of integration – integration within chunks or integration across chunks. The opposite is modularisation – clear physical separation between different functional elements. Following from this distinction, the product architecture of a design cannot be derived simply through the functional definition of a product. Assigning functions to physical elements – thus establishing the product architecture – is an act of design itself and often implies establishing and choosing between several more or less adequate solutions. It can be predominantly integrated or predominantly modular but mostly have (functional) elements of both kinds. Modules, modularity and modularisation vs. integration will be introduced more thoroughly below.

In product development, the concept of *system level design* designates a phase between the concept development and the detail design. A system level design is required when developing complex technical systems with many interacting subsystems and components such as automobiles, aircraft or even smaller systems like a photocopier. Ulrich and Eppinger (2008) defines the system level design phase as including:

> the definition of the product architecture and the decomposition of the product into subsystems and components. The final assembly scheme for the production is usually defined during this phase as well. The output of this phase usually includes a geometric layout of the product, a functional specification of each of the product's subsystems, and a preliminary process flow diagram for the final assembly process.
>
> (Ulrich and Eppinger 2008: 15)

It is in this phase – and before the detail design is determined – that the product architecture is established. In the earlier conceptual phase multiple product architectures may be considered as competing concepts (ibid.: 21). Interesting here is that it thus integrates the way the product is produced and assembled from its constituent elements – subsystems and components – into to the way the product is designed. For the product industry, this to some extent addresses the problem of the gap between conception and production process as stated in this monograph as a main problem for architectural creation and construction.[2]

It is important to point out the – for an architect slightly confusing – use of the word 'architecture'. Particularly within engineering and computer science the term is widely used as referring to the *structural* organisation of elements of both physical and non-physical nature and has little to do with the spatial, material, constructional and other less tangible qualities of an integrated architectural approach within building design. The structural organisation of elements – the product architecture – in the production industry is touching upon how people, production processes and products are organised in order to reach a coherent final result. The choice of a specific product architecture in product development can have various strategic agendas: economy and time will often have important weight and be an inherent part of other agendas, such as life cycle considerations, design for manufacturing, design for disassembly, complying with a product platform, or market availability for subsystems or components. In order to avoid confusion and to adapt the notion of product architecture to a context of construction, the product architecture of architectural design and construction will tentatively be termed the *system structure*.[3]

Modularity and integration

Modularisation and integration are, as reflected above, closely related to the concept of product architecture. Both are as opposites concerned with structure[4] and describe how the different functional and physical elements of a product architecture are respectively on the one hand either isolated as modules (grouped together or one by one) with clear interfaces to surrounding modules or – on the other hand – integrated across the product architecture. The latter situation can be compared to traditional construction where many different systems as e.g. structural system, heating system, façade openings and insulation are distributed over the entire building. Ulrich and Eppinger point out that integral design solutions often aim at the highest possible performance of the particular product in mind (ibid.: 166). Modularisation rather aims at combining product variety and production advantages concerning both time and price and introduce the possibility of *delayed differentiation*. An example used by Ulrich and Eppinger is the power converter of a printer that, although the printer itself is the same sold all over the world, has to vary according to national differences in voltage and power plug design. By adding this element as separate and later in the supply chain, the differentiation is delayed thus meeting both the demand for rational mass production and adaptation to local market conditions (ibid.: 179). However, the question of modularisation and integration is about a balance and seldom, or perhaps never, an either/or choice. Three generic types of modularity of product architecture are described. The types have to do with different ways of defining the interface conditions of the modules and are:

- slot-modular (product) architecture
- bus-modular (product) architecture
- sectional-modular (product) architecture.

While the slot-modular interface condition dictates that different elements or chunks have different interfaces to a basic structure, a bus-modular interface condition refers to a uniform interface between modules and basic structure. The sectional-modular interface condition is also characterised by a uniform interface but here non-hierarchically and directly between modules themselves as opposed to between the modules and a basic structure. The basic structure is also called a platform and will be explained further below. Joseph Pine among others works with a similar but enhanced taxonomy of modularity with six types that is less concerned with the specific interface condition and rather focus on the strategic aspect of how the module form part of the whole (Jørgensen 2007: 47f.). The six strategies are:

- component sharing modularity
- component swapping modularity
- cut-to-fit modularity
- mix modularity
- bus modularity
- sectional modularity.

Component sharing is about using the same module in different contexts like the same Black and Decker motor in various power tools – or a bathroom pod in different buildings. *Component swapping* is the other way around about coupling different modules to an otherwise identical context. Examples could be Swatch watches – or later added differing conservatories to an otherwise homogeneous group of dwellings. *Cut-to-fit* is when an otherwise standardised module is size-adjusted to the specific context. *Mix* can involve the three former strategies but the different 'modules' are mixed together and practically indistinguishable from each other like in a bucket of paint in a specific (mass) customised colour. *Bus* covers both the slot-modular and bus-modular type from above and is about the idea of a basic structure – a platform – where a number of different modules are 'plugged' into – either via a standard interface (bus) or a module specific interface (slot). Examples of both can be found in a personal computer where the USB plug (Universal Serial Bus) enables bus modularity to many different modules whereas the monitor plug represents the more specific slot-modularity. In construction a structural frame can be seen as a bus (a basic structure or platform) based on either bus or slot-modularity or a combination of these. Finally, the *sectional* strategy equals the sectional-modular type above where there is no hierarchy of a basic structure (or platform) and added modules but just coordinated modules that all have one and the same standardised interface. The LEGO toy is a clear product example of this strategy. The sectional strategy and modularity is seldom found in construction but is also the hardest one to achieve due to the requirement of one common interface between widely varying functional and physical modules (ibid.: 50). This is much easier in the USB plug where only electric power and digital signals are exchanged through the interface.

According to Baldwin and Clark who deal specifically with the impacts of modularisation in the product industry, integration requires a high degree of overall design coordination in each specific case whereas modularisation in the sense of isolating discrete systems within chunks makes possible to 'change pieces of a system without redoing the whole. Design becomes flexible and capable of evolving at the module level' (Baldwin and Clark 2000: 6). Here lies the power of modularity that has resulted in considerable innovation and growth in the product industry by facilitating the elaboration of complex products made out of several simpler subsystems that can be designed independently while still working together as a whole (ibid.). Modularity eliminates the factor of limitation of individual human capacity to learn, think and act. Baldwin and Clark consider these complex products as complex adaptable systems that apart from the products themselves also encompass the applied technologies (processes), the involved firms and the receiving market (ibid.: 2). Modularity cannot be isolated to the physical structure of the product alone – it integrates process and organisation.[5] A certain physical division yields a certain procedural and organisational division and equally the other way around. One could say that these different structural dimensions of a product display *isomorphism*, or similar structures (ibid.: 11). The next chapter, 'General systems theory', returns to this notion of isomorphism as a specific systems property. Another characteristic of modularity is the *nested hierarchical structure*:

> Here we define modularity as a particular pattern of relationships between elements in a set of parameters, tasks or people. Specifically, modularity is a nested hierarchical structure of interrelationships among the primary elements of a set . . . a pattern of nested hierarchical blocks.
> (ibid.: 11)

In the attempt to operationalise modularity as a specific design strategy, Baldwin and Clark arrive theoretically at the establishment of six modular operators as '"things that designers can do" to a modular system' (ibid.: 123). The operators express some of the important dynamic possibilities that lie in working with modules as an active part of the design process. Again modules can be physical chunks, tasks or people:

1 *Splitting* a design and its tasks into modules
2 *Substituting* one module design for another
3 *Augmenting* by adding a new module to the system
4 *Excluding* a module from the system
5 *Inverting* to create new design rules
6 *Porting* a module to another system.

In complex adaptive systems operators are actions that change existing structures – or design concepts – into new structures in well-defined ways. The operators constitute a set of actions that make sense for hierarchical divisions and arrangement of blocks (ibid.: 131) – as modular product architectures are examples of. Other operators could also be formulated. The *integration* of two or more sub-modules into one could be an obvious one.[6] The ideas behind the six operators above are relatively easy to understand except perhaps for the two latter. *Inverting* refers to the splitting, generalisation, and transfer of a sub-module or part of a module (of function or process) to a higher level thus serving various sublevels. An example from the computer industry is a printer driver that is needed in many programs to communicate with the printer (word processors, drawing programs, web browsers, picture manipulation programs, etc.). Instead of integrating a driver in each program this driver is generalised on a higher level in the hierarchy and redundant repetition is avoided (ibid.: 138). In construction, the delivery/production of a certain function, material or component found in various chunks of a modularised structure could be coordinated in order to reduce space need or facilitate bulk buying. The *porting* of a module to another system points towards the *commoditisation* of a module thus making it applicable and potentially even reusable in other design contexts.

The appearance of modular designs – a process that according to Baldwin and Clark began around 1970 – has led to the forming of *modular clusters* which are 'group[s] of firms and markets that "play host" to the evolution of a set of modular designs' (ibid.: 16). If certain modules and their particular interface definitions become sufficiently established, industry will adapt to it and emerge around them. In construction this effect is so far mostly known on a relatively simple component level as e.g. bricks, chipboard or windows. More complex systems such as bathroom pods and façade cladding are beginning to form networks of sub-suppliers but they can so far not be characterised as modular clusters.

Product platform and product family

In accordance with the bus- and slot-modularity introduced above, many products based on modular principles are based on a combination of a basic structure and a number of modules that are connected to this structure. True and complete sectional modularity (see above) where modules of a product architecture are structured in a non-hierarchical way based on one or few standardised and universal interfaces is marginal within the product industry and practically non-existent in the construction industry. Complex artefacts – such as buildings – simply include too wide a range of functional elements too make it plausible to have a common interface. A basic structure of a set of common components or a core technology where different modules are added, attached or inserted is, within product development, called a *product platform*. The platform itself can also be modular facilitating the possibility of evolution over time. As with modularity, the constituent elements of product platforms can be both products and processes. The combination of a product platform and a number of different modules that can be combined in different ways to form different products are called a *product family*. Meyer and Lehnerd define a product family as 'a set of products that share a common technology and address a related set of market applications' (Meyer and Lehnerd 1997: 16). Product families can also evolve over time thus representing various generations of one or several products – a 'family'. The idea is that the reuse of the platform can save both time and money in the development of new products that consequently can hit the market faster and at a more competitive price. Quality-wise, platforms can be seen as a way to integrate well tested solutions into new products.

Black and Decker is an early and well-studied example of the advantages in developing a product platform as the base for a product family of power tools (Meyer and Lehnerd 1997). Due to an external legislation demand imposing double insulation in all power tools in order to protect users from electrical shock in the case of failure of the first insulation system, Black and Decker was forced to adapt their entire product portfolio (ibid.: 4). This was used as the occasion to (a) redesign all consumer power tools at the same time and (b) redesign manufacturing simultaneously. The goal was to offer the new double insulated products at no increase in price.

The most common part of the different tools were identified as the motor which subsequently became a major subsystem of the new product platform in the form of a universal motor that replaced the 30 different independently developed motors of the earlier product line. Furthermore the production of it was fully automated and it was designed with a plug-in connection thus eliminating the need for manual wiring at assembly. The new motor had a fixed diameter and the power of different versions for the different tools (drills, sanders, jigsaws or grinders) could be varied simply by increasing the stack length of wrapped copper and steel – all possible within the same automated process on the same production line. Equally the armature of all tools were standardised as a major subsystem and became part of the platform. Gears and other elements were also standardised and integrated into the platform while other parts, as e.g. the drill chuck (device to tighten drill bits), became modules used within parts of the product family (the drills). The increased volume of purchase of each standardised sub-element or material also facilitated bulk buying and good pricing from suppliers (ibid.: 9f.).

In the Black and Decker example, manufacturing became a key driver – although not the only one – for the design solution. The specific manufacturing solution became a 'key enabler of a radical new product platform design' (ibid.: 6). Similar to the gap between architectural ideation and subsequent construction, the product industry also traditionally distinguished between initial engineering (design) and subsequent manufacturing. This was radically changed at Black and Decker and supported organisationally by integrating manufacturing engineers in the design team from the outset thus 'bridg[ing] the traditional divide between engineering and manufacturing' (ibid.: 15)

Configuration and mass customisation[7]

While originally used exclusively within the field of geometry, the notion of *configuration* is today widely used within the product industry, particularly referring to products that production or sales-wise have some degree of openness as systems that make them adaptable to different context or different customers. Configuration is about the ordering of a number of elements into a whole and the shape or (organisational) structure that results from this. To *configure* is then the act of ordering or joining elements into a whole. As used within the product industry these elements are often drawn from an already existing or known 'pool' (conceptual or physical). The concept is inextricably connected to the concept of *mass customisation* that will also be treated in this paragraph and also have connections to what within CAD-programs today is referred to as *parametric design*.[8] Instead of virtually having limitless possibilities, configuration implies the establishment of a solution space defined through a number of standards and parameters. This does not necessarily lead to a finite number of solutions as standards and parameters can have continuous ranges of value. However, in its true meaning it does establish clear limits to what is possible. Through configuration in the product industry, at least theoretically, a unique solution is produced in each case by adapting the variable parameters within a certain platform or *product configurator*.

A product configurator is typically a piece of software that generates a digital parametric model of a given product (e.g. a building component) based on a number of variable values or simple design parameters. Parameters could be length, height, material, etc. This model can be visually accessible to the user but can also simply be (numerical) values on, for example, an Excel-sheet feeding a production system directly with instructions. The configurator can be accessible on the web page of a manufacturer or supplier and can be directed towards different user groups: on the one hand, the configurator can be developed for use in the manufacturing company as a way to rationalise and make more efficient the internal information and workflow. It can form the basis for the elaboration of production drawings, parts lists, price determination, and bidding or in some cases be directly linked to the digitally controlled production machinery. On the other hand, the configurator can also be developed as a tool for use in detail design/design development and execution phases. A product configurator in a way automates the integration of the expert knowledge from the manufacturer thus supporting a design for manufacturing approach in the design and avoiding expensive and time consuming 'translations' from concept to actual production. Finally, a configurator can be a tool purely for communication and visualisation in a sales situation providing customer information about product appearance, price, delivery time for a (mass) customised solution, etc. Ideally, configuration integrates all of these issues into one single integrated configurator. This, however, is seldom found. Configuration can be understood as a shift from traditional drawing, project design and planning to an object based 'intelligent' digital modelling with continuous and direct reuse of data created during the different phases of the design process.

Within construction, the notion of configuration has also gained currency in the more general meaning of adaptability – e.g. in the context of the built-in capabilities of a plan layout to adapt to changing needs of the inhabitants i.e. relocation, removal or installation of partition walls. Configuration in this meaning is not so much about the production of a configurable product as it is about a continuous relation between product and user over time.

The notion of *mass customisation* was first time introduced in the book *Future Perfect* by the North American Stan Davis in 1987 and subsequently elaborated by the other North American business theorist Joseph Pine II e.g. in *Mass Customization: The New Frontier of Business Competition* (1993). *Mass Customisation* encompasses the combination of the advantages in mass production on the one hand and the 'tailor-made' unique solutions on the other hand. This combination has primarily been made possible through the application of modern IT technology. Crucial for a successful *mass customisation* is the determination of an appropriate solution space.

> The solution space can be very narrow thus not enabling variation that can satisfy a broad range of customers – hence Mass Customization is not achieved. Or, the solution space can be very broad thus making possible great variation that gives the individual customer a better possibility of getting a personally suitable product – hence Mass Customization is achieved.
> (Jørgensen 2007: 43)

The German professor of management, Frank Piller formulates the concept of mass customisation in the following way thus integrating the aspect of (end) user or customer involvement (and not only the customisation itself) as an important characteristic:

> Following the simple definition, mass customisation means to produce unique objects with the efficiency of mass production. The traditional balancing between either producing individual objects expensively or producing standardised objects cheaply has been overcome. When you look upon mass customisation over the last ten years I will however add that the most brilliant is that it involves the consumer in the design process. The unique thing is that in order to create individualised objects you have to involve the customer or the consumer in the process.
>
> (author's translation from Mossin 2006, cited in Beim et al. 2007: 30)

In the product industry the notion of mass customisation represents an attempt to meet the increasingly pronounced demand for individualised and flexible user and context adapted products. An important difference between 'contemporary' industrialised products and construction projects is the significance of the platform. In the car industry for example, variation of the platform even across different manufacturers and brands is quite limited while most product variants deals with relatively superficial properties as colours, surfaces, etc. In construction, if the platform is defined as the structural building system, its possible variations have much more direct significance for the end user – the inhabitant. This platform does not constrain the choice of colours, surfaces, etc. but is decisive when it comes to the spatial and organisational possibilities and flexibility in the final design – and its possible change over time and during use.[9] Changes in (choice of) structural system are much deeper and design decisions and production of the structural system is mostly located earlier in the design process making delayed differentiation difficult.[10]

Supply chain (management)

As division of labour has evolved in modern complex societies, the specific task of each individual and/or company has become ever more specialised. From having a close connection between the work performed and enjoying the fruit of it, most people on earth today engage in an extremely complex web of exchange of matter and services ultimately coordinated by one single means: money. A supply chain is a kind of systems approach that expresses how products (or service products) come into being through a sequence or web of processes performed by a sequence or web of different operators that transform resources into end user products to be used and/or consumed. Company internal supply chains are often referred to as logistics. According to Nagurney:

> A supply chain, or logistics network, is the system of organizations, people, technology, activities, information and resources involved in moving a product or service from supplier to customer. Supply chain activities transform natural resources, raw materials and components into a finished product that is delivered to the end customer. In sophisticated supply chain systems, used products may re-enter the supply chain at any point where residual value is recyclable.
>
> (Nagurney 2006)

Another interesting aspect of Nagurney's definition is the latter part that indicates the possibility of an afterlife of a product or parts of it through recycling after the end of its useful life. This 'second half' of the supply chain has lately gained increased attention due to raised awareness of the finite number of resources available for man on earth. Consequently, design today must to some extent take into account this afterlife as well as actively use recycled resources in new product design. Designing the supply chain has become an integral part of product design itself and this is expressed in terms like *design for manufacturing* and *design for disassembly*.[11] Another point is that supply chains both express the operators, the operations and the product as it advances through the chain – or as Hugos puts it: 'Supply chains encompass the companies and the business activities needed to design, make, deliver, and use a product or service' (Hugos 2006: 2). Simple supply chains focus exclusively on the material flow from a supplier over a processing company to a customer whereas extended supply chains can include the entire material flow as well as the different service providers delivering immaterial contribution, that is design, transportations, finance, etc.[12] The terms *upstream* and *downstream* are commonly used in relation to supply chains. Upstream refers earlier in or in the beginning of whereas downstream refers to later in or at the end of a supply chain. Using the metaphor of a creek or a stream (of water) makes it intuitively easy to understand that upstream is prior to downstream. Processes or operators are located along the stream while the material flows through the supply chain from raw material to finished product. In practice, supply chains are often purpose specific (focused) in the way that they are designed or viewed from a certain standpoint, that is a manufacturer's only including what in their perspective is relevant upstream (suppliers) and downstream (customers). In such supply chains *tiers* refer to the number of supplier links between the manufacturer and the suppliers. On the first tier (1) the direct suppliers are found whereas tier 2 are indirect suppliers (suppliers of suppliers) and tiers 3, 4, etc. are further upstream. In some cases the tiers are also used as a way to define the complexity level of a (physical) supply as tier 1: complete components, tier 2: sub-components, and tier 3: raw materials.[13] Tier categories can vary.

The discipline of designing and managing adequate supply chains in order to meet customer demands efficiently is simply called *supply chain management* and arose as a common term in the late 1980s to become widely used from the 1990s (ibid.: 3). Adequate supply chains are a trade-off between what Hugo calls responsiveness and efficiency and the goal is ultimately to ‘increase throughput while simultaneously reducing both inventory and operating expense’ (ibid.: 9). The latter indicates the competitive business environment that all products and product development face in today’s globalised market economy. Products are not just made in isolation to definitively solve a problem or meet a demand. They are constantly pushed by other similar attempts to do the same in better, cheaper and/or faster ways. This drives towards efficient coordination of the realms of production, inventory, location, transportation as well as information – the latter binding the former four together. ‘Timely and accurate information holds the promise of better coordination and better decision making’ (ibid.: 6). In a traditional industrial economy based on slow-moving mass markets this was ultimately handled through vertical integration where business conglomerates such as Ford ended up controlling the entire supply chain from mining of raw material over production to the sales of the finished car to the end customer. Ford’s success was based on what is called economies of scale meaning reducing the average cost per unit. In modern, fast-moving markets, however, responsiveness – the ability to meet fluctuations in demand or rapidly changing needs – compromises efficiency and rather calls for *virtual integration* where companies choose to focus narrowly on core competencies and partner with other companies and together form flexible supply chains that can constantly be adjusted according to changes in the market (ibid.: 20). Instead of encompassing entire supply chains, manufacturers of complex products use materials, components or assemblies prepared by other manufactures as sub-deliveries for their production. This strategy is rather based on what is often termed economies of scope meaning the ability to make product diversification economically viable. Product platforms and product families, as introduced above, can be seen as strategies for obtaining both economies of scale and economies of scope by combining standardised parts or modules with customised parts or modules into unique products. This again can be combined with a virtually integrated supply chain. A prime example of this is the iPhone or other smartphones that act as product platforms for a multitude of apps that are produced by many different suppliers without any direct connection to Apple, HTC or whoever produces the phone or the operating system.

Systems engineering

Systems engineering is a special (scientific) field within engineering seeking to respond to the problem of increased complexity of engineered products as a result of enhanced sophistication in their design (evolution) and the resulting growing amount of specialised knowledge involved. Systems engineering can be defined as ‘a method by which the orderly evolution of man-made systems can be achieved’ (Skyttner 2005: 43) or as the ‘scientific planning, design, evaluation and construction of man-machine systems' (Bertalanffy 1968: 91). Systems engineering is focused on the orchestration of the most optimised combination or sequence of available work processes and tools in order to achieve a predefined goal and has roots in cybernetics (control theory) and operations management. Many sophisticated methods and (software) tools have been developed particularly to address systems engineering's specific focus on looking at wholes of interdependent means, processes and elements. One of these, the *design structure matrix*-approach (DSM) will be introduced below.

Systems engineering has greatly enhanced man's capacity to manipulate the resources of our physical environment into products serving human needs. The engineer occupied with this field is sometimes called a *system architect*.[14] Important in relation to (architectural) building design, however, is to note that systems engineering as a strictly technical field is concerned with the *how* of (well-)defined problems or goals. *What* the need or goal is, is defined *a priori*. This has roots in the historical split between the liberal and the mechanical arts as pointed out by both Gevork Hartoonian and Kenneth Frampton as they are referred in the previous chapter 'Systems in architectural theory'.[15] Peter Checkland, an American systems theorist who will shortly be introduced in the following chapter, exemplifies it in the following way:

> The [systems engineering] approach then boils down to expressing the need to be met in the form of a named system with defined objectives (say, a system to build a supersonic aircraft meeting a defined specification within a stated time and to a stated budget; or a system to supply a small town with pure water at a certain rate for a given cost). If the system and its objectives are defined, then the process is to develop and test models of alternative systems and to select between them using carefully defined criteria which can be related to the objectives.
>
> (Checkland 1990: 17)

Supply chain management, as introduced above, can be seen as a kind of – or sub-discipline to – systems engineering. It is primarily in this sense that it will be used in the present monograph but also the idea of looking at wholes (and selecting between alternatives) will be elaborated as main focus of the following chapter 'General systems theory'.

Design structure matrix (DSM)

Design structure matrix (DSM) is a matrix representation of a (complex) system like a product/project, process or organisation and can be used as modelling tool or technique that expresses dependencies between elements or modules in this system thus helping to manage the design and organisation of these. The DSM was originally invented by Donald Steward in the 1960s exclusively dealing with time-based dependencies of a process. The matrix lines up all elements – or modules – on both a vertical and a horizontal line thus forming a matrix where the interdependencies between the different elements can be registered. In some versions dependencies can be directional (e.g. 'a' depends on 'b' but not opposite) and/or weighed through the use of different values places on each dependency.

Various manual and algorithmic procedures exist to e.g. sequence elements of a process (*tearing*) in process DSMs or grouping functional/physical elements into chunks of a product architecture (*clustering*) in product DSMs. A third 'domain' of DSMs deals with organisational entities. The DSM methods are mostly applied in systems engineering, product planning or project management where products, processes, or organisation entities as well as the design problem are well-defined.[16] The traditional DSM method is less adequate for early design stages as it lacks clear mechanisms to construct the matrix when the constituent elements are ill defined.[17] However, considerable research and practical application of the DSM and related methods constantly develop the field and the range of techniques. DSMs can in a way be seen both as product architectures and as supply chains (product DSMs vs. process DSMs or organisational DSMs that can be both simultaneously). This idea of duality or integration of domains has advantages that will be explored later in Part III – 'Model'. A disadvantage of the DSMs is that they are not so visually accessible. Even with only a small number of elements the matrix quickly disables the overview for manual operations/manipulations and leaves you dependent on the related mathematical algorithms. With a high number of elements the DSMs become very big and the issue of focusing attention and choosing the right level of abstraction is therefore important.[18] The architect Christopher Alexander, in his early work, similar matrices in his attempts to formulate a more systematic approach to architectural design.[19]

A few international research environments work with the direct application of DSM to construction processes. One is a process-focused *Lean Construction* track around the Finnish Lauri Koskela currently based at the University of Salford, UK. Another is a more product-focused approach dealing with how buildings accommodate to change (adaptability), and is inspired by Steward Brand's model of different building layers. This approach is, among others, found around Professor Simon Austin at Loughborough University in the UK.[20] Brand's model introduces the view that buildings should be designed according to a conception of different layers (of building parts) with different life spans. His fairly simple model which is an elaboration of earlier concepts by Frank Duffy contains six layers (the six Ss): Site, structure, skin, services, space plan and stuff. Site is 'eternal', structure (load bearing elements) last 30 to 300 years, skin (exterior building surfaces) change on an average of 20 years, services (mechanical, electrical and control systems) last 7 to 15 years, the space plan (interior layout) 3 to 30 years, while the stuff (furniture and other accessories) change constantly. At Loughborough, the layers are used as a base for coding dependencies (in DSMs) between building parts and components in specific projects in order to understand and provide for a more conscious way of putting buildings together in this sense.

Design for X (DfX)

The notion of *design for x* refers to a wide range of approaches to product design that take on a specific focus during the design process. The 'x' should be understood as a 'variable' that can be replaced by such foci that subsequently leads to different design methodologies. The first of these was *design for manufacturing* and *design for assembly* originally coined by Boothroyd, Dewhurst and Knight in their book *Product Design for Manufacture and Assembly* (1994). The idea was that product design from the outset should include considerations about how the product was to be produced and/or assembled. This would generally reduce costs and make product development more efficient and profitable. The issue could, according to the authors, be addressed through specific procedures concerning the selection of production processes and materials. *Design for x* methodologies in general address different issues of a product's life cycle or its performance rather than its form or aesthetic appearance and marks within product design a concern for avoiding a too narrow design approach.[21] Other examples are *design for installation*, *design for maintenance*, *design for ease of use*, *design for demolition*, *design for reuse* and *design for disassembly*. The approaches are not necessarily mutually exclusive. The two latter and in particular *design for disassembly* has lately gained special attention due to increased environmental concern whether it be for true altruistic dedication or merely for branding reasons. When an overall aim of this book is to discuss the possibilities and the potentials of bringing architectural ideation and the way buildings are subsequently produced closer to each other it touches upon the same issue within architectural design. *Design for* x somehow represents a rejection of (architectural) design as a free art and points – in a general way – towards the reunification of idea, process, and matter. One of the case studies in Part III – 'Model' – shows a general concern at the office of KieranTimberlake for such a broader design approach bringing in the process as a design parameter. It also analyses a project by this office that specifically addresses the *design for disassembly* issue.[22]

Industrialised principles in building projects

Product architecture, modularity vs. integration, product platforms and families, configuration, mass customisation, supply chain (management), and the use of DSM methods as they are used in the product industry can all be seen as strategies used to handle increasing complexity and – perhaps – as ways to reduce the complexity *in focus* when products become complex (adaptable) systems.[23] This does not mean that the overall complexity of products is necessarily reduced. Actually the case is most probably the exact opposite:

it enables control of more complex products, processes and organisations by introducing system properties that exceeds the scope of the individual product thus combining economies of scale and economies of scope, as explained above. It furthermore enables the partition into relatively independent elements that can be treated separately and in a parallel fashion thus saving both time and resources. The result is a more open and flexible industrialised product solution than the traditional standardised and mass produced product that, however, still encompasses many of the qualities of mass production, i.e. uniform quality, fast and (relatively) cheap production, and the ability to draw directly on earlier experience (i.e. products in a product family). This makes systematic product development easier than for both its mass produced and its handcrafted counterparts. A returning question in this book is of course whether such system properties have isomorphic counterparts within the construction industry if buildings and the processes of bringing them into being are regarded as complex systems.

Faced with the problems of coherence in construction, the present chapter has looked into how (structurally) similar problems within the product industry have been met and partly overcome. It seems plausible to suggest that some degree of technology transfer (of concepts, methods and techniques) should be possible between the two fields.[24] This is probably what is already happening in many parts of the construction sector – in particular concerning the processes that are already located in factory environments. Lean-production principles that have not been explicitly treated here are widely applied and have a parallel, *lean construction*, that concentrates on 'project based production management in the design, engineering, and construction of capital facilities'.[25] This track leads rather to a focus on industrialisation of on-site construction processes and has less focus on systematic product development and enhanced commoditisation of such products within the construction industry. Such a project-based approach for development – as most traditional construction – in the worst case fails to provide incentives for the development of robust platforms, modules or principles that exceeds the project level and can thus result in sub-optimisation of each project and within a project. Through what Mikkelsen et al. calls 'developing in projects' instead of 'producing in projects' (2005: 7) the learning and knowledge transfer become embedded in the projects and in the work culture bringing them into being rather than in discrete and robust industrialised products that can easier move across borders and find new markets while continuously 'mutating' through the modular operators of splitting, substituting, augmenting, excluding, inverting and porting as described above.

Notes

1 The degree of prefabrication does not necessarily have a direct linear relation to the complexity and sophistication of industrialisation. Much of the so-called prefabricated construction is merely construction under roof with only limited use of industrial techniques, processes and business models.

2 That such a problem also exist(ed) in the product industry is suggested by Meyer and Lehnerd as described further below.
3 A formal definition of this new term can be found in 'Architectural systems terminology', Ch. 5.
4 Structure in the sense of *organisation*.
5 Here is a parallel to the *Omniclass* distinction between *product and work result* in construction works as presented in the previous chapter 'Classification systems in construction', Ch. 2.
6 Baldwin and Clark regard integration as the exact opposite of modularisation which is probably why it has been left out as a specific operator for modularisation. However, changes made to a given product architecture could easily result in a combination of integration and modularization as defined by the six operators above.
7 This paragraph is mainly the (author's own) adapted translation from (Beim, Vibæk and Jørgensen: 2007: 28ff.). Other direct sources are stated as references.
8 Behind the concept of *parametric design* lies an intention of defining a 'design engine' or model that can generate manifold designs from a given set of parameters that in each case are assigned individual values. Although this system produces different answers to a well-defined design problem, the design of the system – the design engine itself – is not a well-defined problem with a clear purpose.
9 Flexibility can have different connotations in construction. For the author's own discussion of the notion of flexibility in architectural systems distinguishing between design flexibility, conversion flexibility and flexibility of use, see Beim, Nielsen and Vibæk (2010: 26ff.).
10 See explanation of delayed differentiation above.
11 See definition of *design for X* further below.
12 The distinction material/immaterial is not completely consistent in the sense that even the product itself can be more or less immaterial as e.g. a piece of software, a service in itself or merely an experience; cf. *experience economy*. See 'From construction of projects to production in projects', Ch. 6.
13 See http://www.witiger.com/internationalbusiness/SupplyChainManagement.htm (accessed 24 July 2011).
14 See Maier and Rectin (2009: 6).
15 See 'Systems in architectural theory', Ch. 1.
16 See http://www.dsm.org and http://en.wikipedia.org/wiki/Design_structure_matrix (accessed 20 July 2010).
17 See Lindemann et al. (2010: 55). For an elaboration of the notion of ill-defined problems see also Maier and Rechting (2009).
18 See the following chapter 'General systems theory', Ch. 4, for an introduction to notions as *levelled complexity* and *flexible structuration*, dealing with this issue.
19 See 'General systems theory', Ch. 4.
20 For an example of the DSM product-approach combined with Brand's layers in construction, see Schmidt, Deamer and Austin (2011).
21 Available online at http://www.betterproductdesign.net/guide/design4x.html (accessed on 23 July 2011).
22 See 'KieranTimberlake', Ch.10.
23 There is no particular need to elaborate a product architecture for the relatively simple physical composition of a brick.
24 The problems of coherence in construction are mentioned in 'Introduction'.
25 See http://www.leanconstruction.org/ (accessed on 5 July 2011).

4 General systems theory

Introduction

A previous chapter looked into ways that the construction sector, through use of classification systems, has sought to address the increasing complexity and fragmentation of knowledge in construction. The result is extremely elaborate classification and identification systems for elements and processes in construction that, however, as pointed out, have the side effect of an over-specification that only has weak connection to the way architecture is conceived and conceptualised in the early design phases. It can even constrain or complicate this work unnecessarily.[1] The attempt to handle complexity through extensive classification actually seems to further enhance the *fragmentation* of knowledge. On the other hand, the production industry has, as described in the previous chapter, to some extent managed to combine product complexity with systematic approaches and elements of repetition. The current chapter widens the scope a little further and introduces (general) systems theory as a way to look at wholes as *relations* between different parts of an interconnected system such as a building or a construction process. By downplaying the individual characteristics of each of the elements in a system, system models represent an alternative and a supplementary way of handling complexity. The basic assumption of general systems theory (GST) is that complex systems present general characteristics (or behaviour) that are relatively independent of the characteristics of their individual parts. This capacity of abstraction could make system models a useful intermediary tool between architectural concept and realisation that could be applied already from early design phases. Another point is the contextuality or openness of system models; they always express a specific viewpoint according to the specific purpose of the model.

First, the systems view is introduced as an alternative to traditional worldviews. This leads to an introduction of general systems theory as a distinct scientific discipline and its possible application to the field of architecture. Subsequently architecture and architectural creation are presented as complex systems made of sub-elements being systems in their own right.

Hypothesis and questions addressed

Widespread specialisation in construction caused by growing complexity has resulted in fragmentation into isolated fields of knowledge and has produced a need for intermediary models capable of grasping relations between these rather than their individual characteristics.

This hypothesis is addressed through the following research questions:

1. How does (general) systems theory address the balance between specialised knowledge and wholes?
2. How can (general) systems theory point towards answers to the need for an intermediate model that can help combining specialised knowledge (of architectural construction) into coherent wholes?

Mechanistic vs. holistic world view and the systems view

From the emergence of modern science and until recently the world has *either* been seen as a sum of its constituent parts *or*, where science stops, as an integrated entity explained through holistic assumptions established through intergenerational tradition, intuition, faith or pure imagination. Both strategies have their eligibility and usefulness for understanding and navigating in the world but also present clear limitations and severe problems of combination.

Modern science is based on the assumption that exact and highly detailed knowledge can be used to describe real world phenomena and that the degree of detail 'automatically' enhances the level of understanding and the explanative power. This world view is often referred to as *mechanistic* or *atomistic* and has created an enormous amount of specialisations and new sub-disciplines within the sciences as knowledge has developed and available information has increased. Modern sciences are *analytic*. Apparently the sciences seem to have enhanced man's control over the natural world and have enabled an increase in the general material standard of living thus shifting the everyday focus of a considerable amount of human beings on Earth from immediate satisfaction of basic physiological needs and survival towards higher levels on Maslow's famous pyramid or hierarchy of needs. This fact has again further accentuated man's capacity to produce new and specialised knowledge at an ever growing rate. The world is seen as a machine composed of a number of parts each having their particular function. The specialist looks at and describes facts of the separate parts and simple causal relationships between these isolated phenomena in the form of *cause-and-effect* or *stimuli-response*. Relationships can be either deterministic or probabilistic the latter (statistical) version softening the hard-fact character of knowledge while, however, still maintaining the focus of one-to-one linear relations.

The Hungarian philosopher of science and systems theorist Ervin Laszlo (1932–) describes the basic problem – or limitation – within this mechanistic worldview through the observation that real world relations seldom are these simple one-to-one or one-to-few relations. What such explanations lack is the capacity to explain or predict how even small groups of elements interact when they are exposed to several different influences at the same time (Laszlo 1996: 3). He exemplifies with the behaviour, techniques and tactics of an athletic team or a business corporation whose properties cannot be meaningfully reduced to the sum of their individual members who can be replaced without causing noticeable difference in the whole represented by these social entities (ibid.: 5). This problem of the mechanistic world view can be generalised to anything from atoms or molecules in the small scale to entire societies or ecosystems in the large scale. The specialised sciences pursue knowledge in depth but also in isolation that often – and increasingly – fails to integrate this knowledge in breadth. The result is fragmentation where different fields of knowledge, even within the same discipline, potentially lose the capacity to intercommunicate and coherence is lost. Without coherence between the different fields of knowledge the value and real world applicability of the specialised knowledge is challenged.

In architecture and construction an explosion in new materials and components with different static, thermal, visual, acoustic, tactile and other (physical/chemical) properties as well as sophisticated static calculation methods, business and investor models, long-term cultural and short-term market trends, new construction methods and machinery, architectural discourse, legislation, etc. altogether create a cacophony of aspects of knowledge that has little in common with the classical well-established and clearly defined 'divine' compositional rules that were grounded in clear construction techniques around few and simple building materials.[2] Although the classical pursuit of harmony is not necessarily a goal of contemporary architecture even just the technical and managerial challenge in combining the aspects above into a whole is almost insuperable. Coherence has – also in architecture and construction – largely been lost and the isolated fields of knowledge run the risk of sub-optimising from each of their compartmentalised viewpoints causing undesirable or even detrimental effects on the whole.

Traditional holistic thinking and knowledge is not a scientifically viable alternative due to the problem of explicating, testing and validating it. Although this predominantly tacit form of knowledge has many foundations in real life experience the consciousness of this fact has been lost in the fogs of tradition. Furthermore it is often very locally founded, context-specific, and dependent knowledge and the direct connection to its context has been lost through rapid technological and societal change. In a context of architectural construction, vernacular building represents a traditional holistic entity of knowledge-encompassing (tacit) knowledge about the applied local materials, the specific tools and techniques used to manipulate these materials, their application in adequate, economical and durable ways, and, finally, knowledge about the vernacular forms it leads to that are embedded into and at the same time framing the specific culture it forms part of. Holistic thinking and knowledge is grounded in reproduction rather than production and inventiveness.[3] Today architecture as a creative (and globalised) generalist discipline as well as all the related and specialised disciplines that bring buildings into the world have been detached from a considerable part of these local vernacular traditions that no longer represent coherent answers to present needs.

However, instead of seeing the distinction mechanistic/holistic as diametrically opposed and irreconcilable concepts, a point could be to look into how to bridge between them. While the mechanistic approach on the one hand fails to grasp the larger picture that a subsystem is part of, the problem in the holistic approach is the difficulty of applying any analytical means due to the complexity and interconnectedness of the whole. An intermediate 'layer' providing tools for understanding of the interaction between subsystems in a whole or a supra-system could be a way to facilitate creation of coherent wholes of discrete subsystems. As the North American environmental scientist Donella H. Meadows (1941–2001) points out:

> Much can be learned by taking apart systems at different hierarchical levels . . . and studying them separately. Hence system thinkers would say the reductionist dissection of regular [mechanistic (ed.)] science teaches us a lot. However, one should not lose sight of the important relationships that bind each sub-system to the others and to higher levels of the hierarchy . . .
>
> (Meadows 2008: 83)

The systems view

A recently emerged scientific paradigm – the systems sciences – represents a quest for an alternative or at least a supplementary scientific world view. Systems thinking is at the time both holistic and analytic and could thus constitute elements of an intermediate layer bridging the two extremes.[4] The definition and delimitation of a system depends on the purpose of describing it. Hence a system in one perspective can often be a subsystem in another. In his description of natural systems, Laszlo uses the notions of *holarchy* and *holarchic structuration* to describe how different levels or scales of systems are connected – a hierarchy of hierarchies where the entities (the holons) at the same time are both parts and wholes depending on the focus (Laszlo 1996: 51ff.).[5] Important however, Laszlo states, is that systems should be understood as 'integrated wholes of their subsidiary components and never as a mechanistic aggregate of parts in isolable causal relations' (ibid.: 10). Interesting within the framework of this book is that Laszlo points out that such 'systems method does not restrict the scientist to one set of relationships as his object of investigation; he can switch levels, corresponding to his shifts in research interest' (ibid.: 10). Through the capacity to deal simultaneously with various levels (or scales) of interconnections or interfaces systems thinking presents a sort of *levelled complexity* that enables a dynamic management or a *flexible structuration* (or ordering) of the focus of attention. A visual analogue to such a *levelled complexity* and *flexible structuration* could be geometrical fractals.

In a model, flexible structuration and levelled complexity mean that the scale of the individual system entities or the hierarchy in focus can vary according to each case/scenario or viewpoint/focus where the (general) model is applied – cf. 'switching levels'. What constitutes a system entity or subsystem in one version of a model can fold out its own internal system hierarchy or structure in another version. A strategy of flexible structuration enhances the explanative power of a model for analytical purposes as well as making it more robust or resilient to change through the models, capacity of adaptation to scale, context or time. The model becomes more general and thus potentially has a wider scope of application.[6]

System definitions

There are myriads of more or less general system definitions. One particularly clear example can be found in Maier and Rechtin: 'A system is a collection of different things that together produce results unachievable by themselves alone. The value added by systems is in the interrelationships of their elements' (Maier and Rechtin 2009: 27). Another one by Meadows: '[A] system [is a] set of elements or parts that is coherently organized and interconnected in a pattern or structure that produces a characteristic set of behaviors, often classified as its "function" or "purpose"'(Meadows 2008: 188). A complex system is usually defined as one where its elements are in themselves systems that serve relatively independent purposes (as the holons above). Meadows characterises complex systems as inherently hierarchical – Laszlo would expand this to holarchical. Hierarchies or holarchies give a system stability and resilience and reduce the amount of information that any part of the system has to keep track of. Complex systems are partially decomposable into their subsystems – or holons (ed.) (ibid.: 83). Generally, complex systems are defined as systems consisting of many often composite and different parts or subsystems of which their internal organisation or interrelation and relation to surroundings cannot be described in simple terms. Maier, from a systems point of view, terms a complex system as a system-of-systems: 'an emergent class of systems that are built from components which are large-scale systems in their own right' (Maier 1998: 267).

Science of organised complexity

Acknowledging that the characteristics of complex wholes remain irreducible to the characteristics of their parts the systems sciences as 'sciences of organized complexity' has emerged (Laszlo 1996: 8). In Laszlo's terminology these has developed as supplementary applied branches within the established sciences of physics, chemistry, biology, sociology and economics. However, as we will see in the next paragraph these applied system sciences also point towards the emergence of a *general systems theory*.[7]

Bertalanffy and general system(s) theory

In the mid twentieth century, from his standpoint in theoretical biology, Karl Ludwig von Bertalanffy (1901–1972) observed how developments in engineering and computer science intended to overcome the fragmentation caused by technological over-specialisation as described above. Presented with similar problems within his own discipline he conceived, as one of the first, the idea that a general system theory as a distinct scientific discipline should be concerned with general system characteristics crossing traditional fields of knowledge (Bertalanffy 1968: viii):

> . . . it turns out that there are general aspects, correspondences and isomorphisms common to 'systems.' This is the domain of a general system theory . . . General system theory, then, is scientific exploration of 'wholes' and 'wholeness' which, not so long ago, were considered to be metaphysical notions transcending the boundaries of science.
>
> (ibid.: xix)

This idea of *isomorphism* (meaning a similar shape or structure) between systems stemming from widely different fields points towards a *structural* approach with focus on organisational or relational aspects among entities rather than description of characteristics of the entities themselves.[8] In his definition of systems Bertalanffy distinguishes between *real systems* and *conceptual systems*. Where the former are 'entities perceived in or inferred from observation, and existing independently of an observer' the latter are not accessible for direct observation but are 'symbolic constructs' as logic, mathematics, music, etc.[9] In practice, however, this distinction cannot be drawn in any clear way, as perception of real everyday objects which are determined by a considerable amount of mental and cultural factors. Perception is not a mere reflection of 'real things' and '[knowledge] is an interaction between knower and known, this dependent on a multiplicity of factors of a biological, physiological, cultural, linguistic etc. nature'. Knowledge and science is a way man deals with the world – it is not a one-to-one description of it. By acknowledging this 'intertwinedness' of humanistic and mechanistic aspects of knowledge Bertalanffy claims his vision for a unified general system theory to bridge the opposition between sciences and humanities or between technology and history (ibid.: xxi ff.). This is somehow parallel to the gap between construction (technology) and architectural idea (concept) that this book seeks to investigate as an increasing problem in architectural design.

Bertalanffy lists and shortly describes an array of different formalised approaches to investigate systems some being (descriptive) models other proper mathematical techniques.[10] The approaches, however, often evolved within specific scientific disciplines present some level of generality applicable to various fields. However, 'diverse system models will have to be applied according to the nature of the case and operational criteria' (ibid.: 28). None has shown all-encompassing answers to the vision of a *general systems theory*. They can only be seen as steps towards it. A fundamental principle of such a theory is, according to Bertalanffy, that of *hierarchic order*.[11] Interesting here is that he locates this general principle of hierarchy both in 'structures' understood as the order of parts and in 'function' understood as the order of processes that, as he proceeds, 'may be the very same thing: in the physical world matter dissolves into a play of energies, and in the biological world structures are the expression of a flow of processes' (ibid.: 27). The often drawn distinction between process and matter – between a process and a product (as result of this process) is not that clear. If we bring this insight into construction it could indicate a systemic connection between how buildings come into being and how they actually are composed as physical objects. If we combine this with the intertwinedness described above we might even tentatively suggest that systems of matter, processes and *thought* can be integrated into one and the same model. This idea has been followed in the development of the model described later in Part III – 'Model'.[12]

Although Bertalanffy mostly uses mathematical equations and algorithms in his exemplifications and descriptions of systems and their properties he underlines that non-mathematical i.e. verbal or conceptual models can be preferable to forcibly imposed mathematical versions. In his view these models are important as preliminary expressions of new system aspects to be evolved into a more hard-fact model description:

> It may be preferable first to have some nonmathematical model with its shortcomings but expressing some previously unnoticed aspect, hoping for future development of a suitable algorithm, than to start with premature mathematical models following known algorithms and, therefore, possibly restricting the field of vision.
>
> (ibid.: 24)

However, one thing is to elaborate system models that in a precise way can describe (general) structures of and interaction between a number of elements in an existing system (its behaviour). Bertalanffy's point of departure is biology and is mainly descriptive and primarily concerned with understanding existing and observable natural or social phenomena. Another slightly different thing is to elaborate models that seek to describe systems that are (to be) *designed* through human ingenuity. As long as the design problem or the *purpose* of the system can be clearly defined, a mathematical or algorithmic model might be imaginable.[13] In creative processes, such as architectural design, where problems or purpose are mostly ill-structured and multifaceted and often rise and evolve in iterative interaction with a proposed (system) solution it is more difficult to imagine how this could be expressed through mathematical formulae.[14] The concept of *parametric design* deals to some extent with this issue.[15] This brings us to two useful distinctions in systems thinking that can be applied to clarify what kind of systems that are dealt with in the present context: open vs. closed systems and soft vs. hard systems.

Open and closed systems

A closed system in its strict definition is a definite set of elements in a relation without any input from or output of energy, information or material to the environment surrounding the system – it is a system in isolation. Conventional physics following the mechanistic world view is exclusively dealing with the description of closed systems. Most real world systems are open systems in the way that they exist and are maintained – or maintain themselves – for a certain period of time through a continuous inflow and outflow of energy, information or material.[16] Through these inputs and outputs an open system can (a) be in a dynamic but steady state, (b) evolve towards such a steady state, or (c) develop towards a different state. Living organisms are good examples of such open systems. Where, for example, a full-grown horse is in a dynamic but steady state, its foal evolves towards this state (of full-grown horse). Finally, through reproduction over generations the natural evolution has brought forward the horse a species distinct from its earlier stages and from other animals.[17] Any closed system will reach a final state defined by its initial conditions. If conditions are changed, the final state will change correspondingly. This is not necessarily the case for open systems that in some cases can reach the same final state from different initial conditions or in different ways. This principle of open systems is called *equifinality*. An example from biology is the growth of similar organisms exposed to different nutritional conditions. In natural phenomena the (equi) finality or purpose of a system has either been directed to the combinations of physical laws, genetic mutation and Darwin's theory of evolution (survival of the fittest) or to a so-called metaphysical 'soul-like vitalistic factor which governs the processes in foresight of the goal' (Bertalanffy: 1968: 39f.).

Architectural creation as an open system

In architectural creation, the purpose of a building is neither defined by physical or evolutional laws nor by vitalistic or divine intervention. It is ultimately defined by the conscious or intuitive choices of the architect as an integration of an architectural concept and the various demands, potentials and visions for the project – resulting in an ill or loosely defined design problem expressed as the building itself.[18] Architectural creation can, as the combination of concept and process leading to a final product, tentatively be seen as an open system of respectively information (concept/thought), energy (process) and material (product/matter) that evolves from idea or concept towards a dynamic but steady state – the 'final' building' expressed physically through the applied building materials. The idea or architectural concept is the goal or finality – but the ways to reach that goal can be manifold. In this sense architectural creation expresses something similar to the principle of equifinality as explained above. This point will be brought into the later model building in this book as the quality that various (system) structures can lead to the fundamentally same architectural result.

Soft and hard systems and the soft systems methodology

The British professor in systems science, Peter Checkland, introduces a second system dichotomy that is concerned with the *application* of general systems theory in the systems sciences – the distinction between soft and hard system approaches (Checkland 1999). The distinction was the outset for the so-called soft systems methodology or SSM that was introduced as an alternative to, for example, systems engineering[19] in order to solve problems that could not be defined clearly in technical or mathematical terms – so-called *ill-structured problems* (Skyttner 2005: 481) – like architectural design problems! The method(ology) is used to build what Checkland calls 'conceptual models of human activity systems' (Checkland 1981). In SSM the notion of system is to be understood as a mental construct. This resembles what Skyttner calls the fictionalist view:[20] '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).[21] The system becomes an epistemological rather than an ontological entity that serves as an intermediate conceptual model or tool for human understanding. Depending on the system perspective – i.e. its particular structure of subsystems and their interrelations as seen from a particular (stakeholder's) viewpoint – the system can give very different understandings of the phenomena it seeks to describe. In SSM these conceptual models – or systems – can be expressed in bubble diagrams. The idea of viewpoints in a model will be folded out and tested in the case studies of Part III – 'Model'.

The original version of SSM has seven stages. The stages span from understanding and defining the problem over model building to real world application and contain *iterative loops* in the model development stages. The seven stages are:[22]

1 entering the problem situation
2 expressing the problem situation
3 formulating root definitions of relevant systems
4 building conceptual models of human activity systems
5 comparing the models with the real world
6 defining changes that are desirable and feasible – and
7 taking action to improve the real world situation.

While stages one and two take points of departure in a real world problem, stages three and four move into systems thinking about this real world through model building. The root definitions (stage three) are formulated by considering a number of elements (CATWOE): Customers (victims or beneficiaries), Actors (those who act), Transformation process (from input to output), 'Weltanschauung' (worldview which makes transformation meaningful), Owner(s) (who can stop transformation) and Environmental constraints (elements outside the system taken as given). Subsequently conceptual model(s) are built from the root definitions (stage four). Now these models are brought back and compared with the real world (stage five) in order to point out possible/desirable changes (stage six) and propose actions to improve the problem situation (stage seven). Iterative loops can take place between stages four and six before final action is taken. Interesting here seen within the framework of the present monograph is the idea of modelling a flexible intermediate tool of understanding/describing particular systemic aspects – perhaps even seen from varying particular viewpoints – of what is or will ultimately become an entity with (hard) physical existence fulfilling a given purpose namely a building.

Checkland also establishes a *typological map* of systems and system classes as a kind of system hierarchy. At least four classes of systems are necessary in order to describe the existing reality. These are: (a) natural systems, (b) human activity systems, (c) designed physical systems and (d) designed abstract systems (Skyttner 2005: 175). The natural systems are, contrary to the others, 'systems which could not be other than they are, given a universe whose patterns and laws are not erratic' (Checkland in ibid.: 175). They are not merely mental constructs. The natural systems are ordered as a branched hierarchy from subatomic systems to entire ecologies (or ecosystems). Within these natural systems, the human activity systems are embedded with social systems as the most fundamental. The human activity systems are again coupled to designed physical and designed abstract systems. While buildings in this typology would be classified under designed physical systems (as designed and fabricated material entities) they would come into physical being through the human activity systems (man-machine systems and industrial manufacturing) by application of designed abstract systems (knowledge systems). The entities from the general systems theory of energy, material/matter and information is clearly recognisable in the triad of human activity, designed physical and designed abstract systems – or as they are preferably termed and used in this monograph: systems of *matter*, *process*, and *thought*.

Soft system approaches in architectural design

Although the use of conceptual diagrams and abstract representation is very common in architectural ideation it is seldom used as a systematic procedure or repeated as general elements across different projects. The architect and theoretician Christopher Alexander (1936–) has practised the use of intermediary conceptual models already from the initial design phases. For Alexander, the goal of his models, which he call diagrams or patterns, is to get a purely structural description (a conceptual or physical organisation) of a design problem (Alexander 1964: 126). Subsequently, this structural description can be used synthetically to produce an integrated diagram of the solution as a whole. This overall structure both represents a solution (an element in itself) and the internal structuration of this solution in the form of a pattern. It is the expression of a *holon* in the terminology of Koestler and Laszlo as introduced above:

> It is the culmination of the designer's task to make every diagram both a pattern and a unit. As a unit it will fit into the hierarchy of larger components that fall above it; as a pattern it will specify the hierarchy of the smaller components which it itself is made of.
>
> (Alexander 1964: 131)

Instead of splitting the answer to a design problem up into known designated categories (as e.g. *entrance door*, *living room* or *roof*) and using intuition to conceive the adequate configuration of these elements, the idea is alternatively to split (analyse) the problem up into neutral requirements that can be expressed as single – although seldom numerically expressed – variables, or *basic requirements* (Chermayeff and Alexander 1965: 154). These requirements constitute the programme of the design task. A couple of examples of such basic requirements from the elaboration of a housing development scheme are (a) 'rest and conversation space. Children's play and supervision', (b) 'access point that can be securely barred', (c) 'arrangement to keep access clear of weather interference', and d) 'partial weather control between automobile and dwelling' (ibid.: 155). Subsequently the basic requirements are analysed for interactions or dependencies. The two latter (c and d) have obvious links whereas the two former (a and b) seem independent. Visually such a dependency analysis is expressed as a scheme with all requirements listed in both x and y direction. The interactions between each of the requirements can then be plotted in.[23]

The analysis clearly expresses the impossibility to consider all of these at once in order to suggest a coherent answer. They must be considered in groups. These are created by joining requirements with rich mutual interactions into major components that have no or only little interaction with requirements in other major components (groups). Even for a model of this relatively modest size, this has to be done with the help a computer in order to process the more than 10 billion possible joints (ibid.: 160). This more 'hard system' process resembles the *clustering* algorithms found in component-based DSM analyses.[24]

While some requirements only interact *within* such major component, others interact *between* them and should be considered within both major components (or groups) – as either overlapping or alternatively doubled as separate answers to the same requirement in separate major components. Important to point out is that there is no correct clustering solution. As interaction between different major components can seldom be avoided completely, the strength of these as well as the total number of major component will have importance when choosing between various alternatives.

Now structural *pattern diagrams* (Alexander 1964: 130) can be elaborated for each of the different major components in isolation while considering the now considerably reduced number of basic requirements. This process is 'soft' in the sense that here the architect's more traditional intuitive grasp of the whole is made possible through the reduced complexity of each component as compared to the whole. These pattern diagrams should not be understood as plans but are still 'just' abstract representations of an integrated functional organisation that can meet the basic requirements. The next exercise is to integrate these pattern diagrams of the major components into one single diagram of the entire organisation of all the requirements – a complete but purely *structural* description of the design problem (ibid.: 126). In order to make a consistent integration and not just a juxtaposition of the sub-diagrams, the overlaps between the different components become important to consider. To make a detailed description of this is not within the scope of this book and this chapter. In larger more complex (physical) systems, the integrated diagram can even become a component among others thus constituting a subsystem. The method and the resulting model can consist of various integration levels reached step by step from the basic requirements to the overall solution.[25]

Interesting about the sketched systematic design method and the intermediary model of pattern diagrams is Alexander's insistence on that it is possible to separate analysis and synthesis as two equally important parts of architectural creation. The models – or pattern diagrams – are examples of flexibly structured soft systems that are structured around specific design problems but with systematic and procedural elements that are repeated across projects and combined with a relatively high abstraction level. ' . . . because it concentrates on structure, the process is able to make a coherent and therefore new whole of incoherent pieces' (ibid.: 110). The model forces organisation in the designer's or architect's mind; it does not make her think in a specific way or produce a specific result. However, the specific way in which Alexander reaches the initial basic requirements (the analysis) is a little hard to understand as a purely analytical procedure. It still seems to include a great deal of intuitive interpretation to define these so-called neutral elements.[26] Still, the idea of handling complexity through a hierarchy of flexible integrated patterns rather than fixed entities suggests a more architectural approach for a modularisation of buildings or built environment. Alexander's 'soft system' methods have subsequently been developed into a more formal *pattern language* that, like other languages, has vocabulary, syntax and grammar, and that was intentioned to enable ordinary lay people to engage directly in solving complex design problems. This language, however, has never really gained currency.

Hard system approaches in architectural design

Hard system approaches are seldom found strictly engaged with *architectural* design. The integration of many variables of both hard (quantitative) and soft (qualitative) character, as mentioned, make up ill-structured and multifaceted design problems that are usually not adequate for formulation of mathematical formula at least not in their entirety. Although parametric design engines does represent attempts in this sense, they are often far too limited to constitute general models applicable to virtually any or at least a broad range of projects. Within construction planning and execution phases, where the problem or goal is often easier to define clearly, some attempts of system theoretical approaches have been used inspired by the product industry and the applied field of systems engineering. The graph theory-based *Design Structure Matrix* method (DSM) is one example.[27] However, even if an architectural design problem cannot be put on formula in its entirety, aspects of it can be treated using a systems approach that through a probabilistic connection to the success of the architectural whole could help to qualify choices even in early design phases. By dealing with only one or few but *system characteristic* aspects – or emergent properties – of the architectural whole such an approach is both holistic and analytical.

Space syntax

Space syntax can be seen as an approach that presents some of the characteristics of a hard system approach while still dealing strictly with architectural design issues. Space Syntax was originally established in the 1970s by Bill Hillier and colleagues at the Bartlett School of Architecture and Planning in London. Best known are the two books *The Social Logic of Space* and *Space is the Machine* (Hillier and Hanson 1984; Hillier 1996). Space syntax can be applied for numerical analysis of aspects of spatial configuration or patterns that have probabilistic connection to the social performance of a building. The intention was originally to develop a theory of space that, based on objective properties of human environments, can determine underlying spatial laws (invariables) and cultural/social variables. In space syntax, *spatial configuration* has to do with the interrelationship, organisation and order of the different spaces while it does not directly deal with the function, form or specific design features of these spaces. This relational aspect and focus rather than focus on the properties of the parts is a typical characteristic of a systems approach:

> Architecture is not a 'social art' simply because buildings are important visual symbols of society, but also because, through the ways in which buildings, individually and collectively, create and order space, we are able to recognise society: that it exists and has a certain form.
>
> (Hillier and Hanson 1984: 2)

The theory consists of several specific methods and analytical measures applicable to existing or potential designs from regional and urban planning to architectural building design scale. One of the main points of the theory is that spatial order or structure emerges as limitations of an otherwise random accumulative process. Intuitively, this is most intelligible related to settlements and urban structures that to a greater extent than buildings can be said to develop gradually and accumulatively over time. On building scale level it has, however, been applied to building *typologies*. The generating force is the principle of randomness (everything is possible) while the structure is the invariance that emerge when spatial laws and cultural/social variables constrain the amount of valid choices (only some possibilities are applicable). An example of a spatial law could be that every space has at least one opening while a cultural variable could be that the toilet is not accessed directly from the living room or that all living spaces should have a window towards the exterior. Both spatial laws and cultural/social variables work as (mostly) non-conscious motives or indicators in the conception of a building and thus reproduce certain patterns or structures. Equally *movement patterns* in built space (buildings or urban contexts) can be studied. The spatial organisation or structure generates or, in softer terms: supports, a certain pattern of movement – in space syntax termed 'natural movement' (Hillier 1996). A wall obstructs passing while a door – if it is open – on the other hand makes it possible. The theory does not claim that other factors as e.g. different functions defined by the building's programme does not equally have influence. However, it *does* assert that the *natural movement* can either support or work against this programme. Large discrepancy between natural movement and programme can be compensated through (bureaucratic) rules.

Configuration is a central concept in space syntax and concerns a building, a part of a building or can even be a complete urban system of streets, squares, buildings, etc. What connects spatiality and sociality cannot, according to the theory, be understood in static terms as characteristics of specific spaces in isolation. Rather it is, as mentioned, a question of their mutual interrelation – or configuration.[28] This makes movement within and through space central for the perception of this space seen as a configuration. Equally, it points towards the assumption that each space and its specific connection to other spaces influence the configuration as a whole. What is interesting and perhaps less evident is, that even small changes in parts of the configuration often have 'syntactical' consequences for all other parts. A couple of mathematical measures – or *syntactic parameters* – have been developed to enable description and operationalisation of this through what is termed 'configuration analysis' (ibid.).

Configurations can be expressed visually through so-called 'justified permeability maps' – a kind of graph that in principle can be drawn by hand. The graphs give, through circles connected with lines, a simple and direct visually perceivable idea of the depth of a building seen from a specific location or space. By using different locations the graph expresses different relative depths and shows (even without the mathematical values) which spaces are more or less centrally located or segregated in the building. The graph is read 'bottom-up' with each level expressing more depth seen from the chosen point of origin.

Details about the practical implication and explanative power of the concepts and measures of space syntax will not be discussed here. Having existed and evolved for more than 40 years it does, however, point towards some degree of usefulness. Within the present frame of research it can be seen as an extensively elaborated example of how even soft values can be addressed through a predominantly hard systems approach that bring out certain aspects – not all aspects! – of a whole, and to a certain extent makes these aspects quantifiable.

A model based on a system approach?

The examples and concepts drawn from the (general) systems theory and examples of its application in architectural design presented in this chapter point in several ways towards the adequacy of looking simultaneously at a building and the construction of it as one coherent system. The building and its genesis can be seen as an open system that, using Checkland's terms, applies designed abstract systems (or systems of thought) in human activity systems (or systems of process) in order to create and maintain a designed physical system (or system of matter) which is the physical manifestation of the building. Buildings can be seen as much as expressions of the concepts and process that led to an actual result as the result (i.e. the building) itself. Looking at the physical structure of a building tells us about the process that brought it to life just as well as the structure of the architectural design process tells us about the conceptual and physical structure of the building – this interdependency is a characteristic of a complex system.

Buildings and architecture – understood as complex systems – could tentatively be defined as assemblages of subsystems of, for example, relatively independent materials, components and integrated assemblies. In their integrated form (the building), these subsystems form coherent wholes that are more than the sum of the constituent parts. Each subsystem could include both the system as conceptual entity, the process required to deliver it, and the physical matter to become part of the building. All subsystems are systems in their own right (holons) such as a structural system, an electrical system, a building envelope, or a window as a subsystem of the latter. Such systems thus express varying levels of complexity – or *integration* of such complexity. Still, all are equally subsystems that interface conceptually, procedurally and materially, in the building. The following chapter aims at providing definitions of some of these system concepts as for how they can relate to architecture and construction and will be used later on in the book.

Notes

1 For a similar assertion see Berlemont (2009): 'The knowledge to be found within the domain of (construction) technology is not structured in such a manner that it facilitates this transfer [into tacit embodied design knowledge]'.

2 See Vitruvius and Alberti in 'Systems in architectural theory', Ch. 1.

3 In Hannah Arendt's terms – as referred by Frampton – it is connected with the *how* and not the *what*. See 'Systems in architectural theory', Ch. 1.

4 The systems approach is a general term used for the organisation and management of complex systems and is the foundation for both analytic and holistic methods (Jackson: 2010: 29).

5 'A holarchy, in the terminology of Arthur Koestler, is a hierarchy of holons – where a holon is both a part and a whole'. Available online at http://en.wikipedia.org/wiki/Holarchy (accessed 24 April 2011). Structuration means order or organisation.

6 The drawback of a more general model can be the lack of capacity to explain important detail. What is important is, however, relative to the purpose of the model itself.

7 Bertalanffy refers to the *system sciences* as applied science distinguished from *systems theory* as a basic science. The applied system sciences are systems engineering, operation research and human engineering (Bertalanffy 1968: 91).

8 Bertalanffy argues that 'investigation of organised wholes of many variables requires new categories of interaction, transaction, organization teleology etc.' (Bertalanffy 1968: xxii).

9 The distinction resembles the one between soft and hard systems drawn by Checkland presented later in this chapter.

10 'classical' system theory, computerisation and simulation, compartment theory, set theory, graph theory, net theory, cybernetics, information theory, theory of automata, game theory, decision theory and queuing theory (ibid.: 21ff.).

11 Both Meadows and Laszlo equally states hierarchy as a fundamental characteristic of (complex) systems.

12 See 'Model presentation', Ch. 9.

13 This kind of hard fact modelling is the object of systems engineering as shortly described in Ch. 3.

14 Ill-structured or ill-defined problems are also mentioned in relation to product design in 'Industrial production theory', Ch. 3.

15 See 'Industrial production theory', Ch. 3.

16 Within the general systems theory, as summarised by Downing Bowler, 'everything that exists, whether formal, existential, or psychological is an organised system of energy, matter and information' (Skyttner 2005: 52).

17 The dynamic equilibrium of the first is also-called homeostasis – maintaining a steady state by adjusting internal environment. 'Homeostasis stands for the sum of all control functions creating the state of dynamic equilibrium in a healthy organism' (Skyttner 2005: 93). The two latter are also referred to as ontogenesis and phylogenesis – the process from embryo to human and the intergenerational evolution. See Laszlo (1996: 43). As pointed out by Skyttner, the distinction open/closed systems can be defined relatively: '[...] taken together with its environment, [an organism] might be considered as a closed system' (Skyttner 2005: 63).

18 Of course physical laws apply to and in many ways co-structure the final outcome – the physical building. However, these laws can never by themselves lead to a building. Architectural creation always contains human intention. See also the *formula* of Semper in 'Systems in architectural theory', Ch. 1.

19 Systems engineering as a hard method technical approach has been briefly touched upon in the previous chapter on 'Industrial production theory', Ch. 3.

20 Fictionalist: One who subscribes to fictionalism, the belief that certain concepts are simply convenient logical fictions. Available online at http://en.wiktionary.org/wiki/fictionalist (accessed 22 April 2011).

21 Aspect as used here have conceptual links to the notion of aspect in the DBK classification system described in 'Classification systems in construction', Ch. 2.

22 Available online at http://en.wikipedia.org/wiki/Soft_systems_methodology (accessed 22 April 2011).

23 An example of such an analysis with 33 requirements see e.g. Chermayeff and Alexander (1965: 157ff.).

24 For a short introduction to *design structure matrix* methods (DSM), see 'Industrial production theory', Ch. 3.

25 Cf. the notions of levelled complexity and holarchic structuration as introduced earlier. See also Alexander (1964: 131).

26 Alexander refers to precisely defined mathematical operations, but these are not further defined (ibid.: 118). A note (2), however, leads to several external sources.

27 See 'Industrial production theory', Ch. 3.

28 The purpose of the theory is exactly to be able to describe aspects of this connection between the physical and the social properties (laws and variables) of the built environment.

5 Architectural systems terminology

Introduction

The previous chapters of the present Part I – 'System' – have, with reference to the topic of this book, 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 book. This both in the sense of underlining and further clarifying the problems that the book sets out to treat as well as introducing useful concepts for use in the subsequent practical exploration in Part II – 'Product' – and for the model presentation and case analyses found in Part III – 'Model'. The current chapter 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 for how they will be used throughout the rest of the monograph. 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 monograph 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 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 either to a building or to elements of it.[1] 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.[2] Finally knowledge and ideas about buildings stay immaterial if not directed towards processes that manipulates material.[3] 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 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.

Focus in this book 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 subsystems form hierarchies spanning from simple materials to complex integrated systems and can be integrated into each other.[4] This is here termed *nesting*.

Model

The notion of *model* is used here as referring to a visually perceivable coded structure that as an intermediate tool displays a focused 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 appropriate level of abstraction for each of the elements contained in the model.[5] Models are 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

Figure 5.1 Integration of different subsystems serve functions that cannot be reduced to the sum of their constituent parts [Author's photo]

specific purpose of coding, the model should enable *flexible structuration* of both elements and their interrelations.[6] 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.[7] 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. In this way the model can potentially reveal *isomorphisms* (equal form or here: equal structural patterns) between various systems (i.e. 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 be manipulated through the model as a tool. Different codings of the model represent different *system structures* – a main concept coming out of this monograph 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*.[8] 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.[9] This integration helps to reduce complexity of structures comprised of such system entities. Deliveries, as used in this monograph, become physical subsystems and their related processes as they are delivered and nested (integrated) 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 integrated 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 III – 'Model'.

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 delivery* a central concept and a type of delivery to be dedicated special attention in this monograph. Integrated product deliveries 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).[10]

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'.[11] 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 book concentrates on IPDs containing several kinds of physical substance that become nested into the final building. Although configurable for specific building projects, IPDs as systems exceed the project and context specific purpose. IPDs 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 the present definition and become conceptually the opposite of *modularisation*.[12] However, to integrate or nest a delivery 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.[13]

The present monograph works with two main types of IPDs 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 IPDs can also be nested into each other.[14] The two main types are *chunks* that are volumetric (spatial) units that can integrate a wide range of subsystems (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'.

System structure

The notion and the underlying concept of *system structure* are central to and a main contribution of the present monograph. Conceptually, system structure fuses 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* as opposed to a *work breakdown structure*.[15] 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 the 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.

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 equally 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, in accordance with the main problem set out to be treated in this book to bridge between architectural ideation and the way buildings come into being. 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, on the other hand, the work as an *assemblage* of relatively independent elements created outside the work itself 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*.[16] In such works of arts the 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 monograph tends towards the notion of the architectural whole seen as an assemblage of its relatively independent subsystems.[17] The assemblage is the entire system – the building as whole – as both physical object and architectural work.

The system structure is elaborated 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).[18] The delimitation of each delivery is not clear-cut and universal but project specific and depends furthermore on the specific focus, viewpoint, and purpose of modelling the system structure. At the same time, a delivery can also comprise various nested subsystems 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* while not necessarily of the design itself. Apart from aiming at a consistent subdivision according to the complexity and integration of each delivery, the system structure nuances the distinction between off-site 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. Through use of the coded model the system structure can act as an analytical tool (retrospectively and potentially proactively) that gives an overview of different system structure scenarios, read: different ways to produce a given system (i.e. a specific building).[19]

Integration taxonomy

The overall purpose of the system structure in the first place is to handle complexity by focusing (the limited capacity of *conscious*) 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 not, as pointed out, necessarily reduce the actual complexity of the final outcome (i.e. the building – or main system). Through the coded system structure model an abstraction level is established according to the specific purpose in question while less relevant detail are left out of focus.

In this paragraph a tentative taxonomy for classification of each delivery (subsystem) in a system structure is drawn up based on the idea that multiple *dimensions* contribute to the *integration of complexity*.[20] Initially, three dimensions of *preparation*, *standardisation*, and *service* are suggested. Each of the three dimensions is here 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 through production system or delivery service. Potentially, integrated complexity reduces the complexity to be handled by the (architectural) designer/client or whoever is receiving or applying 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:

MAT = Building material (manufactured raw material as one single or a composite material).[21]

COM = Building component (assembled component as a simple custom made component of one or few materials or a standard (industrial) technical device).

ASM = Assembly (integrated assembly of materials and/or components often encompassing one or few subsystems in their entirety – an assembly by system).

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 leave one location as kit-of-parts 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 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.[22]

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:

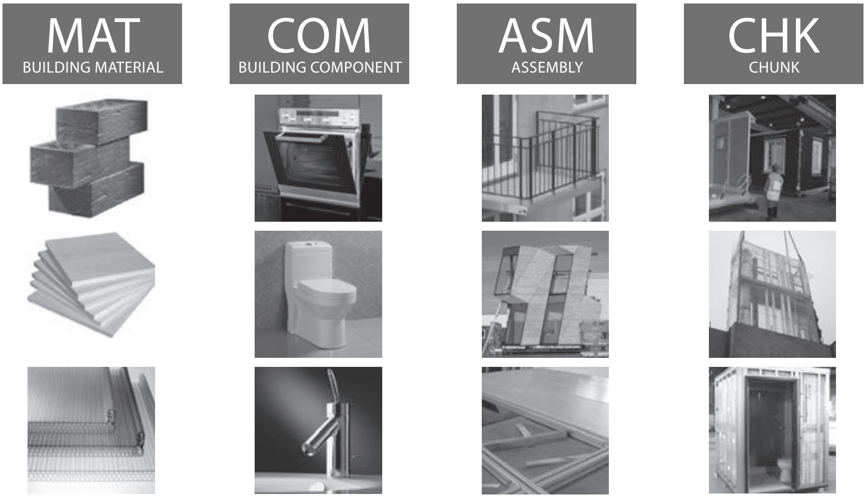


Figure 5.2 Examples of the different preparation levels [Author's diagram]

BSP = Bespoke (custom product/custom delivery – non-standard solution made specifically for a project).

M2O = Made-to-order (custom product/standard delivery – customised product version within existing system – often called mass customisation.

C2F = Cut-to-fit (standard product/custom delivery – cut and delivered in customised dimensions for known customers).

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 and responsibility in the handover of the delivery at the point of destination. The following four levels are defined:

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

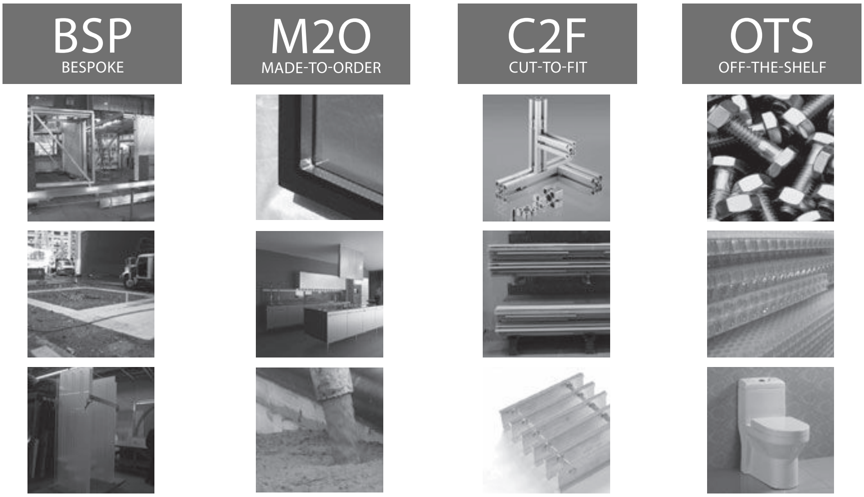


Figure 5.3 Examples of the different standardisation levels [Author's diagram © KieranTimberlake (1st column)]

Note 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. the definition 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. By applying numerical values to the levels of the different dimensions it is tentatively illustrated how 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. 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 or the producing organisation being through, for example, legislation or public regulation such as exteriorly defined standards make it possible to deliver a 'simpler' product by constraining the solution space. The complexity integration implied by the standardisation dimension lies in this case prior to the product itself and its design process.

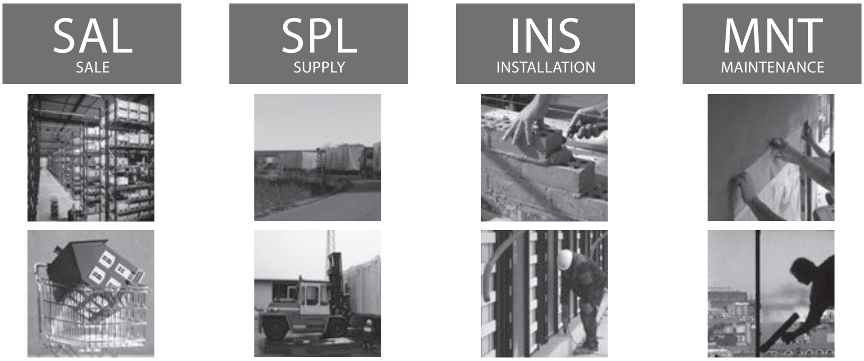


Figure 5.4 Examples of the different service levels [Author's diagram]

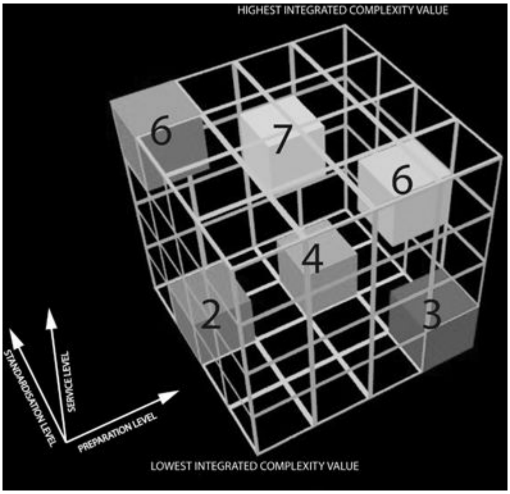


Figure 5.5 Examples of different total integrated complexity values as colour coded cubes in a three-dimensional graph [Author's drawing]

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 5.5 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 (theoretically) stay constant. Working with numerical values of qualitative parameters (as the dimensions) 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).[23] 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.[24] 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 its later installation in the building or as nested into another delivery. However, most deliveries would be located in between these two extremes, such as, for example, a standardised (OTS) ventilation device (COM) supplied (SPL) for subsequent installation by a plumber or a cut-to-fit (C2F) delivery of simple façade cladding panels (MAT) installed on-site 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 design process complexity is kept open/high) and where the effort is rather ‘outsourced’ to other (upstream) suppliers (read: where design process complexity is integrated/low). The following Part II – ‘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.

Notes

1 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’, Ch. 4.

2 Natural processes and systems as opposed to human processes and systems are not governed by external intention but create 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. See e.g. http://en.wikipedia.org/wiki/Autopoiesis (accessed 22 July 2011).

3 A drawing or a description of a building is still only a representation – not a building in itself.

4 Systems organised hierarchically within other systems are called *holons* – simultaneously constituting wholes and parts. See 'General systems theory', Ch. 4.

5 Both Meadows and Bertalanffy point out the need to model specifically according to the purpose of the model. See Ch. 4.

6 For a definition of flexible structuration, see 'General systems theory', Ch. 4.

7 This quality of the model is pointed out by Bertalanffy. See 'General systems theory', Ch. 4.

8 See 'Industrial production theory', Ch. 3.

9 The integration of process and product is, as earlier pointed out, substantiated by Bertalanffy. See 'General systems theory', Ch. 4 pp. 5–6. Also advanced DSM techniques tend towards juxtaposing processes, products and operators (organisational DSMs) See 'Industrial production theory', Ch. 3.

10 Author's 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', Ch. 9.

11 See General systems theory, Ch. 4.

12 See Baldwin and Clark's distinction explained in 'Industrial product theory', Ch. 3.

13 The chapters of Part II – 'Product' – introduce and discuss several different kinds of these integrated product deliveries in construction.

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

15 Se e.g. Armistead et al. (1996).

16 As described in 'Systems in architectural theory', Ch.1, Gottfried Semper in the mid nineteenth century anticipates montage as an architectural and tectonic strategy.

17 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).

18 Configuration is here used in a sense similar to the way it is used in space syntax as explained in Ch. 4.

19 This resembles the notion of *equifinality* as described in Ch. 4.

20 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', Ch. 2.

21 Raw materials are seldom if ever used in a non-processed manner in a *building* as directly from the mine. The 'MAT' 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.

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

23 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). Similar semi-qualitative indicators are found in 'Space Syntax' measures of *relative integration* and *relative ringiness*. See 'General systems theory', Ch. 4.

24 Whether the actual installation and/or maintenance are 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 II

Product

As opposed to Part I – 'System' being a theoretical exploration, Part II – '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 discernible tendencies or development initiatives. A particular focus is the integrated product delivery as a new emerging constituent element in construction. Through two chapters different aspects of building products and integrated product deliveries in construction are examined. The first – *From construction of projects to production in project* (Ch. 6)– shortly discusses differences between production and construction and the problem of handling the increasing complexity in present day architectural construction. Subsequently, the established delimitation and definition of integrated product deliveries as an entity is challenged through specific examples or types. In the second, *Product catalogue* (Ch. 7), the elaborated taxonomy of integrated complexity from *Architectural systems terminology* (Ch. 5) is tentatively applied to different building products in a short catalogue-like format. Finally, Chapter 8 introduces the notion of *industrial ecology* as having special parallels to this kind of integrated building products.

6 From construction of projects to production in projects

General product development within construction

Since the end of World War II a range of different initiatives has had the aim to change the construction industry from a traditional craft-based on-site construction activity towards a more product-based industrialised industry in line with the development in the rest of the product industry. In the USA the means of production left from the war industry was directly converted into facilities for, for example, providing mass produced housing – although in individual units – for a new emerging middle class of Americans partly supported by an exploding production for the general post-war reconstruction of Western Europe.[1] In Europe, housing needs were enormous due to war damage as well as a rising middle class and general population growth. Here the industrialisation of construction mostly led to large multi-storey developments – often based on national standards meant to support standardised industrial production of building components. However, within construction and architecture, standardised solutions and monotonous mass production of, for example, dwellings and urban environments only had a short period of glory in the1960s and 1970s. Architecture, as opposed to the product industry and except from this relatively short although fairly visible (!) intermezzo, has always been concerned with the unique and the industrialised means of construction of that time was primarily geared towards solving the urgent housing need and could not meet the later demand of enhanced adaptability, once this urgency had disappeared. Construction was still considered and organised fundamentally different from the general production industry.

With the general spread and use of information technology in industrialised production from the mid 1990s and on, this seems to change. Gradually the production industry has been able to provide so-called *mass customised* products for construction that – as pointed out in chapter 3 'Industrial production theory' – to some extent bridge the division between the one-of-a-kind logic of the construction sector and the economies of scale logic of the product industry.[2] Within the construction sector in Denmark several public initiatives – including *Det Digitale Byggeri* (Digital Construction) try – to establish standard processes and consistent classification systems on national or international level.[3]

Complexity

However, increased complexity of contemporary buildings as well as the processes of producing them seriously challenge the integrative capacity of architectural practice as e.g. pointed out by Alexander:

> Although ideally a form should reflect all the known facts relevant to its design . . . the technical difficulties of grasping all the information needed for the construction of such a form are out of hand – and well beyond the fingers of a single individual.
>
> (Alexander 1964: 4)

Bachman states that 'architecture is perhaps the ultimate profession of integration' (Bachman 2003: 6). This seems to call for qualitatively new and different means to reduce the complexity of the architectural design and construction process without impairing the capacity of the final result to integrate culturally well-founded high architectural quality with the complex requirements of present-day life, technical performance and legislative regulations. It is thus not primarily about reducing the complexity of the outcome but rather about handling this inevitable complexity through new products, tools or heuristics that do not force architectural creation into the straitjacket of traditional industrialised mass production. While all construction today is industrialised to some extent, industrialisation can be approached in different ways representing varying degrees of *integrated complexity* and flexibility.[4] An assertion here is that the choice of integrating complexity into a product and where and how this is done in the *system structure* (or supply chain) of a building has significance for the degree of flexibility of the architectural solution space, i.e. the available design choices within a given context with a given set of conditions. This correlation, it will be argued, is not necessarily linear in the way that higher integration of complexity necessarily gives lower (architectural) freedom or flexibility. Architectural creation is not a free standing art like painting or sculpture. It is highly dependent on the way it can be produced and/or constructed in a given society on a certain technological stage and with a specific market structure. The general specialisation and industrialisation of our society have enhanced the dependency on industrial production processes and products produced outside the context of each particular building project. The art of building is moving from manually dominated *construction of projects* towards industrially dominated *production in projects*.[5]

Emerging types of integrated product deliveries in architecture

The following paragraphs explore and discuss the emergence of *integrated product deliveries* in architecture and construction as new different *types* of systems. Integrated product deliveries are suggested as a means for handling overall design complexity by integrating design decisions into discrete products of matter, process, and thought thus facilitating a more strategically focused design attention in a building project. Challenging the initially established definition of the concept from chapter 5 Architectural Systems Terminology, specific empirical examples are used to clarify different borderline aspects concerning deliveries as integrated products.

System structure and integrated product deliveries

Contracts as subsystems

Any building and its coming into being can be seen as a structural and hierarchical organisation of a number of subsystems with varying degrees of complexity – any building has a specific *system structure*.[6] In traditional construction, these subsystems would normally correspond directly to the established crafts involved. Hence, the bricklayer would form a subsystem with bricks and mortar as well as the carpenter with woodwork or the later trade such as the plumber or the electrician would do plumbing and with wiring. In complex modern industrialised products, however, the subsystems tend towards division along lines not necessarily corresponding to any craft. Rather the subsystems here represent multi-technological parts defined by their performance – for example, the motion of a motor, the lighting properties of a fixture, or the information provision of a display. Equally, in building projects, complexity has raised and specialisation and division of labour has considerably enhanced the number of stakeholders involved in a project. As a consequence, the task of controlling these subsystems of trades and crafts and their interactions in a specific building project on a trade-by-trade basis has become increasingly difficult. The appearance of turnkey contractors as an intermediate actor specialised in providing the client with a singular contract based on an estimate and coordination of all subcontractors seems both to lock the traditional craft-based division and to leave the control with this division out of the hands of the client and, perhaps more important, out of the hands of the architect who is supposed to specify it.

Stakeholders, processes and physical deliveries are bound together. If the physical structure of subsystems is to be changed, the structure of processes and stakeholders performing them must equally change. Today, only by specifying to an ever greater extent can the architect try to control the subcontracting of the turnkey contractor. This can, however, easily result in over-specification where the focus becomes specific solutions instead of their performance. The result can again be that now the contractor is locked in an inappropriate system structure – this time forced by the architect who does not have direct access to the suppliers (manufacturers and subcontractors) on the market thus specifying on the basis of deficient knowledge.

Integrated product deliveries as subsystems

Integrated product deliveries (IPDs) represent a bridging of a *product perspective* and a *process perspective* in construction. They are normally considered as physical systems that can be configured and customised as a specific delivery and form part of a unique construction project. Assemblages of such discrete subsystems rather than simple materials and components can theoretically form complete buildings. However, IPDs are not limited to the physical realm alone. Process systems or perhaps even systems supporting the ways architecture is conceived – *systems of thought* – can, it will be argued and exemplified, be seen as equally relevant types for development of customisable IPDs in construction. Processes and knowledge can also be integrated into deliveries that do not necessarily comprise physical elements. As these latter system types focus on standardisation and mass customisation of the design and building process rather than physical systems they point out other tracks towards a more systemised yet still flexible architectural solution space.[7] The standardisation and service dimensions of the established integration taxonomy in the previous part encompass this aspect.[8]

The notion of IPDs introduces a more nuanced picture of the system structure of a building which is no longer limited to building materials and components handled by corresponding crafts. As well as the fact that a building can conceptually be decomposed into its spaces – i.e. living space, kitchen, entrance – or its architectural elements – wall, opening, roof, floor, etc. – it can also be decomposed into its systems as actually delivered and/or installed. This division has the advantage of better matching the industrialised means of production behind that is based on delivery of products. The IPDs reduce design complexity in focus through nesting of building materials, components and subsystems into performance based entities that can be installed in the building as discrete integrated or distributed systems.[9] Design work is embedded in the subsystems before they, as specific deliveries, become part of the main system – the building project. Using configurable industrialised IPDs in architectural design moves the architect's attention towards the interfaces *between* subsystems rather than the design of subsystems themselves. The subsystems are *commoditised* as products whereas their combination remains central to architectural design. If the subsystems are flexible enough this facilitates the integrative task of the architect thus potentially increasing the possibility of architectural coherence of the end result. The architects Stephen Kieran and James Timberlake call this 'the architecture of the joint' (Kieran and Timberlake 2004: 93) pointing towards a new role of the architect – a new architectural discipline. A further discussion of this role can be found in the concluding chapter of this book.[10]

Examples

The following presentation will try to relate specific examples to the different dimensions and their levels of integration. Starting with one of the most well established ones – the bathroom pod – this presentation also includes a façade renovation system, a lighting control system, a user involvement software program, as well as a discussion of *systems of thought* as a possible field for complexity integration through development of concept IPDs or supportive functions for concept generation.

Bathroom pod[11]

A well-established IPD in construction is the bathroom pod. The bathroom requires a considerable amount of installations – a functionally and spatially well-defined space or utility, which at the same time represents some of the most expensive square metres of the dwelling. The combination of limited size and many crafts involved in completion often results in long construction time, difficult coordination and a following high risk of errors and deficiencies. This makes the bathroom an obvious target for industrialisation understood as separate controlled production with optimised use of materials and manpower.

Although savings are considerable in larger batches of identical or almost identical bathrooms, factory produced standard deliveries or truly mass customised solutions are still seldom found. Part of the explanation is that market standards never have been established for the bathroom pod as a product. Manufacturers generally have only few and loosely defined types (product families) and no standard measures. In pursuit of flexibly meeting any customer's demand, most pods are still mainly delivered as projects designed for a specific building. They are not configured based on general design parameters embedded in the system and each delivery still requires considerable design effort. Using the taxonomy presented in the 'Systems terminology' chapter of this book, one could say that although the preparation level is high (chunk/CHK), the standardisation level is low (bespoke/BSP or made-to-order/M2O).[12] The service level varies. Some examples of specific national type approvals exist, but it is rather an exception than a rule.[13] This also means that only little automation has been applied – many procedures are rather (traditional) construction under roof than true industrialised production.

Further commoditisation (i.e. consolidation as a product) of the bathroom pod seems straight forward – such as establishing market standards for interfaces and increasing the standardisation level through parametric configuration – but despite the many positive aspects that can be pointed out development is slow. It seems that the manufacturers of bathpods so far have prioritised responsiveness rather than efficiency – construction of projects dominates over the 'true approach' for the integrated product delivery strategy of production in projects.

System for façade renovation[14]

An IPD does not necessarily need to be a factory produced clearly physically delimited product. This example is mainly defined by a sequence of well-defined material processes put together in different ways to form a complete delivery – a façade renovation solution.

Although cladded versions of concrete construction are prevalent in modern Danish (large scale) construction, most of the building stock is still dominated by traditional masonry. RBE – a mid-sized Danish builder – has specialised in façade renovation of these buildings and has engaged in a restructuring of the company and its activities towards a more focused and systematic approach:

> One of the goals has been to decompose a façade renovation into clear and meaningful constituent elements and then to join these again in a whole. A new system for façade renovation!
>
> (Author's translation from RBE 2009: 32)

The system works with four general types of masonry façades: exposed (BM), smooth finished (PM), plastered (FM) or green wall (GM).[15] The different work processes are divided into three main blocks: cleaning, masonry work and finish. By the application of 19 (meaningful) combinations of processes from these blocks the result is either renovation of the existing wall type or conversion into another type.

Although the system reduces complexity of the process for both customer and internally in the company, it is still considerably high due to dependency on the project specific outset – a specific façade to be renovated. The preparation level is low (MAT and COM) due to the fact that most processes are performed directly on the existing building façade. Standardisation level is equally relatively low but still based on the limited number of types (M2O) whereas the service level is high (INS): the façade renovation is handed over to the client as a finished solution.

The 17 established methods are estimated to cover the need for façade renovation of approximately 80 per cent of Danish multi-storey apartment blocks built between 1850 and 1950. Hence the system elaboration has also supported the delimitation of a primary business target (see Figure 6.1).

Lighting control system

Both bathroom pod and façade renovation are physically located in specific areas or parts of a building. This system is physically distributed and makes use of different technical systems while still delivered integrated as one single system around a specific environmental parameter: the lighting conditions of a room, a dwelling or an entire block or office building.

Artificial lighting constitutes a considerable amount of the energy use in modern live and work environments. Furthermore solar heating from daylight constitutes an important energy issue in many parts of the world due to the need for ventilation and cooling. These factors interact in many ways but are, however, industry-wise mostly treated as separate physical systems with separate suppliers leaving the architect as the only 'integrator' of the final solution.

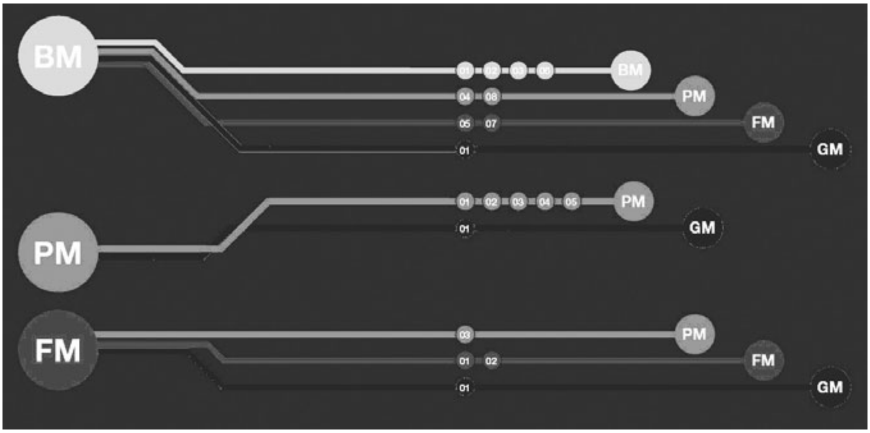


Figure 6.1 Diagram of RBE's different façade conversion types © RBE/ Hovedstadens Bygningsentreprise a/s

Lutron Electronics has specialised in delivery of complete lighting control systems. With offset in light dimmers the company today delivers a range of different lighting solutions for both residential and commercial settings spanning over – and integrating – dimmers, fixtures, lighting control systems, sensors, window systems and shading devices.[16] Partly due to the distributed character of the system it is widely modularised and easily reconfigurable or extendable making use of existing standard wiring and being compatible with most lighting fixtures and window framings. By connecting all devices to a centralised control system different lighting conditions can be pre-programmed to support a variety of activities, scheduled work cycles or changing exterior light and weather conditions.

The preparation level is in this case medium (COM and ASM) and limited by the distributed character of the system. Standardisation level is high (OTS and M2O) in the way that all components are off-the-shelf while joined into a mass customised solution. Finally, the service level is very high (MNT): although installation is outsourced to an electrical contractor, liability issues are kept within the company and '[m]any Lutron products and systems include warranty to cover parts and labour'.[17] Procurement involves client decisions about future maintenance, service and upgrades included in so-called service plans that come as part of the delivery.

Lutron's system bridges and integrates two different fields of technical expertise that share a common parameter – the lighting conditions in built environment. As Lutron also delivers fan control systems, a possible future path could be to deliver complete interior environmental control solutions. However, it is always a business challenge to find the right balance between 'we-can-solve-it-all' and expertise within a delimited field.

User involvement through a process software tool[18]

A software tool – *U_build* – recently developed for user involvement in construction processes exemplifies the process as an equally relevant field for development of customisable integrated product deliveries in construction and integration of complexity. U_build is meant as a tool for knowledge sharing between more and new players in the process of construction. The tool has been developed from an idea coined by the architectural office Mutopia and enables a controlled user involvement and dialogue applicable for the development of building projects and urban planning. U_build has so far had only little commercial application but has been used in a process of user involvement and participatory planning for a new heart disease department at Herlev Hospital in Copenhagen (see Figure 6.2).

Focus is on gathering and ordering user data in order to facilitate a semi-automated dialogue between owner/developer and users (defined broadly) that clarifies ideas and desires in a specific project. The data achieved through the use of U_build can subsequently be applied for qualification of the decision-making by owner/developer or consultants through the programming and early design phases.

U_build has been characterised as an 'integrated product delivery spanning across the [traditional] value chain in construction' (Mutopia 2008: 7). The process is the core whereas the physical outcome itself is not predefined but U_build still matches quite well the characteristics of an integrated product delivery: A system supplier delivers a (software) product that is 'configured and customised' for user involvement in a specific construction or planning project. Content as 3D-model, project material and information and a prepared structure for dialogue and comments is customised for each specific delivery of the software.

Within this book and concerning the present version of the system structure model that will be presented in Part III – 'Model' – U_build falls outside the definition of an integrated product delivery that 'concentrates on IPDs containing several kinds of physical substance that become nested into the final building'.[19] This choice of system boundary definition has, as a start, been made for simplifying reasons. U_build as example, however, points out a potential need for integrating pure systems of process into the system structure – or perhaps even systems of information or thought as the following paragraph gives examples of.[20]

Systems of thought

The above 'dematerialisation' of the concept of integrated product deliveries into elements of process or combinations of process and product can be further enhanced through 'products' that focus on the systematisation of thought in design. What is here termed as *systems of thought* – though still being on a speculative stage – are systems that similar to physical systems or process systems are aimed at reducing the complexity in focus (not the

Når du trykker tilføj oprettes din post-it. Den kan ikke redigeres.

Det skal være luftigt, lækkert og åbent i en planløsning. vi vil have mere lys!

U_build er super! Smukkere farver giver mere energi!

U_Build virker og er superfedt! Jeg syns jeg har oplevet flere gode ting

Det virker ikke så godt

Din kommentar er viktig! Jeg syns U_build er OK.

Hello from Herlev

Figure 6.2 Posted user comments in U_build for a future bedroom at Herlev Hospital © Mutopia Architects

complexity itself!) – in this case particularly concerning the conceptual phase of architectural design. To distinguish this genre of systems from systems of process they are not dictating a particular process but facilitate or support the design process through use of symbols. They provide a structure for thinking and for ‘storing’ these thoughts in a systematic way.

A very basic system of thought – although still providing expression of immense complexity – is a language and its physical manifestation as, for example, letters, words, sentences, texts and its grammatical rules. Another system of thought widely applied in architectural design is the drawing including a number of conventions for the interpretation its elements – lines, curves, hatches, line weights, colours, etc.

Herbert Simon (1996) introduces what he terms the *sciences of the artificial* as a way of systemising design thought as opposed to the analytic thought applied in the natural sciences. Whereas knowledge in the natural sciences is characterised by being ‘intellectually tough, analytic, formalizable, and teachable’ design knowledge is rather ‘intuitive, informal and cook-booky’ (ibid.: 112). Where the natural sciences in the Cartesian or mechanistic tradition *explain* complex phenomena by splitting them up into smaller components, design thought aims at removing differences between desired and present states by synthesising incommensurable parameters into a satisfactory solution thus *changing* or *creating* new complex phenomena. Simon calls this a process of ‘satisficing’ as opposed to optimising (ibid.: 119).

Whereas the first CAD systems were simply digitalised drawing tables imitating their analogue equivalent, new object-based and parametric design tools are more 'intelligent' and integrate and in some cases actively accumulate experience based knowledge through use. As an equivalent, digital word processors can both have pre-programmed spell-check and be able to 'learn' new words or even phrases through its use. This accumulated knowledge can without dictating a specific process or procedure support decision-making in design by proposing patterns or solutions already embedded in or 'learned' by the system. Another example is that even cheap mobile phones today suggest and even learn to suggest words for text messaging. The processing power and memory capacity of computers make them highly adequate for developing supportive systems of thought. However, important to underpin is that design – of, for example, physical form – although often attempted throughout history can never be a direct result of rule application. As Alexander states (1964):

> It is not possible to set up premises, trace through a series of deductions, and arrive at a form which is logically determined by the premises, unless the premises already have the seed of a particular plastic emphasis built into them. There is no legitimate sense in which deductive logic can prescribe physical form for us.
>
> (ibid.: 7f.)

Alexander does, however, claim that the computer and other techniques may be a way to magnify man's intellectual and inventive capability and even compares it to man's magnified physical capacity facilitated by the machines invented in the nineteenth century (ibid.: 11) – the first industrialisation. Advanced systems of thought – perhaps even marketed as products – seem to touch upon the 'last resort of architectural intuition' and challenge the conception of the architect as a singular 'auteur' in architectural creation.

The contextuality of the built environment

The emerging IPDs raise the question whether a new industrialised product-by-product structure of the built environment can be drawn to replace the fading traditional trade-by-trade structure of the crafts involved in construction? While a product–by-product structure is predominantly serial with products nested into each other in a supply chain ending on-site, the trade-by-trade structure is rather parallel with materials brought to site for processing by separate crafts. Earlier we took the standpoint that there is no ideal general system structure for the built environment. Any building project has its specific system structure. This is due to the fact that a building will always have to meet a wide range of contextual factors (physical, organisational, cultural, economic, etc.) that will never meet a 'one-fits-all' system structure. Seen from the point of view of the industry the most rational would seem to have fixed conventions on interfaces between clearly defined integrated building products. This would create the basis for well-structured markets of subsystems as assemblies and chunks. An analogy would be the car industry where almost every car represents the same basic organisation (product architecture) of main components such as chassis, body, motor, doors, four wheels, windscreen, etc. Specific versions of these components can even be produced by one manufacturer and be used across many different car brands. This makes it somehow easier to design and produce a new car as it does not really question what a car *is*! This is different in architectural creation.

Although architects do not necessarily have to 'reinvent the wheel' in every project there are inherently considerable differences due to the much larger web of contextual interactions and dependencies compared to products such as cars or even extremely complex engineered products such as large ships or aeroplanes. Although technically complex, a product such as the car basically deals with the problem of moving you from a to b. This can be done slowly or quickly, comfortably or not, cheaply or expensively, etc. However behavioural, cultural, environmental, and material issues are either universal or relatively simple when compared with the built environment. The tendency is not clear: The case analyses in Part III – 'Model' – will show examples of both parallel (trade-based) and serial (product-based) system structures that diverge more or less from the divisions along the traditional crafts.

Notes

1 See Bergdoll and Christensen (2008).
2 See 'Industrial production theory', Ch. 3.
3 See 'Classification systems in construction', Ch. 2.
4 For a definition of *integrated complexity* see 'Architectural systems terminology', Ch. 5.
5 This distinction is e.g. introduced by Mikkelsen et al. (2005).
6 For a more elaborated definition of the notion of *system structure* see 'Architectural systems terminology', Ch. 5.
7 The concept of *flexible solution space* is introduced in Vibæk (2007).
8 See 'Architectural systems terminology', Ch. 5.
9 Whereas a bathroom pod would have a relatively clear physical delimitation from surrounding elements, an interior climate solution would normally be distributed.
10 See 'Findings', Ch. 14.
11 Parts of this paragraph earlier published in Beim, Nielsen and Vibæk (2009: 90).
12 See *Integration taxonomy* in 'Architectural systems terminology', Ch. 5.
13 The former Danish manufacturer EJ Badekabiner had type approvals on the Norwegian market.
14 Elements of this paragraph including citation is authors own translation from RBE (2009).
15 The letter codes – used in the diagram below – represent the Danish abbreviations for the corresponding: *blank mur, filtset mur, pudset mur* og *grøn mur*.
16 Available online at http://www.lutron.com/ (accessed 18 August 2010).
17 Available online at http://www.lutron.com/Service-Support/Service/Pages/Overview.aspx (accessed 30 July 2011).
18 Parts of this paragraph are taken from Vibæk (2007).
19 See 'Systems terminology', Ch. 5.
20 See also http://ubuild.dk/ (accessed 15 December 2012).

7 Product catalogue

This chapter gives short catalogue-like introductions to a collection of different products currently available from the building industry that can be characterised as integrated product deliveries (IPDs).[1] The examples have all been collected during the course of the research and do not form an intention to provide a truly representative selection. A few of the examples are not yet marketed products (commoditised) in the true sense. They are still under development or at ideation stage but point towards potential market possibilities. Some of the examples from the previous chapter that discussed the different types and their borderlines (systems of matter, process and thought) as well as some of the deliveries presented in the case analyses of the next part (Part III – 'Model') are included in order to give a better overview by using one common format or template. Within the framework of this book, the 'ideal' integrated product delivery has a high level of integrated complexity (read: it reduces through its application the design complexity in focus for a building project) while still being sufficiently flexible to cover a market segment big enough to support efficient industrialised production based on mass customisation and in some cases also elements of automation.

If integrated product deliveries, as here, are considered to meet more than just technical demands, they should – particularly if including exposed/visible parts in the final building – also be visually appealing and be able to adapt to different spatial settings. Using the dimensions from the integration taxonomy,[2] such integrated product deliveries will normally present a high preparation level (assembly or chunk), a high service level (installation or maintenance), while the standardisation level is kept sufficiently low to offer an adequate range of different configurations. The latter point means that integrated product deliveries most often will present standardisation levels like made-to-order (M2O) or even bespoke (BSP). However, bespoke integrated product deliveries should perhaps rather be termed integrated *project* deliveries as the product or system level of these (the thing that different versions of the delivery have in common) are limited. The issue of product delivery vs. project delivery will be discussed further in the concluding part of this monograph.

Examples below are tentatively classified along the integration taxonomy and its dimensions of *preparation*, *standardisation* and *service*. However, sufficient information for each product is not always available. In such cases the total integrated complexity values, as suggested in the integration taxonomy, are based on estimates.[3] Although being expressed in a quantitative manner, the total integrated complexity values can at the present conceptual stage of development not be considered a hard fact coefficient of integration. However, the assertion is that it still gives an idea of how different dimensions contribute in terms of integration. The point is that integration – or reduction of design complexity in focus through the use of products that embed design knowledge and product complexity – cannot just be reduced to a question of prefabrication. Prefabrication, here expressed primarily through the preparation dimension, is just one among several dimensions that define the total level of integration of a product. Using different dimensions, as suggested, nuance the picture so that a highly serviced and standardised solution is considered to have a relatively high-integrated complexity value even if it is delivered and assembled on-site as materials and components thus having a low preparation level. The examples below are ordered alphabetically by the system owner.

INTEGRATED PRODUCT DELIVERIES: ARCHITECTURAL SUBSYSTEMS

Product 1[4]

System name: Altan.dk

System owner: Altan.dk

Short description

Balcony systems for installation on existing buildings as a new project or as replacement of old balconies. Each balcony is based on standard types and basically delivered as a kit-of-parts in three parts from different factories: base, fixture and railing. The base is finished according to standardised principles as e.g. varied but standardised depth. The aluminium type covers 70 per cent of the sale:

> Altan.dk is not exclusively about the balcony itself but equally the process. We take care of everything from A to Z during the course from the first inspection to the finished assembled and installed balcony ready for use. We are not just a balcony contractor but equally a service provider that handle project design, static calculations, processing by the authorities etc.[5]

Market and opportunities

Altan.dk provides 30 years of warranty which is quite unusual on assembly level in construction. Most balcony solutions are practically maintenance free for the user. The typical client is non-professional/private clients and typically in groups represented by smaller housing associations. From 2006 and forward, Altan.dk have established balconies in more than 500 different locations. The total average price is approximately 100,000 DKK (13,500 euro).

Integration levels

Preparation level: ASM (2)
Standardisation level: M2O/C2F (2.5)
Service level: MNT (3)
Total integrated complexity value: (7.5/9) – high
Further information: http://www.altan.dk

Product 2

System name: X-tension

System owner(s): City of Frederiksberg, Karsten Pålsons Tegnestue, Falcon Rådgivende Ingeniører, Skanska et al.

Short description

System for renovation of multi-storey masonry apartment blocks constructed before 1945 through insertion/addition of an integrated solution with new bathroom and kitchen installations based on prefabricated components like concrete structure (slab and panel assemblies), bathroom pods (chunks) and a light building envelope assemblies of glass and aluminium:

> The main principle in the X-tension renovation system is to remove the vulnerable wet room areas in the old building and replace them with a completely new self-supporting core comprising prefabricated bathroom, kitchen and façade elements.[6]

Market and opportunities

The system clearly focuses on a specific part of the Danish building stock typically located in larger Danish cities and solves a common problem of modernisation of these older buildings. The system both has roots in earlier experience as well as provides reference for future projects – particularly for the architectural office involved. Only few specific projects based on the system have been carried out. It is rather meant as a principle for renovation of this specific type of building than a marketed product solution. While specific manufactures have gained general knowhow through the projects, X-tension has (so far) not been turned into a unified business concept with a specific supply chain.

Integration levels

Preparation level: COM/ASM/CHK (2)
Standardisation level: BSP/M2O (0.5)
Service level: INS (2)
Total integrated complexity value: (4.5/9) – medium
Further information: http://www.paalsson.dk/pix/pdf/Udv_Byggesystem.pdf and Karsten Pålsons Tegnestue (2003)

Product 3

System name: DEBA Module

System owner: DEBA Badsysteme GmbH, Germany

Short description

Complete flexible made-to-order (M2O) bathroom solutions delivered installed and ready to use based on a standard self-supporting modular metal sandwich construction system where fully fitted off-site produced planar assemblies are put together (nested) – usually on-site but volumetric chunks are also an option:

> at DEBA finished means that: floor and wall coverings, all installations as well as the horizontal piping to the sewage area are all included. No additional work is needed. The bathroom is ready for immediate use.[7]

Market stage and opportunities

Although the system is marketed towards both new buildings and refurbishment, its real advantage when delivered as planar assemblies is within refurbishment where access is often difficult and installation of volumetric chunk systems is not an option. The DEBA-system has been used widely in five-star hotels, liners (ships) as well as in residential refurbishment. DEBA has 190 employees and produces approximately 5,000 bathpods per year.

Integration levels

Preparation level: CHK (3)
Standardisation level: M2O (1)
Service level: INS (2)
Total integrated complexity value: (6/9) – medium
Further information: http://www.deba.de/

Product 4

System name: Dolle Modular Staircase (Models: Rome, Copenhagen, Chicago, etc.)

System owner: Dolle A/S, Denmark

Short description

Modular staircase delivered as a finished kit-of-parts where the number of treads and the rise can be adjusted within certain margins to fit the specific context and floor-to-floor height where the stairs are to be inserted. The modular staircase product line comprises several models that have different materials, finish and tread design. Most models can be assembled with a straight flight or a quarter turn, some also with a half turn. Different banister solutions are optional:

> We CE mark our modular and spiral staircases . . . which means they comply with EU's essential requirements on health, safety and environmental protection. CE marking guarantees clients that our products, as a minimum, meet the common European requirements; although in many cases we set the bar higher with even more stringent requirements.[8]

Market and opportunities

Dolle has specialised in smaller interior staircase solutions mainly for private customers. Apart from the modular products they also do attic stairs (flagship product), spiral stairs, special space saving staircases and banister systems. A staircase configurator available on the webpage lets you specify all relevant parameters of a model for placing an order which can then be executed directly online.

Dolle is one of the world's largest manufacturers of staircases selling in 40 countries with over 90 per cent of sales as export.

Integration levels

Preparation level: ASM (kit-of-parts) (2)
Standardisation level: M2O/OTS (2)
Service level: SPL (1)
Total integrated complexity value: (5/9) – medium
Further information: http://www.dolle.dk/en-us/dolle.aspx

Product 5

System name: Heated earth walls

System owner: Lehm Ton Erde (Martin Rauch), Ernst Waibel, Austria

Short description

A stove combined with a room divider with integrated heating all made of off-site fabricated rammed earth modules. While the stove is made as one tile or block in standard shape and size, the room divider is modularised and assembled on-site where the joints of the flexible earth material then can be smoothed out to form one monolithic heated wall:

> This type of stove is generally used, in combination with integrated hot water heating and solar collectors, in low energy houses, where it supplies all necessary heating. It can be mass produced, although individual variations in the material can make each stove unique.[9]

Market and opportunities

Although the particular solution or production method might be patented the whole idea of constructing in earth is that it is found (almost) everywhere as a local material. The off-site fabrication enables standardisation and facilitates quality check. The oven itself is marketed as a product. It is not known (to the author) whether the room divider solution is equally commoditised.

Integration levels

Preparation level: ASM (2)
Standardisation level: M2O/OTS (2)
Service level: INS (2)
Total integrated complexity value: (6/9) – medium/high
Further information: Kapfinger (2001), http://www.lehmtonerde.at/ and http://www.lehmo.at/

Product 6

System name: Quantum

System owner: Lutron Electronics Company, Inc.

Short description

Lighting control solutions comprising lighting fixtures, switches, sensors, dimmers, and shading devices delivered in modules and assembled as one integrated lighting solution including installation and later servicing:

> Quantum total light management maximizes the efficient use of light to improve comfort and productivity, simplify operations, and save energy. This powerful and efficient system dims or switches all electric lighting, and simultaneously controls daylight using automated shades.[10]

Market and opportunities

Although the installation is outsourced to (local) subcontractors, one of the great advantages of Quantum and other Lutron systems is the service packages that remove the burden of maintenance of the finished solution. Another is the modularity and openness of the system that makes it flexible both concerning reuse of existing installations as well as reconfiguration and extension of an installation. Yet another one is the green aspects of energy optimisation based on combination of several technical realms.

Integration levels

Preparation level COM/ASM (1.5)
Standardisation level: OTS/M2O (2)
Service level: MNT (3)
Total integrated complexity value: (6.5/9) – medium/high
Further information: http://www.lutron.com[11]

Product 7

System name: Installation shaft

System owner: NCC Construction Denmark

Short description

Off-site factory-produced installation shaft system for multi-storey housing projects. The shaft is produced in one-storey high modules and comprises a finished plug-and-play installation of all vertical risers and technical systems within one volumetric chunk. The chunks are stacked on-site in sequence with the erection of the structural building system – in Denmark mostly prefabricated slab assembly systems:

> The prefabricated installation shaft is one of NCC's innovative suggestions for how the industrialisation of construction processes can lead to reduced construction periods, lower construction costs and a more uniform quality – an optimisation of the construction process.[12]

Market and opportunities

Equal to products as the bathpod, an installation shaft is one of the places in a building with the highest concentration of and level of coordination between different traditional trades that all have to install a minor part of the overall solution. A strictly planned factory production considerably reduces risk of faults. An idea has been to develop a user interface integrated with a bathpod solution. Other development areas are similar products for the office and laboratory developments.

Integration levels

Preparation level CHK (3)
Standardisation level: OTS/M2O (1.5)
Service level: INS (2)
Total integrated complexity value: (6.5/9) – medium/high
Further information: http://www.ncc.dk/skakt and http://www.dac.dk/db/filarkiv/13563/skakten-rapport_19-korrektur.pdf

Product 8

System name: Stavne blocks

System owner: NTNU (Anne Sigrid Nordby) and Stavne Rebygg, Norway

Short description

Wall blocks of massive reused timber that can be joined into self-supporting wall panels. Initially the blocks have been used as interior partitions but an exterior version is on the way. The blocks are supposed to be produced close to the construction site where they will be deployed and by use of locally available reclaimed timber. A set of standard solutions for joining and other details have been developed as part of the system:

> The wall has a strong expressive character and stands like a piece of installation art in the space. The project for a further development of the Stavne block into an exterior wall and the establishment of a production line is now in the pipeline.[13]

Market and opportunities

The system represents an attempt to establish a new construction material based on the principles of reuse and a specific construction method. No nails are used. Dimensions and weight make them manageable by hand. With roots in academic research it has so far only been produced for test purposes and is not an established product or brand.

Integration levels

Preparation level: COM (1)
Standardisation level: OTS (3)
Service level: SAL (0)
Total integrated complexity value: (4/9) – low/medium
Further information: http://stavneblokka.blogspot.com

Product 9

System name: Façade renovation system

System owner: RBE, Denmark

Short description

RBE delivers façade renovation of traditional masonry buildings. Based on a classification into four main façade types, 19 combinations of cleaning, masonry work, and finish are offered as 'standard solutions' supposedly covering the needs for 80 per cent of Danish multi-storey apartment blocks built between 1850 and 1950:

> One of the goals has been to decompose a façade renovation into clear and meaningful constituent elements and then to join these again in a whole. A new system for façade renovation!
>
> (RBE 2009: 32)[14]

Market and opportunities (advantages)

The façade renovation system is particularly directed towards minor private housing associations that by choosing RBE get both consultancy and delivery as an integrated and lucid solution that potentially obviate the need for costly external building consultants.

RBE has over 100 employees.

Integration levels

Preparation level: MAT (0)
Standardisation level M2O (1)
Service level INS (2)
Total integrated complexity value: (3/9) – low
Further information: http://www.rbe.dk/Facader.182.aspx[15]

Product 10

System name: Alevator

System owner: Altan.dk, Denmark

Short description

Alevator solutions are complete mini lift solutions designed for integration in existing (older) building stock not originally planned for lift service. Although small, the lifts still comply with the requirements for wheelchair use. Mini lifts are typically installed in the middle of an older stairway, as replacing the backstairs, or as an extension to the backstairs:

> Local politicians in the cities encourage the establishment of mini lifts in older multi-storey apartment blocks in order to keep them attractive for a wide range of user groups including elder people and families with small children.[16]

Market and opportunities

The Alevator concept focuses attention on a limited and difficult part of the market thus seeking away from the 'red ocean' with most competition into a 'blue ocean'.[17] Many of the target dwellings were originally constructed for the emerging class of industrial workers moving in from the countryside. Today, these dwellings are centrally located in inner city areas which has made them attractive for higher-income groups with financial capital, and provided an incentive for improvements.

Alevator is a subsidiary of Altan.dk specialised in delivering balcony solutions.

Integration levels

Preparation level: ASM (2)
Standardisation level: M2O (1)
Service level: MNT (3)
Total integrated complexity value: (6/9) – medium/high
Further information: http://www.easyvator.dk/

Product 11

System name: Rucon færdigkvist (Rucon finished attic)

System owner: Rucon, Denmark

Short description

Finished off-site produced attics like the Rucon solution have become an increasingly used way to produce high-quality solutions in a protected and controlled environment before final installation on-site. Several manufacturers offer more-or-less bespoke solutions – some of the more standardised versions have online configurators where the customer can design his own mass customised solution:

> Easy installation and adaptation mean shorter time with a hole in the roof, quick installation due to high degree of completion from the factory, and an affordable solution with lower scaffolding and labour cost.[18]

Market and opportunities

Heavy technical and legislative demands connected to the physical resolution of the roof in a rainy and humid climate such as, for example, southern Scandinavia, make roof openings a complex part of buildings. This makes integrated building assemblies that include southern parts of this area an obvious target for off-site produced solutions manufactured in controlled workshop or semi-industrialised factory environments. However, larger truly industrialised manufacturers have so far not been found.

Rucon is – as many of the other manufacturers in this field – a smaller company with over 20 employees and roots in carpentry.

Integration levels

Preparation level: ASM (2)
Standardisation level: M2O (1)
Service level: INS (2)
Total integrated complexity value: (5/9) – medium
Further information: http://www.rucon.dk/færdigkviste/

Product 12

System name: Podwall

System owner: Swift Horsman, UK

Short description

Podwall is a modular system of cladded steel frames forming wall assemblies with integrated installations and appliances mounted from the factory. The modules arrive fully fitted and can literally plug together on-site to form entire bathroom environments, reception areas, acoustic walling, office fronts, etc.:

> Podwall is a fully prefabricated modular walling system incorporating finishes and services all of which are manufactured completely off-site in a dedicated controlled environment.[19]

Market and opportunities

As a modularised panelised assembly but with appliances and other accessories mounted from the factory, the Podwall seeks to combine the advantages of the high degree of completion of the chunks with the more flexible dimensions of panelised systems in a kind of semi-volumetric solution. The highly customised solutions address primarily a high-end market.

Swift Horsman has several product lines within off-site manufactured fit-out solutions and operate mainly in the UK.

Integration levels

Preparation level: ASM (2)
Standardisation level: BSP/M2O (0.5)
Service level: INS (2)
Total integrated complexity value: (4.5/9) – medium
Further information: http://www.swifthorsman.co.uk/companies/swift-horsman/products/podwall

Product 13

System name: Corefast

System owner: Tata Steel Europe (former Corus), UK and Netherlands

Short description

Modular construction system for creating structural lift and stair cores in multi-storey buildings made of Corus's Bi-Steel™ – a steel/concrete composite material that combines high strength and structural rigidity with low tolerances. The *Corefast* system is manufactured as off-site fabricated panelised assemblies joined into one-storey high complete volumetric chunks before they are stacked into a finished multi-storey core on-site. The system is suitable for cores from eight to over a hundred storeys:

> Corefast is a superior construction system to traditional reinforced concrete cores – it is faster, easier to construct, more accurately engineered and can offer reduced structural thickness.[20]

Market and opportunities

The main advantages of the *Corefast* system is the low tolerances that makes it easier to combine with other high precision off-site manufactured building components and assemblies. Furthermore the construction time on-site is reduced with up to six times as compared with in-situ reinforced concrete cores. Tata Steel Europe is Europe's second largest steel producer and a subsidiary of Tata Steel Group with over 80,000 employees worldwide.

Integration levels

Preparation level: CHK (3)
Standardisation level: M2O (1)
Service level: INS (2)
Total integrated complexity value: (6/9) – medium/high
Further information: http://www.tatasteeleurope.com/en/products/construction_products_and_services/ structural_steelwork/corefast/

Product 14

System name(s): ONE by Transwall, Z-WALL, CorporateWALL, and REASONS

System owner: Transwall, USA

Short description

Transwall manufactures, sells, and delivers made-to-order movable floor-to-ceiling and architectural wall systems for office environments. The company markets four product lines addressing different partition wall needs. The wall systems are delivered and installed by Transwall as finished panelised assemblies and are both highly configurable and re-configurable:

> The marketplace interests were just starting to come together around green architecture through use of modular walls and construction, addressing flexible architecture, and growing desires for increased daylight in office spaces through the use of glass. Transwall's products were, and continue to be positioned at the intersection of these forces.[21]

Market and opportunities

The advantage of partitions like Transwall's systems is the double flexibility of both initial configuration and later conversion that makes the systems highly adequate for office environments with frequent need for reconfiguration. The residential market requires a more permanent look that has so far not been addressed by Transwall.[22]

Transwall has 60 employees and an average order is in the $200,000–400,000 range.

Integration levels

Preparation level: ASM (2)
Standardisation level: M2O (1)
Service level: MNT (3)
Total integrated complexity value: (6/9) – medium-high
Further information: http://www.transwall.com/

Product 15

System name: NV Comfort™ and NV Advance™

System owner: WindowMaster

Short description

Indoor climate solution and control system based on natural ventilation through controlled openings in façade and roof. Openings in the building envelope are automatically opened and closed based on pre-programmed values for room temperature, CO_2-levels, outdoor temperature, rain, and wind speed:

> The setting of a desired room temperature and CO_2-level can be adjusted for each single room from a central location in the building on a NV Comfort™ touch screen. Additionally, the user can always use the system to directly open or close a window if more or less fresh air is desired.[23]

Market and opportunities

The system combines a sophisticated pre-programmed environmental solution based on several measurable parameters with the possibility of direct user interaction based on personal here-and-now sensory perception of an interior space. It thus seeks to overcome the alienation often produced by completely automated solutions.

Integration levels

Preparation level COM/ASM (1.5)
Standardisation level: OTS/M2O (2)
Service level: INS (2)
Total integrated complexity value: (5.5/9) – medium
Further information: http://www.windowmaster.dk/

Notes

1 See 'Architectural systems terminology ', Ch. 5.
2 See 'Architectural systems terminology', Ch. 5.
3 The values should rather be understood as qualitative estimates or classification (as e.g. *made-to-order*, or *bespoke*) The numerical values are not exact values. See also 'Architectural systems terminology', Ch. 5.
4 Information partly retrieved from Beim, Nielsen and Vibæk (2010: 96f.).
5 Available online at http://www.altan.dk/media/Altan_droemme_2010.pdf – page 36 (accessed 9 August 2011) – author's translation from Danish.
6 Karsten Pålsons Tegnestue (2003: 8).
7 Available online at http://www.deba.de/index. php?id=33&L=1 (accessed 8 August 2011).
8 Available online at http://www.dolle.dk/en-us/dolle/quality.aspx (accessed 9 August 2011).
9 Available online at http://www.lehmo.at/lehm/index.html (accessed 9 August 2011).
10 Available online at http://www.lutron.com/Products/WholeBuildingSystems/Quantum/Pages/Overview.aspx (accessed 8 August 2011).
11 For an extended description within this book see also Ch. 6.
12 Available online at http://www.ncc.dk/skakt (accessed 4 September 2011) (author's translation from Danish).
13 Available online at http://stavneblokka.blogspot.com (accessed 9 August 2011) (author's translation from Norwegian).
14 Author's translation from Danish.
15 For an extended description within this book see also 'From construction of projects to production in projects', Ch. 6.
16 Author's translation from http://alevator.dk/Forside.910.aspx (accessed 27 May 2013).
17 The distinction red ocean/blue ocean was introduced by Kim and Mauborgne (2005).
18 Available online at http://www.rucon.dk/færdigkviste/(accessed 9 August 2011).
19 Available online at http://www.swifthorsman.co.uk/companies/swift-horsman/products/podwall (accessed 1 April 2011).
20 Available online at http://www.corusconstruction.com/bi-steel (accessed 15 October 2011) and http://www.tatasteeleurope.com/en/products/construction_products_and_services/structural_steelwork/corefast/ (accessed 8 August 2011).
21 Available online at http://www.transwall.com/index.php/profile/about (accessed 8 August 2011).
22 This assumption is partly based on author's own market research.
23 Available online at http://www.windowmaster.dk/regado.jsp?type=page&id=122 (accessed 8 August 2011) (author's translation from Danish).

8 Industrial ecology

A strategy for discrete controlled products

The increasing demand for environmentally sustainable solutions that takes better into account the human ecological footprint and use of non- or slowly renewable resources will undoubtedly heavily impact the construction industry in the years to come. Being the most resource-intensive industry material-wise and among the most energy consuming counting both construction and operation, the built environment constitutes a major field for resource optimisation. This calls for technically more advanced solutions but also for a more systematic use of *simple* and context sensitive solutions based on knowledge that already exists in an often tacit form embedded in traditional cultural behaviour or vernacular building styles. Entities such as climate, created physical environment, and the life span and use of it (behaviour) must be considered in their interaction in order to evaluate on a building's impact on our ecosystem.

Commoditisation as eco-friendly

Industrial ecology covers the idea of closed material loops of production where waste and recycling are used as input for new production in a continuously closed cycle thus virtually leaving no ecological footprint. However, grasping material cycles of all components and materials of an entire building and its use is an immense task and outside the information processing capacity of a single designer or even a design team working on project basis. Actually *controlling* these cycles is even more unrealistic and can never be the task of architectural design alone. This does not, however, mean that architectural design should not be concerned with such issues. A further commoditisation of the construction industry by the development of integrated product deliveries, as has been exemplified, can move some of this need for information and knowledge processing into a (non-project specific) system level (i.e. a product) with possible workload and economic amortisation over many individual building projects. Such *products* can still be mass customisable (made-to-order) in order to fit certain project specific requirements that are kept open or held within a certain predefined range of flexibility as in parametric design.

Cradle to cradle

Under the slogan of *waste equals food*, McDonough and Braungart (2002) theoretically eliminate the concept of waste and divide materials into biological and technical nutrients thus leaving open the possibility of closed material cycles without excluding the use of artificial and potentially environmentally harmful materials (technical nutrients) as long as they are kept strictly separate from biological nutrients and their cycles. Biological nutrients return to the biological cycles and are ultimately always biodegradable whereas technical nutrients return to technical cycles in a kind of industrial metabolism controlled by human activity (ibid.: 103ff.). Technical nutrients do not have the same general decomposability as biological nutrients (composting) and often need to be kept separate material by material. Systems integrating both kinds of nutrients should be easily separable into these two general systems of material flow.

Nested systems and embodied energy

As pointed out by Meadows, systems can be nested within systems (Meadows 2008: 15). In the case of products, this means that material flows can be considered on various levels of integration. Materials do not need to be brought all the way back to their raw material state in order to be recycled in new products – they can in some cases be used directly on a higher integration level as, for example, a component or a complete integrated product delivery (assembly or chunk). Even entire buildings are reused for other purposes with smaller or larger amounts of retrofitting needed. This perspective on reuse makes good sense when it comes to the question of embodied energy – or *emergy* as it has been termed (Odum 1996) – meaning the total amount of energy applied to bring a product into its present state. Decomposition or disassembly also requires energy hence second-hand use is not just a question of saving money! However, the amount of embodied energy must be weighed against the actual reusability of a certain subsystem (constituting a certain amount of integrated complexity). Aluminium for example takes a lot of energy to produce but is then highly remouldable through various techniques not necessarily requiring intensive use of energy. Thus using aluminium for very project-specific components that can then be remoulded for new use makes sense. Other materials perhaps requiring more energy for later conversion could be designed for reuse on higher integration levels. The integration level of reuse (i.e. material, component, assembly, chunk or building) is important to consider in design seen from an environmental point of view.

Design for disassembly

As explained in the chapter on *general systems theory*, Meadows introduces hierarchy and hierarchical organisation as a common characteristic of complex systems including natural systems as ecosystems or living organisms:

> A cell in your liver is a subsystem of an organ which is a subsystem of you as an organism, and you are a subsystem of a family, an athletic team, a musical group, and so forth.
>
> (Meadows 2008: 82)

For Laszlo these hierarchically organised subsystems being systems in their own right became *holons* of a *holarchic structuration*.[1] Buildings as complex systems are equally hierarchically organised. This, however, does not entail that buildings are also *designed* as such hierarchical systems – even less that they are subsequently physically decomposable or dismountable into their subsystems (or holons) and the subsystems of these subsystems. *Design for disassembly* as one of the *design for x* strategies is preparing buildings for salvageability and reuse on various integration levels already in initial design stages.[2] By designing hierarchies or (supply) chains of nested systems on various integration levels, ideally leading through integrated product deliveries (assemblies and chunks) to be integrated in a building, the complexity needed to be handled on each level is considerably reduced – it is integrated upstream in the nested deliveries. This equally concerns the integrative design work to be performed by the architect – it is partly embedded further upstream.

Vola fixtures are popular components that are often specified by the architect. These fixtures, as others, use standardised connections and washers that are nested into the product thus obviating the need for designing or choosing these parts each time. *Vola* fixtures can equally be standard fixtures in, for example, a bathpod product thus obviating the choice of fixtures when you choose this integrated product. Both connections, washers, fixtures and potentially the entire bathpod can (later) be replaced as discrete elements. This principle here tentatively termed '*nested commoditisation*' could potentially enable closed material loops (of technical and biological nutrients) that interface materially and procedurally in a building as discrete products forming a whole. If nested systems can be independently replaced on various integration levels (e.g. according to life span or changed requirements) the result will be a very robust architectural design led by equal flexibility of design, conversion and maintenance.[3,4]

The integrated product deliveries (IPDs) in construction introduce a possible way to handle the complex material cycles in the construction, use and disposal of buildings after the end of their useful lives through the use of industrialised products on various levels of integration that potentially can be nested into each other through various tiers.[5] A construction industry of (integrated) products based on the principles of industrial ecology and design for disassembly would, however, require new infrastructures for dealing and trading with salvaged materials, components, and systems with different degrees of integration – understood as integrated complexity. Although some industry within the field already exists, salvageability and the establishment of material *cycles* instead of one-way streams from raw material to waste are still in embryo.[6]

However, products and systems can, as pointed out, not simply be reduced to the materials they comprise. Elements of process and thought – or knowledge – also have to be considered when trying to close the material streams into loops. Processes are equally resource consuming – and even embedded design work constitutes a considerable part of the investment in a product and should perhaps not just be 'thrown away'.

Notes

1 See 'General systems theory', Ch. 4.

2 See 'Industrial production theory', Ch. 3.

3 *Flexibility* can have different connotations in construction. For author's own discussion of the notion of flexibility in architectural systems distinguishing between *design flexibility, conversion flexibility* and *flexibility of use*, see Beim, Nielsen and Vibæk (2010: 26ff.).

4 As shortly introduced in 'Industrial production theory', Ch. 3, Steward Brand works with the concept of several layers in a building, each with their life span and argues for the necessity of designing for replacement of parts according to these life spans and layers (Brand 1994).

5 The introduction of deliveries on different tiers in a supply chain will be elaborated in 'Model presentation', Ch. 9.

6 For an elaborated discussion of the topic see Nordby (2009). The concept of *urban mining* also deals with similar themes. See http://urbanmining.org.

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Part III

Model

Parts I and II have mainly constituted explorations of respectively theoretical and practical fields in order to obtain a better understanding of the main problem formulated as the scope of this book as well as establishing a terminology for the latter parts and – hopefully – for the field of knowledge in general. Part III – 'Model' introduces a *system structure model* and the system structural view it provides.

The model and its application to a number of case studies is considered one of the main contributions of the present research. Perspectives in the conscious use of such system structure model could be architectural, ecological, economic, legislative and technical by introducing *a new way of handling the complexity* of architectural design and of focusing design attention.

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9 Model presentation

The *system structure model* has been developed iteratively with initial inspiration in the introductory explorations (Parts I and II) and from a primary case study and analysis of an existing architectural project 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 their own right as a way of further unfolding aspects of the field of contemporary industrialised architectural construction as well as giving valuable feedback for the evaluation and modification of the model.

Inspired by the notion from general systems theory of *equifinality*, an assumption is that two fundamentally equal buildings can constitute significantly different system structures, i.e. be built and assembled in different ways. Equally, using the notion of *isomorphism*, widely different building types can have similarities on a system-structural level. An ambition is that the proposed model clearly expresses these different situations.[1] Thus the model should contribute to the understanding and in a simple way facilitate the discussion of *different* production scenarios for *specific* building projects as well as *similar* production scenarios for *different* buildings. A given system structure will always be influenced by the context it forms part of regarding culture, geographical location (geology, climate, etc.), technological stage of the society, socioeconomic factors, special local building techniques, available (local) production facilities and a range of other factors. The model is to be seen as a descriptive and potentially proactive tool for understanding buildings on a system level that lies beyond their direct appearance. This requires, as argued earlier, a *soft system* approach of *levelled complexity* and *flexible structuration* where the model can be used to produce and look at system structures from different viewpoints, expressing different level of detail according to the specific purpose of using it.[2]

Purpose of the model

The concept of system structure and the system structure model address an increasing need for tools to handle the complexity of architectural design from idea via construction to the final physical result. The initial outset is an apparently growing distance between how architecture is conceived and how it can be produced. The industrialisation of the construction sector has considerably accentuated this tendency. With point of departure in the idea of an integrated systems approach, the suggested model is supposed to help bridging the gap between architectural ideation and contemporary industrialised construction by enabling a more active use or integration of products from the building industry already from early design phases. This can potentially reduce the need for resource intensive and time consuming translation of architectural concepts into physical matter and form as well as limiting an otherwise infinite number of design choices and enabling a more strategically focused design attention. *Architectural system structures*, as accessible through the use of the model, provide a system-structural view on buildings and how they are put together which helps to qualify the choice and combination of different more or less industrialised systems – with varying degrees of integrated complexity – into a coherent modern industrialised architecture: buildings as assemblages with both high artistic and technical quality. The system structure brings in issues of supply chain management and product architecture into the architect's toolbox as supplementary design parameters that are, however, meant to simplify rather than complicate the overall design process.

The ambition has been to develop a model that can visualise the use of systems, their integration level – understood as their degree of (integrated) complexity – and their combinations, interrelations and nesting into a complete building seen as a complex system. As a visual tool, the model communicates various levels of information in an easily perceivable way. The primary target group is the architect – working in practice, education, and/or research. Other potential users are construction engineers, other consultants and contractors as well as manufacturers of building products of more or less integrated and industrialised nature. The visualisation provided by the model serves in the first place scientifically as an analytical tool for understanding the system structure of already built projects. In a more developed form the model can potentially become a proactive design tool used both in architectural conceptual and design development phases for a more conscious decision-making concerning the combinations of systems into specific building projects. This aspect is much in line with Christopher Alexander when he states that:

> Scientists try to identify the components of existing structures. Designers try to shape the components of new structures. The search for the right components and the right way to build the form up from these components, is the greatest physical challenge faced by the designer. I believe that if the hierarchical program is intelligently used, it offers the key to this very basic problem – and will actually point to the major physical components of which the form should consist.
>
> (Alexander 1964: 130)

Alexander's use of 'patterns' is, however, concerned with the *functional* organisation whereas the proposed system structure model is rather focusing on *physical deliveries* thus integrating the genesis of the physical structure into the model. The focus – with roots in the theoretical exploration in Part I – 'System' – is how buildings can be divided into constituent subelements or systems in different ways, how these systems in some cases are nested into larger assemblies or chunks (= more complex systems) and, finally, how they interface with adjacent systems in the final building.[3]

Tier model and supply chains

KieranTimberlake – an architectural office in Philadelphia, USA – has worked with a way of describing applied systems in building projects through the use of supply chain models. These models are inspired by industrial management and production systems. KieranTimberlake's version of the supply chain model is not to be understood as complete supply chains showing the absolute flow of materials from 'natural resources, raw materials and components into a finished product' (Nagurney 2006). Rather these 'chains' are limited to the focus of the architect in a particular architectural project. The model is split into two separate chains – of off-site and on-site processes ending respectively with a fabricator delivering off-site production *to* and a manager controlling on-site processes *on* the building site (see Figure 9.1). Each of the chains is divided into a number of tiers – three off-site and two on-site tiers.

Interesting about KieranTimberlake's model is the capacity of displaying how the architect is working with systems and their interfaces. To some extent it also shows the nesting and combinations of these systems (or deliveries) from simple subsystems over more integrated ones into the final building. However, while working with the concept of different tiers in sequence, the model does not include the integration level – the integrated complexity of each delivery – as a consistent parameter of the different systems found in the diagrams. The integration level will here be more specifically defined as *the integrated complexity of a subsystem at the moment of its delivery*.[4] To use KieranTimberlake's tier model for this aspect is further complicated by the distinction between off-site and on-site suppliers in separate supply chains.

New tiers and the dimensions

Strongly inspired by KieranTimberlake's supply chain model and applying the concept of system structure and the elaborated taxonomy of dimensions,[5] a revised version is proposed that combines off-site and on-site deliveries into one single tier hierarchy that integrates a graduation of integration levels with a slightly enhanced number of tiers (T1–5). Lower tier numbers express a higher system complexity *downstream* in the supply chain while higher tier numbers represent simpler systems *upstream*. The sequence of the tiers is: raw materials (T5), building materials and standard components (T4), subassemblies and system components, (T3) assemblies (by system) (T2) and volumetric chunks (by zone) (T1). A last 'tier 0' (T0) is the finished building on-site where all systems

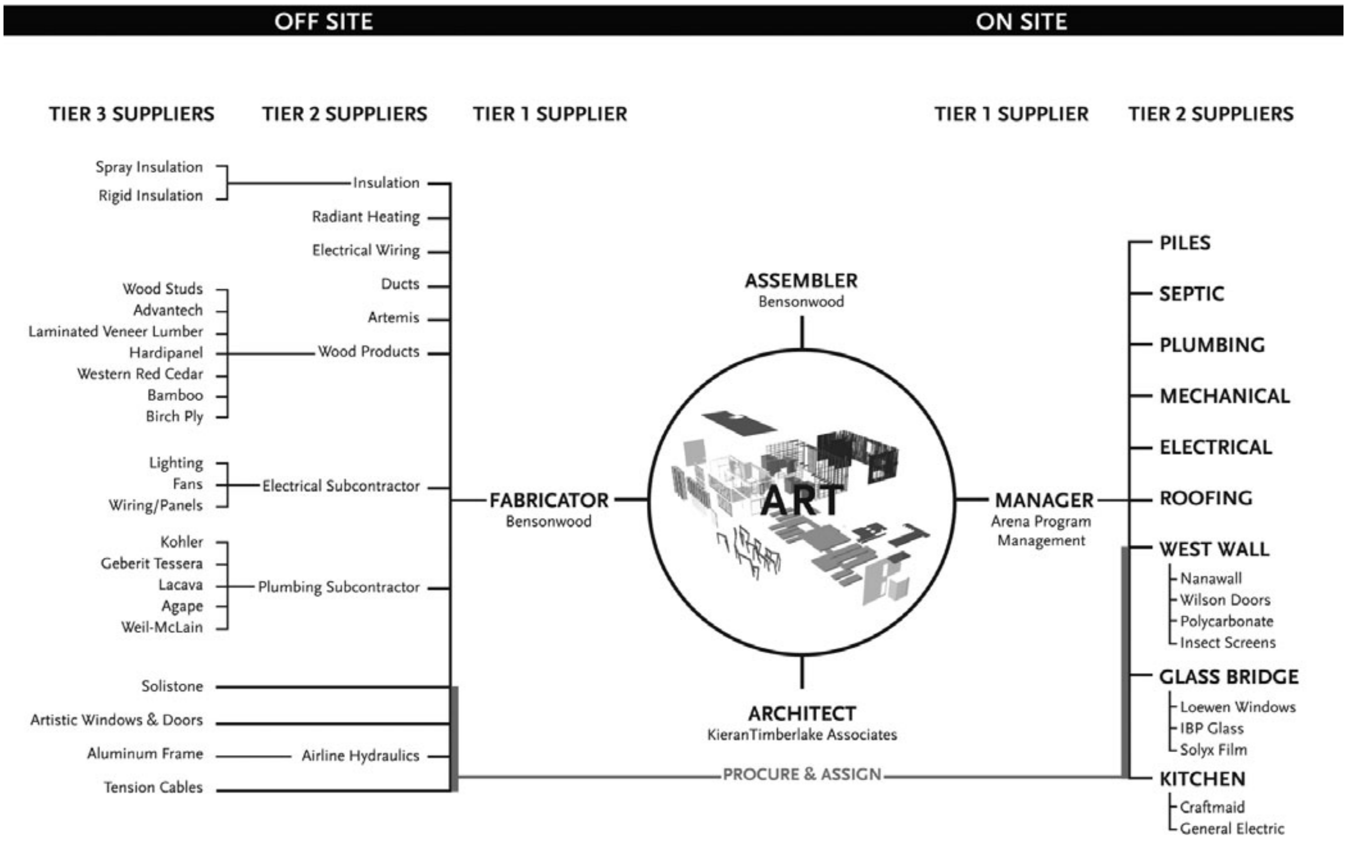


Figure 9.1 Supply chain for Loblolly House by KieranTimberlake. © KieranTimberlake

Figure 9.2 New tiers expressing the system levels of the system structure model [Author's drawing]

independently of their complexity are integrated (see Figure 9.2). Theoretically there could be additional 'upstream' levels in the hierarchy (higher tier numbers), for example, a next level (T6) focused on molecular properties of materials. However, the included levels express the range of what would normally be the focus of the *architect* within normal building projects.

The integration level (expressed by tier #) is parallel to the values of the dimension of *preparation* as it is explained in the taxonomy and is, for each delivery, supplemented by the two other dimensions of *standardisation* and *service*. Figure 9.3 shows the relation between tiers and dimensions. While the preparation level thus is consistent with the tiers (tiers 4–1), standardisation and service level can vary relatively independently. A high standardisation level, however, is most common on upstream tiers of simple materials, components. The service level has to do with additional delivery aspects of immaterial quality around the actual physical system. It expresses issues about, for example, warranty, liability and responsibility connected to a building product and its delivery. The purpose of these supplementary dimensions for each delivery is to introduce a second layer in the model that makes it more robust in terms of capacity for consistent classification of *any* system or delivery applied in a building project and particularly regarding what has earlier been termed integrated complexity. The *total integrated complexity value* indicates to what extent the architect (or another 'customer') can draw on knowledge and processes already embedded and nested into the delivery further upstream. The dimensions nuance the coding of the deliveries that each of them is graphically represented by a simple box in the system structure model.

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 *focused* view representing a specific viewpoint, that is 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

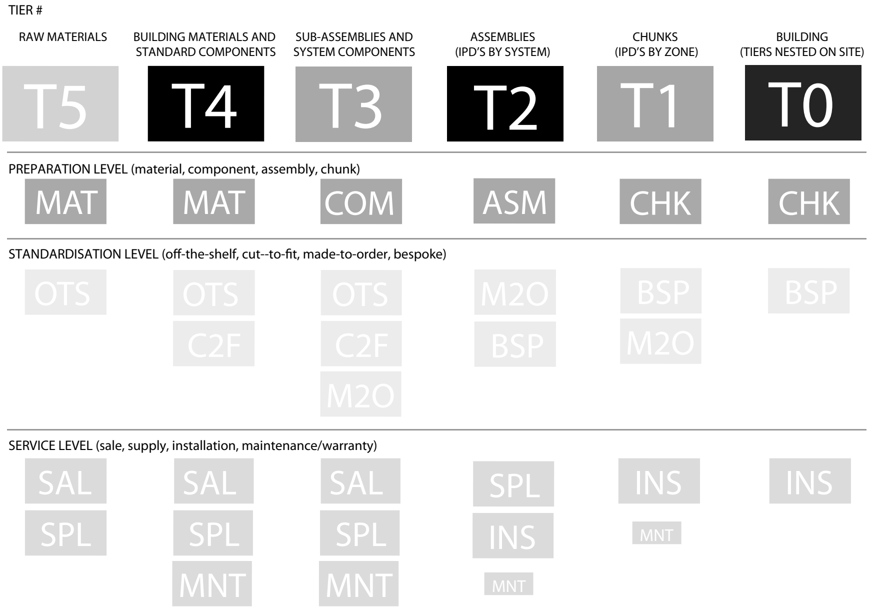


Figure 9.3 Relations between tiers and dimensions [Author's drawing]

by the concept of delivery and visually expressed like a box (see generic model, Figure 9.4). 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.[6]

Simplified theoretical scenarios have been put into the generic model for showing (and testing) its explanative power in a simple way (see Figures 9.5 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 on-site 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 principal integration point at the T1 level – in volumetric chunks (by zone). Finally a more tentative 'future industrialised construction' scenario will have longer supply chains of serially nested deliveries on various integration levels. While some deliveries are nested into others upstream, other deliveries on various levels are integrated directly at T0 – the building. Future industrialised construction, it is asserted, will tend towards a larger amount of mid-level deliveries as T2 and T1 – assemblies (by system) and volumetric chunks (by zone).

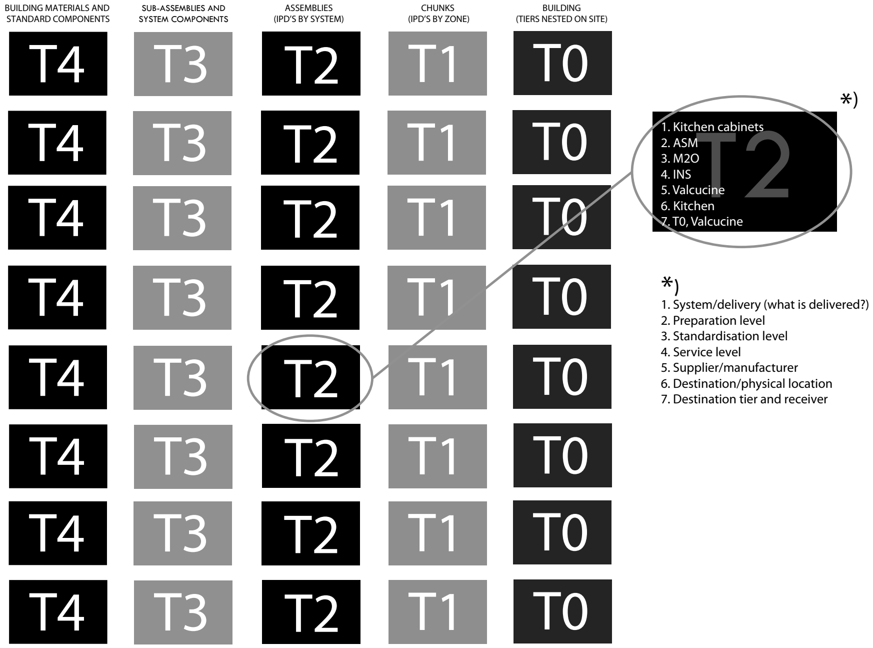


Figure 9.4 Generic system structure model and an example of a specific delivery coding (a box) [Author's drawing]

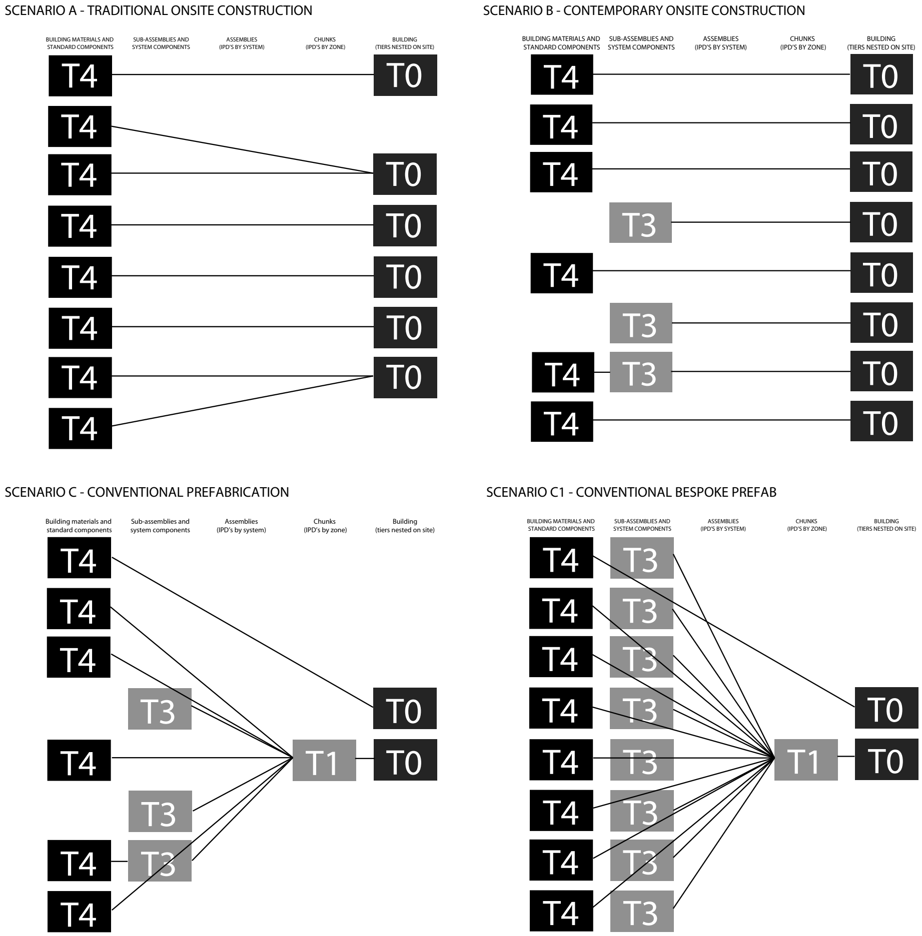
Model test, further development and perspectives

So what are the perspectives of applying a more systemic approach to architectural design and facilitate a better understanding of the integration of systems in construction projects as they move towards the application of more industrialised and complex integrated product deliveries? An easy answer could be that there is no way back to traditional construction exclusively based on the use of simple building materials and components brought directly to and processed on the building site (T0). As Alexander points out there is no way the current and increasing complexity in architectural design can be grasped intuitively by the designer.[7] If that is the case, several arguments could be put forward for an industrialised architecture as assemblage of integrated and nested systems managed through the use of system structures as they are expressed by the model:

- Architectural advantage of nesting/embedding complexity (in discrete subsystems) while still leaving more flexible and robust the solution space than in closed all-encompassing building systems (economies of scope).
- Ecological advantage of being able to select the subsystems (deliveries) most adequate to the local situation (performance, transportation, etc.).
- Business/legislative and liability advantage of dealing with products – not buildings.

- Systematic product development, specialisation and quality improvement is more probable in (sub) systems such as assemblies and chunks (integrated product deliveries) by allowing high up-front research and development expenses to be amortised across bigger and more international markets (economies of scale).
- Real industrialised/automated *production* rather than off-site *construction* is more feasible as solutions become commoditised as products (not simply traditional construction under roof).
- New market possibilities (compared to closed all-encompassing systems) within retrofitting of existing building stock as an alternative to demolition and new construction. This is particularly interesting concerning sustainability aspects.

The last point indicates another ambition pursued namely to be able to follow the disintegration or un-nesting of a building and/or its systems through



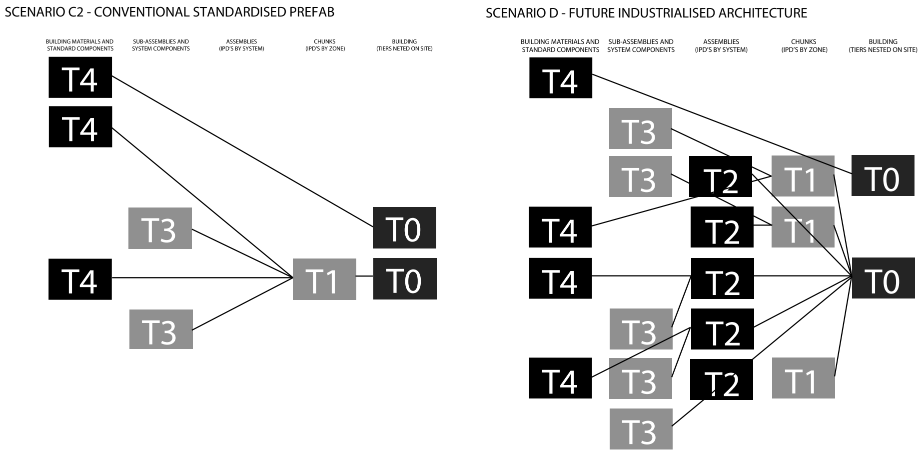


Figure 9.5 Different theoretical construction scenarios expressed as simple system structures [Author's drawing]

reuse, disassembly and demolition after the end of its useful life. Although most buildings in our part of the world are conceptually designed as if they were to exist forever this is seldom the case. The world and our culture are non-linear, turbulent, and dynamic entities – perhaps even at an accelerating rate. Changing needs put demands on buildings as systems to be adaptive over time. Concepts as design-for-disassembly and cradle-to-cradle design have been introduced. A mirrored version of the present model draft could provide a scheme for handling deliveries as sophisticated supply chain systems where, as Nagurney (2006) was cited earlier: 'used products may re-enter the supply chain at any point where residual value is recyclable'[8] (see Figure 9.6).

Model iteration

The model has been conceived through iterative loops that gradually increase the quality and applicability. The case analyses following this chapter form an important part of this iteration. This makes it hard to describe the model conception in a logic linear manner as dictated by the text as primary media. A couple of the iterative loops experienced during the work with the model are described below.

The idea of lines between the different deliveries (the boxes) placed on their respective tiers works fine for simpler buildings or buildings where a very detailed system structure of simple upstream deliveries has been omitted. This can be due to irrelevance for the chosen focus or because they actually are opaque from the chosen viewpoint (of e.g. the architect). If a system structure contains many highly integrated downstream deliveries as assemblies (T2) and chunks (T1) their substructures of materials and components are often rather an issue of attention for the manufacturers of these deliveries than for the architect that specifies them. The lines constitute an intuitively

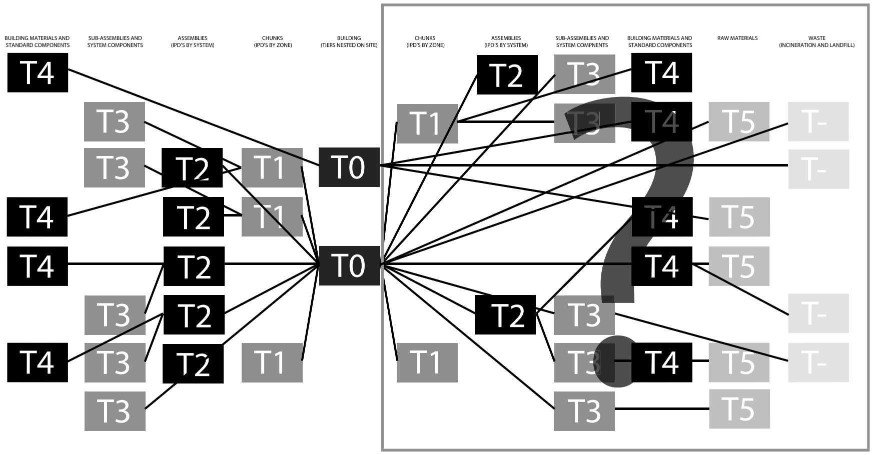


Figure 9.6 Sketch for a disassembly scenario expressed as system structure [Author's drawing]

straightforward way to follow the deliveries and their nesting. However, if all nested sub-deliveries are to figure in the system structure, for example – from a manufacturer or a contractor viewpoint – the number of lines (and deliveries) quickly exceeds what is easily visually perceivable. This consequently conflicts with one of the objectives of the model. In the Scandi Byg case analysis, representing a manufacturer perspective, an alternative visualisation has been attempted. Here the lines have been replaced by *connectors* that by use of different geometrical interfaces indicate the receiver and the sender of a given delivery thus obviating the lines by integrating the corresponding information in each delivery (the box) itself. Figure 9.7 illustrates how this visualisation works. The connectors facilitate use of larger numbers of deliveries without losing control of the connections. The visual appearance is cleaner. The sender/receiver connectors, however, do require a more thorough scrutinising by the reader in order to understand a specific system structure.

The *service dimension* is a later addition to the model introduced to catch, for example, integration aspects of deliveries that are only sparsely produced off-site while still integrating considerable complexity – in some instances termed as *parallel* deliveries as opposed to *serial* (nested) deliveries. Not all coding found in this book comprises the service dimension. The parallel deliveries can in some cases simply be an expression of the traditional scenario as explained above, where delivery divisions primarily follow the traditional crafts working with upstream deliveries directly on-site. However, in turnkey contractor or total-consultant perspectives as the NCC and Arup cases, these parallel deliveries can also conceal nesting of highly off-site fabricated solutions that lies within contractual divisions following more product or performance based entities. These system structures break the tier divisions with deliveries comprising various integration levels in the same final on-site (T0) delivery. Figure 9.8 shows examples of such opaque parallel deliveries.

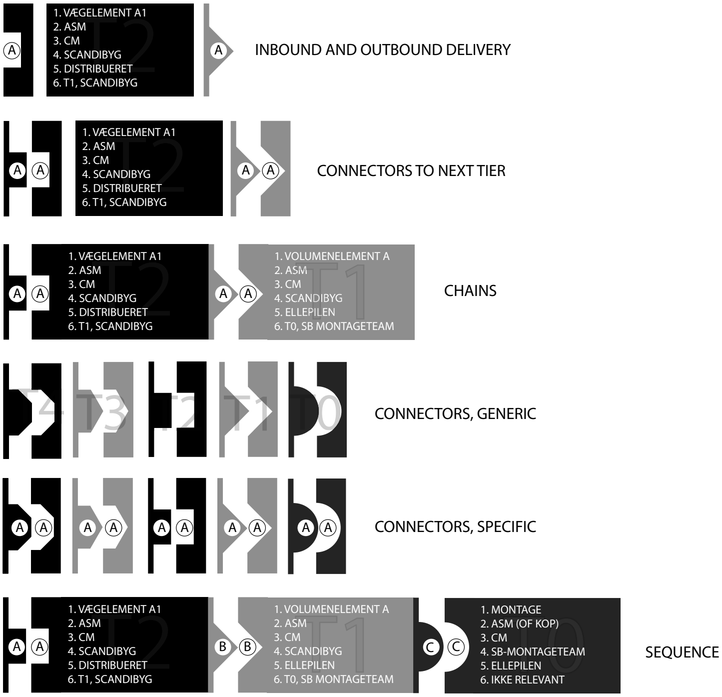


Figure 9.7 Deliveries and supply chain with connectors instead of lines [Author's drawing]

Figure 9.8 Opaque parallel delivery potentially comprising various integration levels in one single on-site delivery. Examples from Arup case [Author's drawing]

Letting go

In the eagerness of systemising and controlling architectural design it is important to keep in mind as Meadows ironically states that:

> Encouraging variability and experimentation and diversity means 'losing control'. Let a thousand flowers bloom and anything could happen! Who wants that? Let's play it safe and push this lever in the wrong direction by wiping out biological, cultural, social and market diversity!
>
> (Meadows 2008: 160)

Perhaps there is no need – or wish – at least from an architectural point of view to get the process of building and architectural design completely under control. This is not the same as saying that it does not make sense to understand and visualise buildings and their coming into being as complex systems of ideas (thoughts), processes and products. The model in its present and future states is a step in this direction but is not an ambition to establish an all-encompassing systems view on architecture and construction. However, the ability to handle complexity has become crucial in order not to lose architectural coherence in industrially produced architecture. What Maier and Rechting state for the systems architect (engineer) in the product industry could equally fit the building architect:

> It is the responsibility of the architect to know and concentrate on the critical few details and interfaces that really matter and not become overloaded with the rest.
>
> (Maier and Rectin 2009: 9)

Case selection

The following chapters are the result of the specific application of the model to a number of case studies. The selection of cases was delimited as recently finished building projects with 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. The 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.

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

1. Company: KieranTimberlake (primary case)
   - 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.

2 Company: Scandi Byg
  - A Danish housing manufacturer located in Løgstør, Jutland. Scandi Byg is specialised in prefabricated volumetric elements thus representing 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+.

3 Company: NCC Construction
  - A major Scandinavian contractor located in Søborg, 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).

4 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 and core' high-end office building development in London.

Notes

1 See 'General systems theory', Ch. 4.
2 Ibid.
3 To talk about a final building is intuitively easy to understand. It can however be problematic to conceptualise a building as something stable over time. In the current context we will not go further into this discussion and, at least provisionally, accept that such finished state of a building will exist for an amount of time.
4 See also the definition of delivery in 'Architectural systems terminology', Ch. 5.
5 See Ch. 5.
6 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 also be found between deliveries on the same tier. This is a question of the 'granulation' of the model rather than an expression of inconsistency.
7 See 'General systems theory', Ch. 4.
8 See 'Industrial production theory', Ch. 3.

10 KieranTimberlake

Cellophane House™ and Loblolly House

Introduction

The present analysis is based on material retrieved at KieranTimberlake (KT). The study draws on two cases from the office. Where the primary case is the Cellophane House™, the analysis and discussion is subsequently nuanced and put into perspective by introduction of the Loblolly House as a secondary case. After short descriptions of the cases and the architectural office, two system structure models are established and discussed in relation to each other as well as concerning their relation to more conventional construction scenarios.

From the KT office, direct contributors to the study have been James Timberlake (JT), Stephen Kieran (SK), David Riz (DR), Billie Faircloth (BF), Carin Whitney (CW), Mathew Krissel (MK), Andrew Schlatter (AS), Steven Johns (SJ), Christopher Macneal (CM), Rod Bates (RB), Jason Niebish (JL), Elizabeth Kahley (BC) and Marilia Rodrigues (MR). During external visits main contributors have been from the Cellophane House™ manufacturer, Kullman: Amy Marks (AM) and Chuck Savage (CS) and from the Loblolly House manufacturer, Bensonwood: Hans Porchitz (HP) and Paul Boa (PB). Several others have assisted in different more indirect ways. Whenever interviews are referenced or directly cited in the analysis they are followed by the initials of the person in brackets.

Project type: Description of the case(s)

The main case of this book, the Cellophane House™ (CH) is a full-size structure originally made for a temporary exhibition. It is designed as a freestanding multi-storey single family house but does with its limited footprint, deep plan, and five storeys also allude to a more urban setting as a townhouse. The Cellophane House™ is the result of a competition held in 2007 by MoMA – the Museum of Modern Art in New York – which led to the selection of five projects, among these the Cellophane House™ (CH), which were to be built as a part of the exhibition *Home Delivery – Fabricating the Modern Dwelling* in 2008.[1] The competition brief asked for an off-site or prefabricated house that could be assembled in a very short period of time on a site close to MoMA in New York City. Proposals should include not only the concept of design, but also the fabrication process and a budget (DR). The CH project was explicitly designed for disassembly (DfD) thus making possible an afterlife as more than a temporary exhibition structure, and it is currently stored for possible reassembly in a different location. Both as competition entry and final result the building draws considerably on earlier ideas and experiments from other KieranTimberlake (KT) projects and seeks to bring these a step further. Thus the *SmartWrap*™ PET film used on the façade is inspired by a pavilion by KT made for a Cooper-Hewitt exhibition in 2003 and the Bosch Rexroth structural frame used was equally applied in the Loblolly House from 2007 (DR/AS/SK/JL).

The Loblolly project is here used as a secondary case and will be introduced more in detail below. In line with this re-interpretation of earlier KT ideas another important characteristic of the building concept is the idea of mass customisation through the intended use of existing systems of more or less standardised nature as different kinds of infill applied to a robust architectural concept of a general frame – in this case the Bosch Rexroth system. The aspect of mass customisation will be treated more in detail below. Finally concepts of transparency and lightness are central for understanding the project (MK/DR). Although the exhibition setup posed other requirements and gave other possibilities than had it been an inhabited structure, the CH should be understood as much more than just a pavilion. Partner James Timberlake defines it rather as a *prototype* for a real house – or for a series of mass customised houses based on the same principles:

> [It was] truly an opportunity to . . . develop a program and a typology that could act as a prototype that then with a modest amount of modifications could go to production . . . the prototype gave us opportunities to try some things like applying polycarbonate floors and putting a polycarbonate stair in it that wouldn't necessarily go to production.
>
> (JT)

The nature of prototype includes the element of test and many unconventional materials and solutions were introduced as possibilities that can point into subsequent versions of the CH or into other KT projects: 'There is every intention not to leave the Cellophane House™ behind but to figure out a way of commoditising it, should we have the economy and the developer/producer that is interested in that' (JT).[2] The CH can be seen as an investigation as to where current KT research efforts were at that time in a variety of projects (MK) or as taking the most compelling elements of earlier ideas and pushing them into an extreme that was made possible by the competition setup (AS). The main part of the building was off-site produced as volumetric elements – or chunks – in New Jersey and came into New York on trucks.

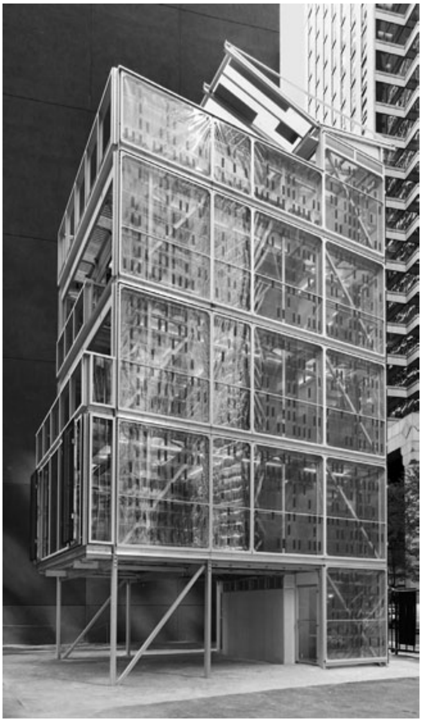


Figure 10.1 Cellophane House™ at MoMA in New York in 2008 © KieranTimberlake/Bosch Rexroth

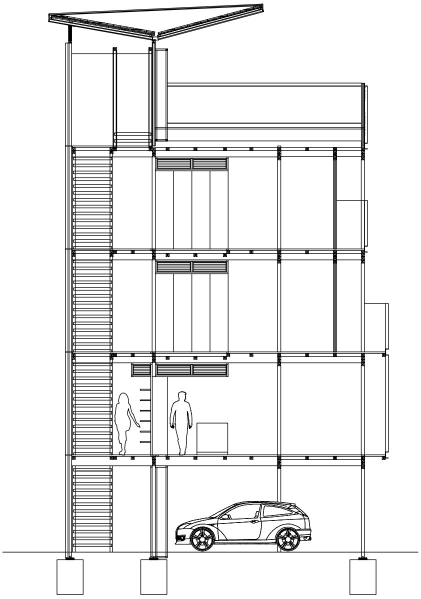


Figure 10.2 Cellophane House™ – section © KieranTimberlake

Secondary case – the Loblolly House

The Loblolly House is a single family detached holiday home located on a natural plot on Taylor's Island, Maryland. It was finished in 2007 thus time-wise prior to the Cellophane House™. The building was conceptually conceived as consisting of five main elements – *the elements of a new architecture* in the words of the architects.[3] The building was partly delivered as these elements to and on the building site. Elements were:

1 piling and collar beams – the interface between the irregular ground conditions and the low tolerance industrially produced building systems;
2 structural frame – a refinement of an aluminium frame system (Bosch Rexroth) originally applied for industrial production lines into a structural system for building construction;
3 floor and wall cartridges – planar prefabricated assemblies divided into 'intelligent' floors and 'dumb' walls concerning the degree of integration of different (installation) systems;
4 volumetric prefabricated chunks containing technical rooms and bathroom facilities;
5 final fit-out as an external building skin, kitchen installation, furniture and other accessories.

The Loblolly House was, as the CH mainly produced off-site – in this case in New Hampshire by Bensonwood. The system structure analysis will include a comparison and discussion of the similarities and differences between these

Figure 10.3 Loblolly House is located on a beach plot in Maryland, USA © Ulrik Stylsvig Madsen

two projects and the way they were produced and constructed. While both have been largely fabricated off site a major difference is the applied strategy of modularisation.

The company and the zoom of the analysis

The coding of the system structure models for the two cases, Cellophane House™ (CH) and Loblolly House (LH), are in this analysis seen primarily from the perspective of the architect represented by the architectural office KieranTimberlake. The office was founded in 1984 in Philadelphia by Stephen Kieran and James Timberlake and comprises today well over 50 professionals. The project portfolio includes new structures as well as renovation, reuse and conservation of existing structures with many projects for cultural and educational institutions and mostly in the US. A little unusual is that in both of the selected cases KT can be considered both client and architectural designer of the projects. Although MoMA curated the exhibition in the case of CH they were not clients in a traditional sense and it was KT themselves that disassembled and stored the building elsewhere after the exhibition. In the case of LH, the client was partner Stephen Kieran and his wife. This combined with the prototype character of the CH somehow made it easier to experiment also on the contractual and procedural levels of the projects which is a special interest of the office. KT explicitly state process as the *first art* and claim to employ collective rather than singular intelligence in the making of architecture thus acknowledging the importance of interplay between architect, client and other stakeholders in the process of architectural creation.[4] KT works consciously with bridging the claimed gap between how architecture is conceived and how it is or can be produced, for example, by using the industry, its production logic, and its systems and products as an active element in the architectural design process. In the book on Loblolly House, KT directly address this problem:

> What if we no longer were to think backward from the first image of form so that conceiving and building could proceed in unison, not competition . . . the new tools of today promise to rejoin our processes of thinking and making.
>
> (Kieran and Timberlake 2008: 40)[5]

System structure: Coding and special project specific features

Cellophane House™ (CH) being the primary case will be more thoroughly presented than the Loblolly House that will rather serve as comparison and background for discussion of the specific CH system structural features. The CH was organised around several individual trade contracts on several integration levels of delivery which were generally controlled by the architect, KT. Representing as the final result a bespoke design solution, the manufacturer, Kullman, did in this case not provide an integrated solution based on their particular standard systems, nor did they deliver turnkey on-site as it is often the case in many of their other projects. In fact Kullman is specialised mainly in structural steel frame solutions and aluminium was new to them. However, the competition brief's emphasis on an off-site or prefabricated house that could be assembled in a very short period of time made Kullman the primary system integrator in the system structure.[6] The building was thus from the start conceptualised as a series of highly integrated volumetric tier 1 chunks (T1) that were to be factory produced, transported to the site, stacked with a crane and bolted together with the use of a wrench. The idea included a similar process of disassembly where the same volumetric chunks after the exhibition were to be unscrewed, lifted down and onto a truck and relocated and reassembled in another place. The main driver for embedding most of the systems into these T1 deliveries (the chunks) at Kullman was rather dictated by the exhibition setup than the constraints of local weather conditions or other site considerations normally motivating a high degree of off-site completion.

> It was part of the show . . . Particularly when you are doing a show like this it is not only about the design – it is about ideology. Half of our submittal probably talked about ideology and half about the design. This was going to be a much more public assembly and disassembly process than at Loblolly House. If we are holding 'Refabricating Architecture' as an example of how we should do things . . . this is the way you should do it – as chunks.
>
> (DR)[7]

The building had to go up in less than two weeks and 80 per cent of the building actually went up in only six days on-site (JT). Apart from the show aspect there was also a considerable economic incentive in minimising labour use on-site in central New York where prices are among the highest in the world.

Being a bespoke solution that does not draw on the manufacturer's own standard solutions and systems did, despite the main strategy of T1-deliveries, bring the architect to focus intensively on upstream deliveries (T4–T2) that were procured directly from a supplier and not, through a contractor or, in this case, the building manufacturer. The high profile nature of the exhibition enhanced the quest for unique and innovative materials and solutions. Although an idea was to use existing products these products were often – such as the Bosch Rexroth aluminium frame system – transferred from different contexts and uses and were either applied directly or in a modified form in the CH project.

The Cellophane House™ system structure

As a smaller and relatively simple building that, although prepared for it, does not comprise the normal mechanical systems and ducting, the CH system structure contains only a limited total number of deliveries (see Figure 10.4).

At the MoMA site, no water outlet and inlets were provided and heating and cooling were considered redundant during the exhibition period (July to October). However, the simplicity is also substantiated by the mentioned conceptual ideas of mass customisation and design for disassembly (DfD) resulting in a thorough and conscious selection of solutions with simple and reversible connections and relatively high standardisation levels (OTS or C2F). The choice of the sophisticated Bosch Rexroth frame as structural system combined with custom made connectors easily accommodate the different infill systems with very little need for additional fixing solutions.[8] Finally, the simple but non-traditional system structure can be explained by the specific focus or viewpoint in this case, the architect's, where (sub) supply chains for the more integrated (downstream) deliveries such as kitchen cabinets or bathroom pods often remain opaque. While the CH thus has few tier 4 (T4) and tier 3 (T3) deliveries it also has few tier 0 (T0) deliveries on-site due to the high degree of off-site fabrication. This means on the other hand that the two integrated tiers – tier 2 (T2) and tier 1 (T1) have relatively high weight and the deliveries on these tiers can be considered the primary elements – or systems – of the CH. The T1 chunks had an 80 per cent degree of completion upon delivery on-site thus integrating most upstream deliveries already from the factory including several of the T2 deliveries as staircase and most partition walls and SmartWrap™ panels (JT). Others were integrated on-site i.e. kitchen cabinets and bathroom pods (T1). Some partition walls and SmartWrap™ panels could not be factory integrated due to the specific on-site assembly sequence or the risk of transportation damage and were instead delivered to site for final fit-out. The Bosch Rexroth frame, although being the basic structural system, becomes in CH a (T3) subsystem to the chunks. This is different from the Loblolly House where the same aluminium frame system is the primary system delivered as a kit-of-parts on-site and erected as the frame for on-site infill. Although in the system structure, the Bosch Rexroth frame is hierarchically not considered the primary system it was *conceptually* still a leading element in the competition and is far the most visually dominating element of the finished building.

Mass customisation

The idea of mass customisation is as mentioned a central part of the architectural concept of the CH as well as a general goal or 'ideology' in the office in general. The idea was the frame and not the specific (Bosch) product which was rather chosen from earlier experience in the LH and the SmartWrap™ pavilion for its sophistication and elaborated accessory sample and for its obvious qualities when it comes to disassembly.[9] The Bosch system works in a certain scale – it wouldn't work for high rise (DR). Having this separation between what is structure and what is not gives a lot of freedom when it comes to infill (DR). By use of the Bosch Rexroth system as frame, the

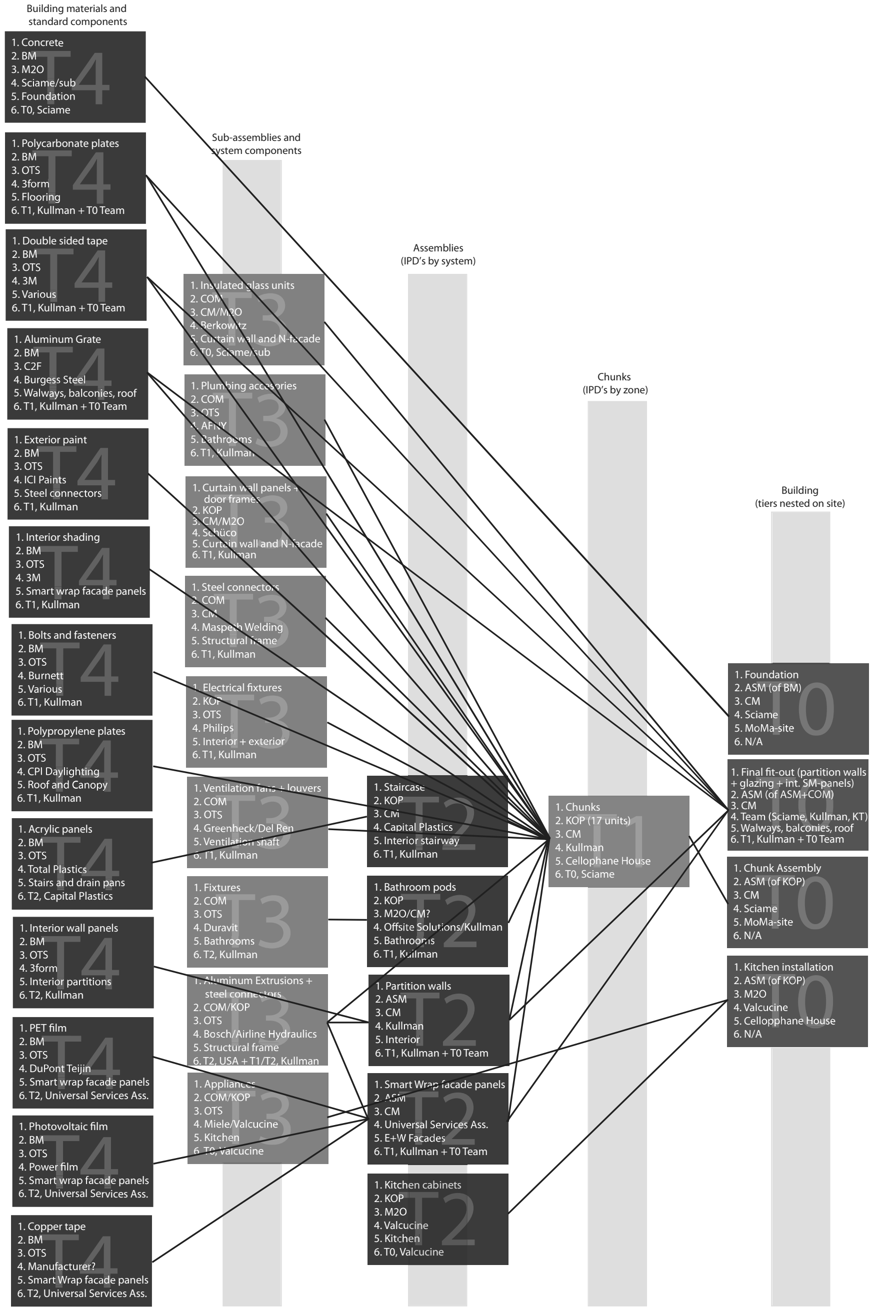


Figure 10.4 System structure of the Cellophane House™ [Author's diagram]

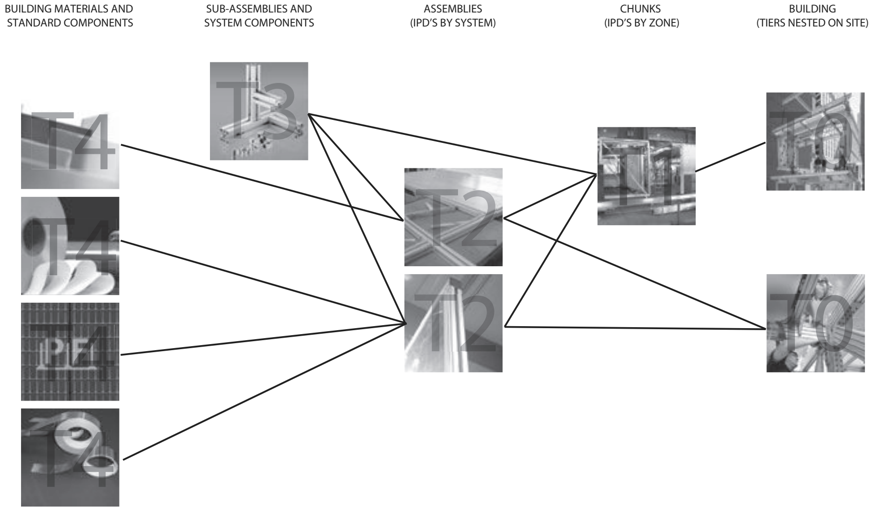


Figure 10.5 A segment of the Cellophane House™ system structure clearly displays chains of nested (serial) deliveries [Author's diagram + © Albert Vecerka/Esto (File numbers 2008AV19.444 (right top) and 2008AV19.427(right bottom)]

intention was to use both standard and innovative materials in a mass customisable way (JT) by *hanging*, *placing*, *stretching*, and *bolting* them onto the frame:

> [The Cellophane House™] is first and foremost, a matrix for holding materials together in such a way that they create an inhabitable enclosure. The critical term here is holding, as opposed to fixing. Materials that are held are allowed to retain their identity as discrete elements, and can be released at any time. Materials that are fixed to one another can be freed only through the expenditure of great amounts of energy. The actual materials are, in a sense, irrelevant: it is the manner in which they are joined together that defines the essence of a structure.
>
> (KieranTimberlake press-kit 2008)

The specific accommodation of materials in the frame became in a way mass customised where, as partners came on board, the design development team would tweak the design to accommodate their system or product (DR). The slightly odd building site for a detached single family house enhanced the CH's aspect of – as a prototype – being a broader non-site specific platform. This is very different from the Loblolly House project that, although drawing on similar ideas, is the specific result of a specific site (JT). Still, there could have been a more rigorous systematising of the components having probably too many one offs (DR). One of the lessons learned in the CH concerning mass customisation in construction could be the idea of adopting off-the-shelf (OTS) materials and components (T4 and T3 deliveries) from some other use to create new integrated systems for a different application (AS). The Bosch frame, developed for industrial production line facilities, combined with the custom made steel connectors is the prime example but others such as the honeycomb polycarbonate staging panels used for flooring or the PET film as base material for the integrated SmartWrap™ panels are equally adaptations from other contexts. However, it is also possible that systems that are more systematically developed directly for architectural use could be applied – as long as they are flexible enough. There are probably aspects of building that would benefit from being treated like appliances that the architect could specify within a known system. In fact this is already the case within mechanical building systems, for example (CM).

Design for disassembly – and for reassembly

The Cellophane House™ to some extent directly tackled the question of design for disassembly (DfD) as part of the originating design concept. Choices of materials, systems and design solutions were thus to a considerable extent dictated by their ability to be disassembled (JT). The disassembly of the house was as integral an experiment as putting it up in the first place (BC):

> One of the things that I concentrated on in this proposal was the system in terms of how things were assembled – how the Bosch was integrated – these plug/unplug, wrap/unwrap – this idea of reversible construction and mechanical connections – design for disassembly with off-the-shelf pieces. (AS)

The idea was on the one hand that the CH would have zero waste at the end of its useful life by being integrated into different recycling streams. On the other hand the idea was also that, before reaching this state, it would have a second or multiple afterlives as it would be reassembled in another location and used for another purpose. Hence, design for reassembly was equally an issue – a little different from the DfD. This led to the unusual exercise of designing the *disassembly* process (JL) and although the idea was planted from the outset and to some extent already was integrated into the design at competition and design development level, a special DfD team was assigned the specific task of getting the house down by the end of the MoMA exhibition. The overall task was 'how to get this building down as fast as possible with the least amount of waste for the least amount of money' (JL). Several strategies and scenarios were at stake: one was to sell it, take it down as the factory produced chunks it was made of, ship it to some other location and reassemble it directly. This required a client willing to buy the building as a whole. Another strategy was to partly or completely dismantle the building into its components and materials that could then be sold as discrete elements for use in other contexts, and finally the building could be recycled as materials each one going into its specific stream. The latter option did not seem ideal for a house that had only been in use for four months (DR). Although there were negotiations, at the end the house was neither sold as complete nor by parts. The cheapest thing would have been just to rip the building down, demolish it, and sell for scrap but maintaining the intention of disassembly alternatively it was decided to store it for possible later reassembly (JL).

The transport and storage circumstances ended up dictating how the CH was disassembled as KT couldn't afford shipping chunks out of New Jersey and the storing as chunks (T1 volumetric elements) (JT). A factory disassembly which would have solved some craning and weather issues on-site was equally beyond the budget. Instead of loading 15 flatbeds – one per chunk – the house was, with some exceptions, dismantled on-site into the smallest possible parts and packed like a 'Swiss watch' (DR) on only four flatbeds and a closed tractor trailer used for the more sensible parts. Every flatbed not used not only saved money on storage but also as transportation costs. First, however, the building was brought to the ground as chunks and this was done in only four days (JT). In order to combine efficient packing with keeping track of the many parts for later reassembly, the disassembly team developed a consistent labelling system including a packing ID for all the parts which were then packed by family of item so that e.g. all the Bosch Rexroth framing got on one flatbed (see Figure 10.6).[10] The Bosch Rexroth and the Varier-panels used for the interior partition walls were delivered from the factory with ID-numbers – systems that had its root already in the BIM-model used in the design development phase – but everything else had to be done from scratch and while the building came down. A logical next step for subsequent projects including a systematic DfD would evidently be to apply such a labelling before the building goes up in the first place (BC). That would require the DfD to become a more integrated part of the design development phase. From an estimate of three days for labelling it took the team five weeks while simultaneously packing all the parts. Although most of the building was brought down to its original T3 and T4 deliveries, that even in some cases until then had been opaque for the architect as integrated in T2/T1 deliveries,[11] some elements were retained as assemblies: the SmartWrap™ panels, the polycarbonate partition walls, part of the balconies and the staircase. The latter were the heaviest individual components in the buildings and were neither designed to stand on their own nor to be brought down to component level. The stairs were braced, lifted with a small forklift and placed on the back of a drop deck flatbed. All five stair assemblies were shipped whole. A few items had to be scrapped: the roof and gutter flashing and the 3M double-sided tape joining the partition walls came easily off the panels but could, as non-reversible attachments, neither be reused for reassembly

GLA-3F-6.2
GLASS
BALCONY LGU SIDE
PACK GROUP C13

BOP-1C-113
BOSCH [PARTITION]
[C] 45x45 NORTH
BOP-1C-113

STT-2R-207
STAIR TREAD
PACK GROUP P16

STG-2C-P13
STAGE FLOORING
KITCHEN LEVEL
PACK GROUP P12a/b

CON-XX-1.1
CONNECTOR
VERTICAL DIAGONAL
PACK GROUP B1.1

PAN-2F-1
ACRYLIC DRAIN PAN
PACK GROUP P13

Figure 10.6 Examples of labels and coding system used for the disassembled components. © KieranTimberlake

nor for recycling. A couple of other items were also damaged by accident during the process. Finally 30–40 per cent of the bolts had to be recycled as metal because they either got stripped during the assembly or the disassembly process (JL).

Another revelation during disassembly was that even if the building was to be reassembled in another location it would have to come completely apart first. The bolts used in the first case were normal black oxide hardened steel bolts and would not – although working fine for the exhibition – not withstand a longer period on, for example, a beach in California. Depending on where it would be going up some of the elements would have to change (JL). Although reselling by component was one of the reuse scenarios the CH was not explicitly designed for reassembly in other configurations than the CH itself. At the T1 chunk level, different combinations are not possible (BC).[12] However, T2 floor, wall or partition panels as well as most T3 and T4 deliveries could potentially be reconfigurable as parts in other buildings. Figure 10.7 is an attempt to elaborate a system structure expressing how the CH through its disassembly was brought back to varying system levels. Disassembly does not necessarily mean to disassemble all the way back to (raw) materials (MK). Certain integration levels of delivery can still be appropriate for other use. Other things will have to be scrapped. In the case of the CH, 98 per cent was recovered for direct reassembly.[13]

The disassembly process and the specific design of it contributed to a general awareness of issues concerning transportation, different environments at different locations, and inevitable wear and tear (BC). If the design mandate for a project is rapid assembly and disassembly then materials must be evaluated based on that criteria which also includes the criteria of durability and weatherability (BF). Water proofing details in particular seem hard to solve as 'dry' connections that can easily come apart – and together again – without producing waste. Another material criterion in question is that of embodied energy. If rapidly disassemblable structures meant for short or temporary use include materials high on embodied energy – such as aluminium – then their potential afterlife on different system levels become more critical

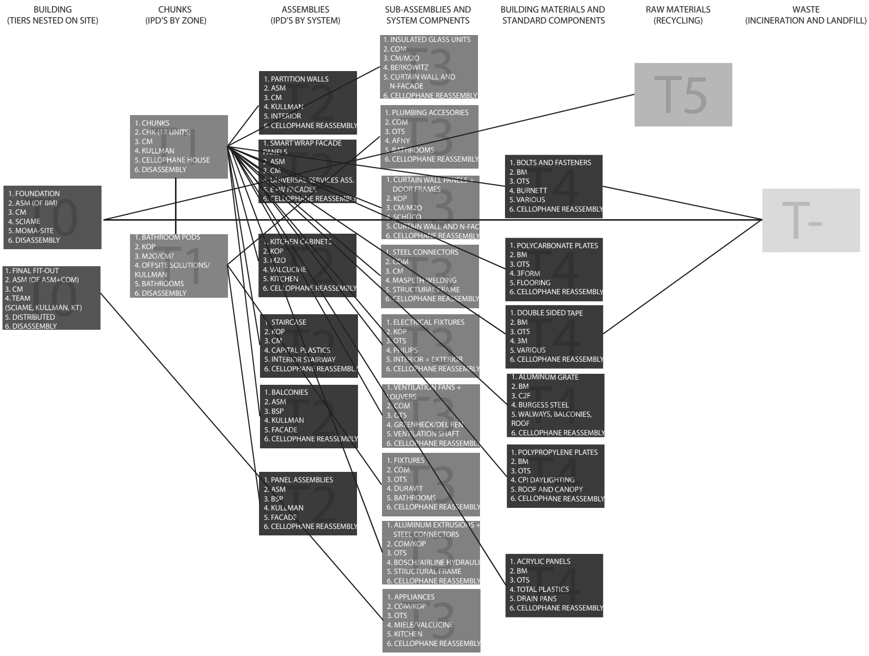


Figure 10.7 Cellophane House™ system structure of disassembly, sketch [Author's drawing]

than if rapidly renewable resources with low embodied – such as wood – are used. DfD can work as a special kind of design driver that, however, will be more relevant in some cases than in others depending on the purpose and lifespan of the building in question. Evidently it is harder imagining a disassembly process 50 years down the road, but CH made it possible to test many ideas connected to a more general strategy of DfD. Again, as with the question of off-site/on-site, a DfD strategy whatever general it might be will always need adjustment and adaptation to each specific project and its specific context.

Cellophane House™ vs. Loblolly House – degree of prefabrication

Some significant differences between the Cellophane House™ (CH) and the Loblolly House (LH) can be explained from a system structural perspective (Loblolly House system structure: see Figure 10.8). One particularly important is the difference in the final on-site delivery from the main manufacturer – respectively Kullman and Bensonwood. The two projects represent considerably different strategies of modularisation which can be illustrated through their different system structures. Where LH has certain

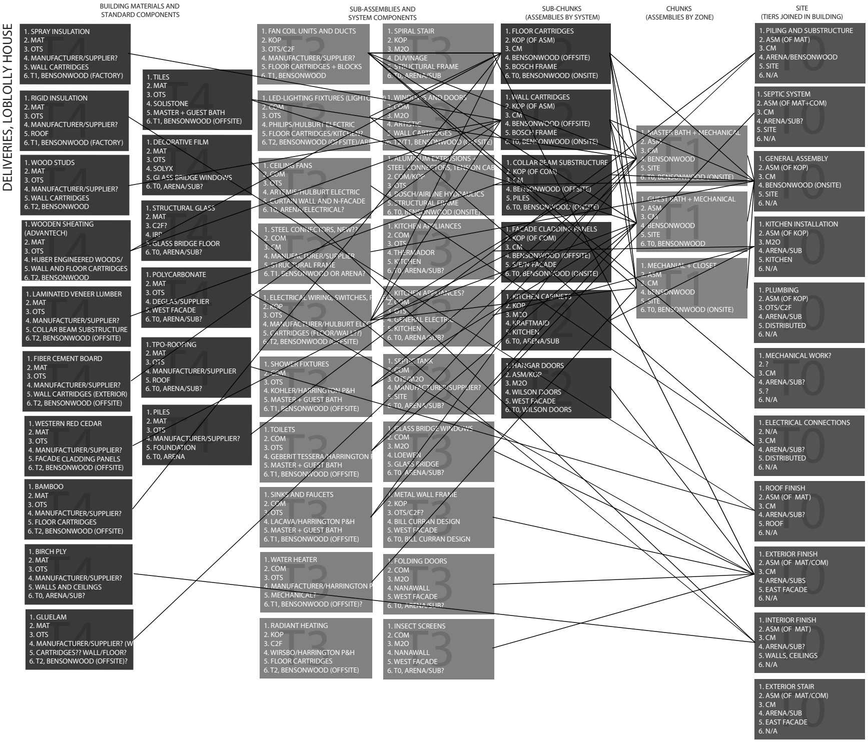


Figure 10.8 The system structure of the LH [Author's drawing]

chunk ideas (T1), the CH goes much further into that realm (DR). In the LH, the chunks – here called *blocks* by the architect – are limited to the most system-intensive spaces such as bathrooms and mechanical rooms whereas other spaces are made through on-site assembly of panelised (T2) floor and wall assemblies called *cartridges*. Both blocks and cartridges are in the LH inserted into a (T3) prefabricated but on-site assembled version of the Bosch Rexroth frame – here termed the *scaffold* – delivered as a kit-of-parts. Despite this reduction in (T1) chunk deliveries, the LH still has a relatively high degree of off-site system integration due to the nesting of wiring and mechanical systems into the floor cartridges that are delivered as assemblies (ASM) with 'plug-and-play' system connections.[14] The wall cartridges are less system-intensive thus introducing a further distinction between smart and dumb cartridges (DR) – both to be considered as T2-deliveries. In the CH on other hand the nesting of upstream deliveries (T4–T2) into the chunks (T1) is deliberately maximised with one of the only limitations being the earlier mentioned transportation and on-site assembly issues that resulted in on-site assembly of some few of these. The (T3) Bosch Rexroth frame, again delivered as a kit-of-parts but this time to the factory, here becomes a sub-element – although the primary one – of the (T1) chunks. Flooring, partition wall panels, SmartWrap™ exterior wall panels and other more or less upstream deliveries are fixed to this frame on chunk level in the factory:

> We were working with systems within systems because from very early on we were interested in embedding [the Bosch Rexroth system] in another system. That is the system of chunks of fabrication . . . we were both engaging with and getting around or tweaking the rules of one system to make it work as part of the greater system – the modules [or chunks (ed.)].
>
> (MK)

One of the main reasons for the (T1) chunking strategy applied for the CH was, as mentioned earlier, the extremely limited period of time for the on-site assembly and the site constraints such as difficult access and only little space for laying out construction elements. Where the CH is thus mainly assembled on-site as chunks 'by zone', the LH is mainly assembled on-site as assemblies 'by system' supplemented with other systems constituting the proposed *elements of a new architecture*: (a) the piles and collar beams, (b) the structural frame, (c) the floor and wall cartridges, (d) the blocks and (e) the final fit-out.[15]

Both times, economy and site constraints were not as critical for the LH project where, although the vision was equally fast on-site assembly based on a high degree of prefabrication, the intention was also to examine possible new divisions in construction – the elements of a new architecture, as explained above. LH was put together in rural Maryland where labour and rent of equipment is cheap and KT had a fixed fee contract with Bensonwood (DR):

> Largely you have to make a decision first about [on-site] time before you make a decision about tactic. If time is critical generally speaking the more you do off-site the faster the assembly on-site will be . . . On Cellophane House™ time [on-site] was a huge premium . . . Whereas [for] Loblolly House time wasn't such a premium and being there 6–8 weeks on-site was acceptable.
>
> (SK)

In many ways the conceptual division of constituent elements in the LH project seems clearer and more 'innovative' than for its successor, the CH, where other foci such as the design for disassembly and mass customisation perhaps had more attention. Design for disassembly was also claimed to be an integral part of the LH. However, if disassembled for *reassembly* the LH would have to stay mainly on the level of T2 deliveries. If cartridges and blocks were to be brought further apart as the original T3 and T4 deliveries many of the elements would lose their reassembly capacity and consequently the reclaiming of these would be reduced to recycling into their respective waste streams.

Integrated product deliveries: Examples and innovation in commoditisation

General

As introduced above, the CH and the LH projects represent different ways of modularisation and different balances between off-site production and on-site construction. The system structure model enables the establishment of a conceptual distinction between two principle forms of integrated product deliveries: the T1 chunks 'by zone' and the T2 assemblies 'by system' and although the two buildings are not clear versions of one or the other they do, as mentioned, have a bias towards this. While a range of T2 deliveries combined with few T1 deliveries dominate the LH scheme of (T0) on-site assembly the CH is characterised mainly by its T1 chunks arriving to the site with the T2 deliveries nested already from the factory. As a special feature of the CH, these T1 chunks are based on the concept of mass customisation that by nesting a considerable amount of standardised ready-mades (OTS or C2F) on T4 and T3 delivery level into the T1 chunk makes the concept more open to changes over time or in different versions while reducing design complexity in each case. The CH is a prototype of a building while the LH is a one-off building. The idea of accommodating existing products as direct deliveries (with high standardisation levels) is far more prevalent in the CH than in the LH and further enhances the need to take into account already from early design phases the way the building is divided up into elements and put together. However, only few standardised products are used on the more complex T2 and T1 levels. In the LH, for example, the cartridges, substructure and façade cladding panels are all bespoke (BSP) whereas the hangar doors and the kitchen cabinets are made-to-order (M2O). In the CH staircase, partition walls and SmartWrap™ panels are BSP whereas bathroom pods and kitchen cabinets are M2O. No off-the-shelf (OTS) or cut-to-fit (C2F) products are found on integrated product delivery levels (T2 and T1). Bathroom pods could theoretically in many cases be OTS standards, but the market is so far not really prepared to make use of such a product, that would have to be integrated in early design phases and subsequently determine certain features of the rest of the building such as the location of risers and waste pipes.

The chunks

The chunks that constituted the primary T1 delivery of the CH have already been presented in some detail above that do not need to be repeated. What is quite interesting though – and particular to the use of volumetric chunks in the CH – is the choice of using a combination of two towers of stacked 'table top' chunks and a number of bridge chunks spanning between these.

> The front modules and the back modules [chunks, ed.] were boxes with columns at the corners and structure between them. The centre piece was a bridge between the front and the back and its wall panels came in afterwards. (CM)

While the back tower contains the T2 staircase nested into it from the Kullman factory, the bridges carry the bathroom pods that were placed there on-site before hoisting them into place. The front tower is basically open space towards the north façade's sliding doors and balconies. This strategy almost eliminates the double construction which is otherwise so common to prefabrication based on volumetric elements, or chunks, and improves both the reading of the building as a single piece rather than a stack of modules as well as the sensation of large open interior spaces (MK and AS). By omitting the ceilings and simply using the floor plates from the storey above, the design of the chunks is further simplified. The downside is that more upstream deliveries (T4–T2) have to be mounted on-site partly to give access to the bracket joints partly because of fragile detailing. In order to enhance stability during transportation from the factory to the building site some temporary bracing was used and removed on-site during the T0-chunk assembly. As mentioned above the chunks were about 80 per cent complete as T1-chunk deliveries from the factory.

Bosch Rexroth aluminium frame

The Bosch Rexroth frame used in both the CH and the LH are in their respective system structures coded as a T3 delivery. The system represents a huge variety of parts and accessories that can be combined in an infinite number of spatial configurations which could make it a candidate for T2 status as an assembly by system. However, as developed originally for factory scaffolding it does not constitute a complete and directly applicable structural building system in itself. It needs the complimentary custom made steel connectors to become such a system. As these have been designed and are produced and delivered separately either on-site (for the LH) or on factory (for the CH), the structural system is system-structure-wise in both cases considered as two T3 component deliveries rather than one integrated and more complex T2 assembly. Potentially the combination of aluminium extrusions and steel connectors could be commoditised into one single integrated product delivery. Originally the intention in the CH was to push the refinement of the connector towards a click-system where the bolting process became redundant (SJ). This idea of accommodating an existing system to a different use is typical to the way KT have worked with mass customisation in the CH. During the disassembly of the CH the Bosch Rexroth was, as described under *design for disassembly*, brought all the way back to T3 level with exception of the profiles used in the partitions walls and the SmartWrap™ panels that stayed on T2 level.

Acrylic staircase

The acrylic staircase in the CH was delivered as a bespoke (BSP) kit-of-parts T2 delivery to be assembled and nested into the T1 chunks by Kullman at the factory. Together with the Bosch Rexroth frame the staircase is one of the iconic pieces in building contributing with a more artistic touch (DR). As assembly the staircase was, as one of the few elements, not designed for disassembly thus integrating tread, sidepieces and lighting into a number of fixed and glued modules corresponding to a whole ride of stairs up to a landing (SK). James Timberlake classifies the staircase as construction as *opposed* to assembly in the sense, that the staircase is not directly recyclable and do not come apart into its constituent sub-deliveries without being damaged (JT). For comparison the LH steel stair was assembled thread by thread on-site and could come apart in the same way. The staircase as a general building element is a typical example of how a T2-delivery can develop into more standardised and commoditised versions. One of the advantages in this sense is the relatively clear interface to its surroundings as well as a limited and well-defined function. Completely bespoke stairs as the one in the CH are only seldom found today and most solutions are delivered as assemblies – often as a finished kit-of-parts.

Partition walls and SmartWrap™ panels

Both interior partition walls and exterior façade panels were made as Bosch Rexroth frames with infill together forming two separate T2-deliveries. Again alluding to the initial idea of mass customisation this infill could comprise many different materials. The supplementary conceptual ideas for the CH of transparency and lightness combined with KT's earlier experience with the SmartWrap™ (SW) – a PET film with different functions integrated, i.e. photovoltaics, sensors, LEDs and colours/decoration – dictated the use of this film for the exterior façades that should have fully functional photovoltaics contributing directly to the power supply of the building. The CH SmartWrap™ thus became a second generation prototype of this material that also included extending the idea from a concept of a single layer composite material into the idea of an assembly (CM). The proposal envisioned a double panel construction, each panel with two layers of film, forming an intermediate cavity for insulation and ventilation. The specific design and size of the panels were informed by physical experimentation with stretching of the film over the frames which again informed back to the overall building scheme (AS). The SW panels were, contrary to the partition walls, not produced by Kullman, the main fabricator, but were delivered separately by Universal Services Associates – partly to Kullman for the nesting into the T1-chunks, partly to the site for final fit-out assembly (T0). Although bespoke (BSP), the SW panels are a good example of a discrete off-site produced T2-delivery with different nested T4 and T3 deliveries (i.e. PET film, 3M-shading film, photovoltaic film, copper tape and the Bosch Rexroth frame). The partition walls were produced by Kullman but still as discrete elements that were then mostly nested into the (T1) chunks at the factory. Some panels were, however, mounted on-site (T0) for practical assembly reasons. Apart from the aluminium frame, the partition walls included 3form Vara wall panels, and some double-sided tape – both T4-deliveries.

Bathroom pods

The bathroom pod is, as mentioned earlier, one of the few more established discrete T1-deliveries existing on the market and thus one of the deliveries of the CH that comes closest to the ideas expressed in *Refabricating Architecture*.[16] For the CH, originally a made-to-order (M2O) product from the British fabricator, Offsite Solutions, was chosen – again as a discrete off-site produced delivery with different nested upstream deliveries (T3 and T4) where most of these would be opaque to the architect/client and based on the specific system and production method behind the product. Overall layout and choice of fixtures (T3), however, was within the realm of the architect. In the end Kullman took over the delivery of the bathpods through a licence with Offsite Solutions. The pods were delivered separately and sealed to the site and placed on the bridge chunks before they were hoisted into position.

Other integrated product deliveries

The south façade of the CH is a full-height curtain wall with a combination of photovoltaic panels and operable windows based on insulated glass units (IGUs). Although curtain walls are often delivered as discrete and fully finished unitised (T2) systems that with brackets and gaskets constitute an entire façade, this solutions was not chosen for the CH – partly due to transportation and hoisting issues.[17] Any kind of shifting in the aluminium frame could have caused the glass to break so alternatively it was decided to install IGUs and photovoltaic panels as part of the final fit-out delivery on-site (T0).[18] However, the frames including the sliding doors on the north façade were factory installed at Kullman (T1). Thus, as with the aluminium framing, the curtain wall delivery was split up into two separate T3 deliveries, here with different tier destinations (T1 and T0).

Although not fully functional installation-wise at the MoMA exhibition, the CH includes kitchen cabinets and appurtenant appliances that were all delivered (T2) and installed on-site (T0) by Valcucine. Kitchen deliveries are – probably even more than the bathroom pods – a well-established discrete off-site produced delivery with many different suppliers and levels of price/quality on the market. Interesting about this kind of delivery in the present context is that it often includes installation and in some cases even subsequent service thus representing an example of a high service level that are only seldom found in construction deliveries.[19] In the CH case Valcucine delivered and installed thus leaving most of the upstream deliveries opaque to the architect/client that apart from the choosing type and layout didn't have to care about the nested supply chain behind the delivery. This kind of delivery resembles the concept of work packages as used in the Arup Associates case below, where the system structure is split into discrete parallel deliveries spanning all system levels from T4 to T0 but, as opposed to traditional craft based construction, also includes a large amount of off-site work and processes.

Explanative power of the model

The first draft of the system structure model draws, as mentioned in the introduction, on the preliminary results from the primary case study, the Cellophane House™. The choice of this case has from the outset been KieranTimberlake's specific interest in and attempts to work with and clarify the supply chains of construction – particularly the parts of it related to off-site fabricated buildings and the balance between off-site and on-site processes. The CH case was chosen as the primary due to the office's scope of interest lying very close to the frame of the present research as well as due to the particularly explorative nature of the CH case within this field. Given this fact it can perhaps seem a little like arguing in a circle to discuss the explanative power of the model concerning this case that, in a way, gave birth to it. However, the first draft of the system structure model should be seen as an act of *abduction* (Peirce 1994) leading to the suggestion of a probable or satisfying hypothesis about what needs to be explained. The hypothesis is only a first model draft which should subsequently be tested and refined through 'successive approximation' (ibid.: 147). The present model is thus a result of several reiterations of the first version over theoretical scenarios to other secondary cases and is consequently claimed to be more general than at the outset. At the same time, the model as a hypothesis is never a direct reflection of the object studied and will always be subject to an interpretation of the observer of the case – here the researcher. The model is exterior to the case itself and a discussion of its explanative power is thus relevant even if it is just a first model draft.

Both for the CH as well as for the LH, the system structure models show considerable distribution of deliveries into the different tiers of the model combined with a relatively limited number of upstream deliveries on T4 and T3 level and only few T0-deliveries/processes.[20] This can be explained by the specific focus on off-site or prefabrication in both projects that moves deliveries towards or nest them into the more complex off-site T2 and T1 tiers (the middle tiers of the system structure model). The distribution brings both system structures close to the theoretical scenario of 'future industrialised architecture'.[21] However, the CH has a larger concentration on the T1 tier compared to a LH concentration mainly on the T2 tier. The fact that one of the specifically claimed aims of the CH was to maximise off-site fabrication – which is not necessarily the same as optimising the use of it – does bring it closer to the theoretical scenario of 'conventional prefabrication' than the LH. This aim was predominantly determined by the competition setup, the brief and the limited amount of time available on-site. The highest possible degree of prefabrication leads to T1-deliveries whereas the highest possible industrialisation perhaps rather points towards T2-deliveries or a combination of T1s and T2s – the latter both as direct deliveries on-site as well as nested into the T1s from the factory. Prefabrication and industrialisation are – although related – not the same thing and prefabrication processes are often very close to conventional construction even though they are made in a factory environment. As pointed out later in the analysis of the Scandi Byg case, large volumetric elements (T1) are not the most obvious object for automated production and need much more sophisticated robotics than when working on planar or smaller scale assemblies and components (T2 and T3). On the other hand, the focus in the CH project on mass customisation and the use of ready-mades from different fabricators as direct infill in the aluminium frame seem more industrialised than the rather conventionally assembled chip-board cartridges of the LH manufactured with use of a considerable amount of manual labour force in the factory.

In fact, the comparison of the two different strategies applied for respectively the LH and the CH is easily expressed through the use of the system structure models and the related concepts and seem to underline the explanative power of the model. The two cases are both of them good examples of a nuanced and deliberate approach to the challenges and possibilities in off-site fabrication each with their specific and project dependant context that shapes their different system structures. This can be read out of the coding of the model. The design for disassembly process that was accomplished for the CH points towards an equally relevant use of the model and the notion of system structure when it comes to taking a building apart for reassembly or for recycling by the end of its useful life. The CH was not intended to be brought down to the level it actually was at the end – it was thought as staying as chunks until the end of its useful life. Early considerations of how and to what extent to break a building up into elements of different complexity can be informed design wise both from the way it is put together as well as how it can be taken apart and the system structure can easily encompass both levels under one common scheme and terminology. The system structure potentially helps to illustrate and discuss pros and cons of different design scenarios for the same project.

Starting to look more closely into both KT cases and using the system structure as the lens, a lot of the nuances of how KT actually uses existing systems are clarified: by using existing systems and standardised solutions already from early design phases these can be used actively as generators for the architecture and the architectural concepts and the detailing of these two buildings. Just keeping the model as the post-fact analytical result it so far is helps to understand and explain this strategy as opposed to the very simplistic conception of prefabrication that often dominates the debate where buildings are classified as either (completely) off-site fabricated or as traditional on-site construction. The appropriate degree of prefabrication and different levels of industrialisation is and will always be project and context-dependent and it is never an either/or-choice between on-site and off-site processes. Furthermore, it is important for the result to bring in architectural considerations in the choice of balance between the two (theoretical) extremes – not just production time and economy.

Notes

1 See Bergdoll and Christensen (2008).

2 The next (third) generation of SmartWrap™ façades was introduced in the winning competition entry for the new US Embassy in London settled in April 2010. In Kieran and Timberlake (2008: 40f.) the BIM model is presented as another way of prototyping a unique or one-off building 'benefitting from its precursor'.

3 Kieran and Timberlake (2008).

4 Information in this paragraph partially retrieved from http://www.kierantimberlake.com/profile/profile_1.html (accessed 28 May 2011).

5 See also Kieran and Timberlake (2008: 43): 'Thinking is the hardest part of beginning, because conceiving architecture and building it are not parallel processes'.

6 See the following Scandi Byg analysis for a similar tier 1 off-site strategy.

7 *Refabricating Architecture* is a book published by KieranTimberlake describing how new production technologies are poised to transform the construction sector (Kieran and Timberlake 2004).

8 The Bosch Rexroth profiles come with standard grooves that are used for fixing and also can serve as track for e.g. sliding doors.

9 A steel frame system would often be welded and thus harder to take apart for reassembly.

10 The notion of 'family' used by the disassembly team (BC) corresponds closely to an organisation and delivery of an assembly 'by system' rather than 'by zone' as defined in 'Architectural systems terminology', Ch. 5.

11 Bathpods were taken apart.

12 '[I]t was designed to have a specific relationship between the parts – a specific configuration. It could have been designed to reconfigurable but that wasn't part of the process' (CM).

13 The 98% recovery is a measure from an embodied energy analysis performed. It does, however, give a good idea of the material proportion that was recovered.

14 *System connections* is one of the three interface types mentioned by KieranTimberlake in 'Refabricating Architecture'. The others are *connection joints* and *closure joints* (Kieran and Timberlake 2004).

15 For an explanation of the distinction between assembling 'by zone' and 'by system' see Ch. 5.

16 Kieran and Timberlake (2004).

17 For an example of the curtain wall as a true T2-delivery see e.g. the Arup Associates case later in this part.

18 Final fit-out is coded as an independent delivery of the CH system structure.

19 The service level is one of the three dimensions of integrated complexity as defined in the 'Integration Taxonomy', in Ch. 5.

20 The different case studies are not directly comparable due to their different levels of complexity and different focus or viewpoint (architect, contractor, manufacturer or 'total consultant'). While other cases like the day care facility by Scandi Byg or the office building by NCC have a relatively high number of upstream deliveries this is partly due to these two aspects.

21 The theoretical scenarios are explained in 'Model presentation', Ch. 9.

11 Scandi Byg

All-encompassing factory produced housing solutions

Introduction

The following analysis represents a study of a building manufacturer mainly delivering all-encompassing building solutions. Particular focus is put on the internal organisation of the production. The study includes a specifically built day care facility as well as a production line for a large series of dwellings. After a short introduction to the cases, the 'zoom' or viewpoint of the analysis, and the company, two system structures are established and discussed. In a final paragraph the explanative power of the model is discussed in relation to the chosen viewpoint.

From Scandi Byg, direct contributors to the study have been the CEO, Jesper Hoffman, sales director, Flemming Dalgaard, project architect at *Ellepilen* – the day care facility, Finn Christensen, and head of production development, Allan Pedersen Kjølner. A visit at the day care facility also involved an informal discussion with an employee on location.

Project type: Description of the cases

The project type in this study is buildings made of factory produced volumetric elements with a high degree of off-site completion supplemented with only limited preparatory and final works on the building site. The specific built project studied is *Ellepilen* – a day care facility designed by the Danish architectural office ONV-arkitekter and produced by Scandi Byg for the City of Copenhagen in 2010. The analysis and the discussion are further nuanced by the introduction of a newly initiated production of a large number of dwellings being realised as several individual building complexes within one common concept and organisational framework for social housing. The concept is called *Almenbolig*+ (social housing+) and provides within a fixed unit price social dwellings for local housing associations under the general housing association KAB – Københavns Almennyttige Boligselskab (Copenhagen Social Housing Association). Scandi Byg won the first contract for these projects comprising approximately 650 dwelling units distributed over local projects of varying size. Although at the moment of the study, the production of the first projects had just started, they are still interesting as a supplement

Figure 11.1 Street view of Ellepilen [Author's photo]

to the discussion of *Ellepilen* in the sense that, whereas the day care institution is a one-of-a-kind, this large number of dwellings represents only three different standardised solutions with a limited number of optional choices or modifications possible on the project level. Having these standardised bases give an excellent possibility to establish a truly industrialised production line with continuous repetition of a wide range of different processes. Scandi Byg uses this specific contract as a lever to build up general experience within areas that is just-in-time and automation principles that subsequently is anticipated to be applicable to one-of-a-kind projects like *Ellepilen*. Finally, the analysis also draws on couple of inputs from a laboratory project carried out by Scandi Byg for a major pharmaceutical company.

The company and the 'zoom' of the analysis

The concept and the specific project are in this case primarily seen from the perspective of a building manufacturer who, however, also acts in the role of main contractor. Scandi Byg A/S was established in 1978 and is today a subsidiary under the major Danish contracting company MT Højgaard A/S. The company is located in Northern Jutland in Løgstør and comprises two production facilities, own drawing office and administration. Scandi Byg develops, systemises and produces light prefabricated building structures for larger private and public clients. This means that detached single family housing – with few exceptions – lies outside the business area which typically encompasses mid-size and larger housing estates, office buildings and office extensions as well as schools and other public institutions. Branded as

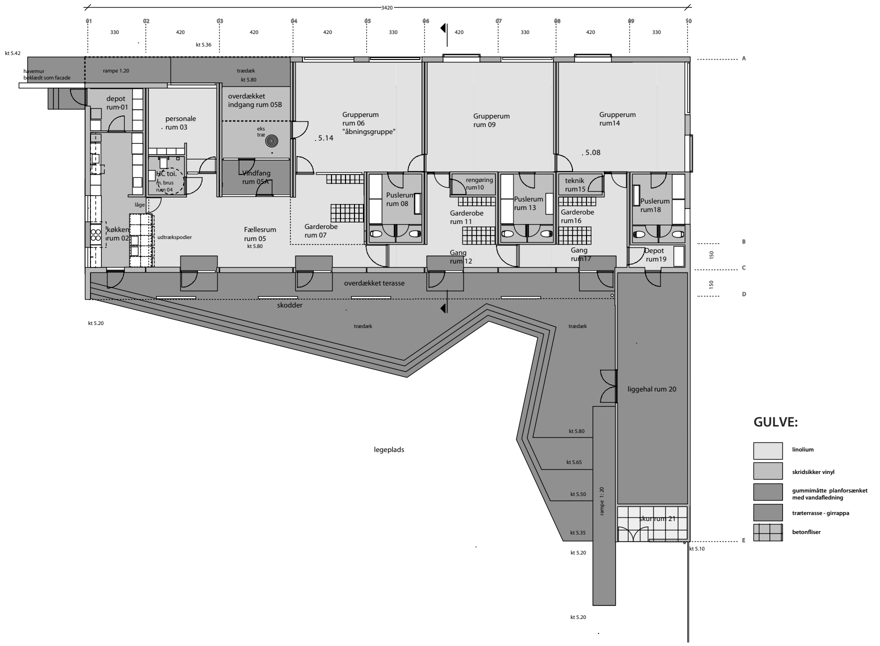


Figure 11.2 Plan of Ellepilen © Scandi Byg a/s and ONV Arkitekter

SB Modul (SB Module), Scandi Byg furthermore produces site huts, pavilions, and other temporary and portable cabins. All projects are produced and delivered as highly finished and fully outfitted volumetric (tier 1) chunks although the degree can vary slightly between projects.

Important to point out is that analysing *Ellepilen* from the viewpoint of the manufacturer does not necessarily yield the same system structural view as if it had been seen from the viewpoint of the architect, the client or a traditional contractor.[1] The chosen viewpoint has influence on how the system structure folds out due to the model's quality of *flexible structuration* that allows focus on different parts or different levels of complexity in the overall system constituting the final building.[2] The choice of viewpoint in this case has consciously been chosen with regard to the overall purpose with the analysis which is to test the explanative power of the developed model within different types of cases and seen from different viewpoints. However, the analysis is also – and can consequently be read as – an analysis of the particular case(s). An initial assumption within this case analysis is that the manufacturer viewpoint enhances focus on the more fundamental upstream deliveries on tier 4 (building materials and standard components) compared to what would be the focus of the architect in the same project – as least as long as the architect uses the standard structural solutions and joint details provided through the manufacturer's building system concerning e.g. slabs, walls and roofs. By relying on the *integrated complexity* inherent in these subsystems, the architect can direct focus towards other aspects as shape, dimensions and location of larger technical systems which are not included in the standard solution. The manufacturer undertakes detail design of the elements, the procurement of sub-deliveries, the production, the delivery and the installation on the building site as closed (tier 1) volumetric chunks. The *total integrated complexity value* of these volumetric elements is potentially very high thus facilitating a more free choice of design attention for the architect.[3]

System structure: Coding and special project specific features

As producer of volumetric chunks with a high degree of off-site completion corresponding to tier 1 in the system structure model, Scandi Byg assembles most deliveries (tier 4 to tier 2) in these integrated product deliveries before they are delivered for final assembly on the building site. As with most of their projects, the final on-site assembly of *Ellepilen* (on tier 0) was equally handled by Scandi Byg themselves except for minor preparatory and finishing works as well as the landscape treatment. The established system structure of the project (See Figure 11.3) comprises, compared to the two system structures from the KieranTimberlake case, a relatively large number of tier 3 and 4 deliveries. This can, as initially assumed (above), partly be explained by the manufacturer focus of the analysis. Equally, the system structure of *Ellepilen* shows a collection of the more integrated (downstream) tier 2 deliveries that subsequently are nested either (and most often) via tier 1 deliveries of volumetric chunks or (in a few instances) directly as deliveries on-site (on tier 0).[4] This structure can be interpreted as a strategy aiming at maximising the degree of off-site completion – read: integrating the highest possible number of deliveries and consequently also of complexity – before delivery at the building site (on tier 0). The advantages of such a strategy can be a minimised dependency on weather conditions and less risks of encapsulated humidity in the light construction elements and assemblies while the primary drawbacks are the difficult handling of the considerably big and heavy volumetric chunks that need to be shipped to the building site as expensive specially escorted transports. Another issue is that the volumetric chunks contain considerable amounts of 'air' or void space compared to flatpack assembly solutions on tier 2 level or to tier 3 to tier 4 deliveries supplied directly to the building site. However, the tier 1 delivery enables a much higher number of tier 3 to tier 4 deliveries to become nested before the building site (upstream) than if tier 2 planar assemblies are supplied directly. Both versions of off-site produced deliveries (volumetric chunks or planar assemblies as slabs and walls) are common in a Danish context but Scandi Byg has exclusively specialised in the delivery of the tier 1-volumetric chunk solution. The tier 2 slabs and walls do not leave the factory as discrete deliveries – even

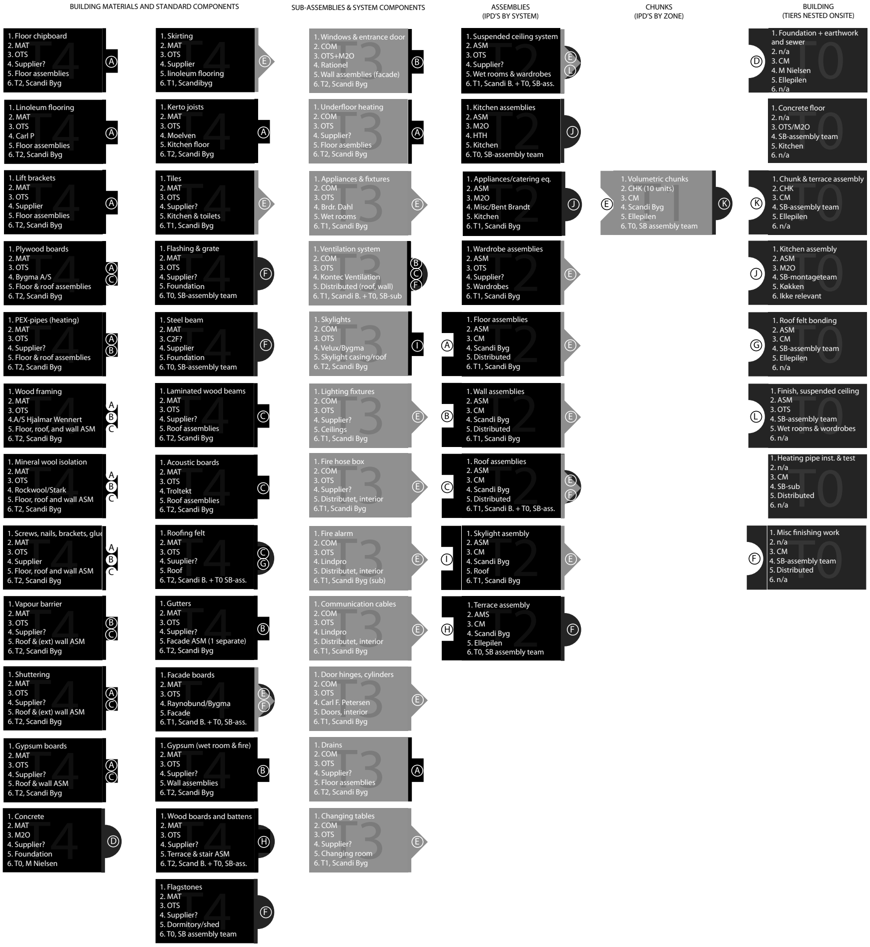


Figure 11.3 System structure, Ellepilen (coded with connectors instead of lines) [Author's drawing]

though they are mostly produced that way. The description of the system structure of the *Almenbolig+* production line (below) will elaborate further on this issue that seems to represent a clear division between different manufacturers on the market. Either they do volumetric chunks or they do planar assemblies – combinations are unusual.

The discussion of advantages and drawbacks of a relatively high degree of integrated complexity within off-site produced large tier 1 deliveries is accentuated by site and project specific conditions as climate and geographic and infrastructural location. There are many clear advantages for a relatively humid and rainy climate like southern Scandinavia that on the other hand would be rather insignificant in a drier climate where the infrastructural issue would consequently have higher relative weight. Both the distance between manufacturer and final destination and the local accessibility will *always* have decisive impact concerning how big and how integrated deliveries can be while still being cost efficient compared to less integrated solutions. Apart from the transportation issue there also exists a range of economical, organisational and legislative issues that can vary considerably according to the specific national and regional context. Whether a building is industrially manufactured is not only a question of prefabrication – and it is *never* an either/or question.

Change propagation in the system structure

Some issues during the course of the project realisation have resulted in changes of the system structure of *Ellepilen* compared to the initially planned pattern. However, it is important here to point out that neither for the manufacturer (Scandi Byg) nor for the architect (ONV) have these changes in the present case been interpreted as changes in any system structure. They are simply changes to the project. Visualising these changes by use of their system structure is so far exclusively an exercise performed within the present research. The assumption is that, when viewed through the optics of a system structure, such changes can be put into words in a different way that works on another abstraction level (like the tiers) and potentially sheds light on and makes comparable similar *system structural* changes that are constituted by completely different deliveries if they are considered on a detailed level.[5]

Reduction of integrated complexity – enhanced complexity in focus

For the design of *Ellepilen*, the architect chose to equip the kitchen and the adjacent storage room with a continuous casted floor. As kitchen and storage room are located within the same volumetric chunk this, in the first case, did not cause any obstacle. Off-site produced casted floors are not standard but are sometimes used in, for example, bathrooms. The casted floor resulted in a change of the standard construction of the floor plate due to the demand for level free access from adjacent linoleum flooring. Standard joists were replaced with lower and more expensive laminated joists (Kerto joists) that have better load capacity in order to make space for the casting. However, even though placed entirely within the same volumetric chunk, the size of the continuous floor was estimated too big and consequently too fragile for transportation from the factory to building site. The risk of cracks would be considerable and a possibly cracked floor would be past recovery once brought to site. The solution was that the laminated tier 4 joists were factory installed into the tier 2 floor slab assembly which was subsequently nested into the tier 1 volumetric chunk equally factory assembled. The casting, however, had to be postponed as an extra tier 0 delivery on-site after the tier 0 chunk installation. Casted floors of the size designed by the architect were not a known and well-tested standard solution. This again forced other changes to be made from the standard solution (change propagation): the kitchen installation located upon the casted floor had to be postponed to the construction site instead of, as the standard, being nested already at the tier 1 chunk level. The individual kitchen units are often procured as kit-of-parts from the kitchen supplier rather than as the finished assemblies (which is normally how an end-user would have them delivered). The factory environment and the trained staff make it more cost efficient to assemble them in-house. In the case of *Ellepilen* this was no longer the case and the slightly more expensive solution of preassembled tier 2 kitchen elements were installed on-site. Figure 11.4 displays as a focused partial system structure the changes from the originally planned standardised and highly integrated tier 1 delivery of a chunk to a more complex mix of several deliveries on-site (tier 0). However, by having chosen another kitchen floor solution or perhaps by having split the continuous casting into smaller modules, more deliveries could have been maintained as deliveries nested further upstream. Price-wise this would probably have been a cheaper solution while better combining Scandi Byg's standardised supply chain and integration process (nesting) with the design specification of the architect. The idea and its realisation would have been better tuned! Whether the quality of the present solution is better than the sketched alternative is an issue open for discussion. One of the explicit arguments, forwarded by manufacturers such as Scandi Byg, for maximising the number of nested deliveries in the tier 1 volumetric chunks is that the controlled factory environment, the integrated building process, and early nesting in general gives a better base for achieving high *technical* quality and for keeping up with the time schedule. This does, however, not in itself lead to architectural quality in a broader definition.

The day care facility includes the installation of a distributed tier 3 ventilation system that is already from the factory nested into the tier 2 roof and wall assemblies. The system is served by a ventilation device that is located in a technical room behind one of the wardrobes. The considerable size of the ventilation device makes it impossible to install after the installation of the partition walls enclosing the device. Consequently it has to be installed

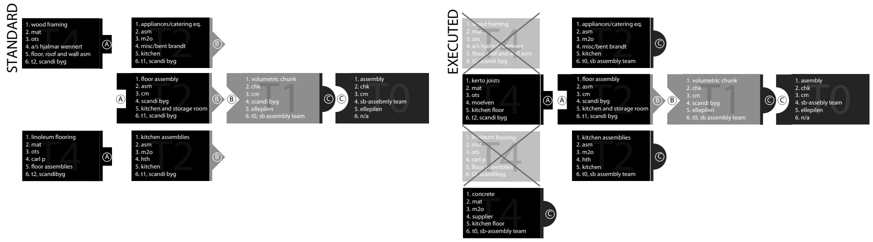


Figure 11.4 Subsystem structure of kitchen solution – standard and as executed [Author's drawing]

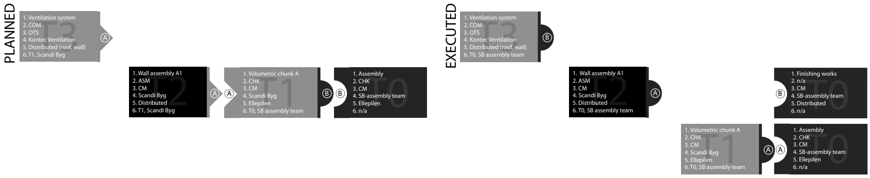


Figure 11.5 Subsystem structure of ventilation device – planned and as executed [Author's drawing]

prior to access door and partition wall. In the factory environment this did not pose any particular problem but when the delivery of the device was delayed it could no longer be nested into the tier 1 volumetric chunk at the factory. Installation had, as above, to be postponed to on-site installation. As the aggregate had to go in before the partition wall, this tier 2 wall assembly equally had to be postponed and delivered to the construction site instead of the standard prior nesting at the factory as part of the tier 1 chunk delivery (see Figure 11.5). Further three discrete wall assemblies and a small roof assembly for the shed behind the dormitory chunk (all tier 2 deliveries) were delivered directly for on-site tier 0 installation. The shed has flagstone flooring directly laid on the ground making inadequate the chunk solution.[6] For the ventilation aggregate it is a postponed delivery that impedes nesting the tier 2 wall assembly into the tier 1 chunk at the factory whereas for the shed assembly process it is the result of a decision made at the outset of delivering discrete wall and roof elements as being most appropriate. A chunk solution would probably have required temporary bracing during transportation. This was actually used for the 'table-top' chunks of the *Cellophane House*™ described in the KieranTimberlake case above.

Limited integration

The degree of prefabrication can in some cases be too high and inappropriate. Scandi Byg installs as a standard the suspended ceilings in offices and institutions as nested into the tier 1 chunks already in the factory. In the case of connection joints for distributed installation systems (e.g. ductwork) across chunks at on-site (tier 0) installation, the ceilings can be taken down as single sheets in order to get access. This, however, represents – although in a limited amount – triple work (sheets up, down and up again). Alternatively, the installation of the affected sheets can be postponed and these placed within the sealed tier 1 chunk as it leaves the factory. In a recently finished laboratory project by Scandi Byg, the intensive on-site (tier 0) installation work on the hidden ductwork above the suspended ceilings required a large amount of these to be taken down again after factory installation. Here the triple work became problematic. Apart from more work, both subsequent

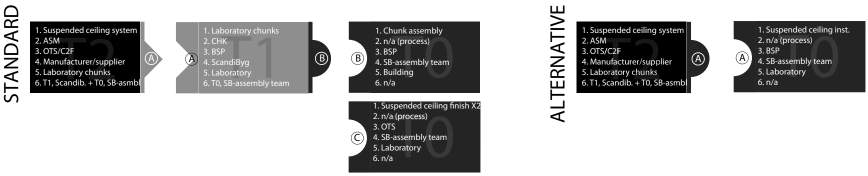


Figure 11.6 Moving tier 2-ceiling delivery from tier 1 to tier 0 thus avoiding triple work [Author's drawing]

on-site processes are furthermore subject to more uncertainty due to the less controlled 'production environment' compared to the factory setting. Seen from a system structural point of view, the problem was that the suspended ceilings at the outset should have been nested on the building site (tier 0) rather than into the volumetric chunks (tier 1) (see Figure 11.6). In the same project, Scandi Byg had procured preassembled tier 2 installation shafts as a made-to-order delivery (M2O) to be nested into the tier 1 chunk deliveries. However, as with the ventilation device above, delayed delivery from the supplier demanded postponement which caused a displacement in the system structure: The tier 2 shaft had to be installed on-site. Due to the limited information available for this outsourced delivery, access hatches in the tier 1 chunks could not be factory installed either. The uncertainty about the exact location of these displaced this sub-delivery posterior to the shaft installation on-site. As shafts came as full-storey assemblies, the on-site installation of the shaft further had to be coordinated directly with the tier 0-chunk assembly. The result was a postponed hand-over due to considerably increased on-site work.

Integrated product deliveries: Examples and innovation

Ellepilen seen as a system structure displays a number of integrated product deliveries (tier 1 and 2). Some are more well established and standardised (commoditised), some are specific for the project type, some are manufacturer specific (Scandi Byg's in-house proprietary solutions), and a couple of them can be seen as innovations that have a more general applicability if considered as types that potentially could create new market standards.[7]

Tier 2 deliveries

The suspended ceilings, the standard kitchen assemblies and the catering facilities (professional kitchen) belong to the first category of well-established and more standardised deliveries (made-to-order – M2O and off-the-shelf – OTS products), while the wardrobe-delivery is specific for day care facilities.

Floor assemblies, wall assemblies and roof assemblies are all manufacturer specific internal assemblies in the sense that they are developed by Scandi Byg and are exclusively used within Scandi Byg's own specific system. According to the present coding of the system structure these tier 2 deliveries are supplied to Scandi Byg by themselves (Figure 11.4). One could argue that these internal subsystems analytically should be coded as (external) tier 3 and 4 deliveries of materials and components directly nested into the volumetric tier 1 chunks as sketched in the theoretical scenario of *traditional prefabrication*.[8] However, the inclusion of the intermediate levels shows something about the production process at the factory which is particularly relevant from the viewpoint of the manufacturer as in the present case. An imagined scenario could also be that Scandi Byg either supplied these tier 2 deliveries (planar assemblies as floors, walls, and roofs) to other external receivers i.e. manufacturers or contractors or themselves procured these assemblies externally (outsourcing). Such a strategy could provide for a more stable production volume if the planned automation of Scandi Byg's production line is successful. The fact that Scandi Byg actually *does* start with the production of discrete planar assemblies and subsequently assembles these into volumetric chunks points towards the theoretical scenario of *future industrialised architecture* where a considerable part of the system structure is integrated as tier 1 and tier 2 deliveries before final nesting as tier 0 assembly on the building site. Assemblies like floorslabs, roofs, and walls could potentially create market standards as mass customised integrated product deliveries (made-to-order – M2O). Concrete hollow core slabs are an example of such a market standard widely used in a Danish context. Completely standardised off-the-shelf – OTS or cut-to-fit – C2F-products of this type are probably less realistic. A C2F-delivery of this kind would also, due to its considerable size, constitute a waste and resource issue that would need to be handled.

The tier 2 terrace assemblies used on the south façade where the building opens up towards the playground area are bespoke (BSP), but could in principle also be a mass-customised integrated product delivery (made-to-order – M2O) where wood species, board profiles and specific measures could vary but be based on a fixed structural principle and a standardised production process. Such a production scenario is even more obvious for use in the deployed integrated skylight solution that apart from tier 4 materials also nests a tier 3 skylight. In the analysed project, however, Scandi Byg again becomes its own supplier although the assemblies are produced separately as discrete assemblies. In line with several already established prefabricated attic products (tier 2 assemblies), the skylight assembly has the nature of a clearly delimited subsystem that functionally as well as physically makes it highly marketable as a discrete integrated product delivery. The many technical performance demands concerning, for example, waterproofing, insulation value and light transmission could form the basis for the integration of a considerable amount of non-project specific knowledge into a common product structure.[9] The general applicability of an integrated skylight solution enhances the probability of hitting a sufficiently big market to make the product profitable through the combined strategy of economies of scale and economies of scope (mass production vs. responsiveness).

Tier 1 deliveries

When it comes to on-site deliveries, *Ellepilen* is as mentioned mainly based on tier 1 volumetric chunks. These chunks have in the present case the feature that the slightly sloping roof is delivered as nested into the tier 1 chunk from the factory. Often roofs are built from less integrated tier 3 and 4 deliveries on-site as trusses and roof battens or, if prefabricated, delivered as discrete tier 2 subsystems directly to the building site. While the roof splits up according to the chunks it constitutes two continuous surfaces with a pitch towards a mid-diagonal leading away the rainwater towards the southeast corner of the building. Despite the different roof heights for every chunk, this solution has been chosen in order to minimise site work. The roof surface receives a first layer of roofing felt as nested onto the tier 1 chunks from the factory followed by felt strips burned onto the roof between the chunks and finally a finishing layer. The two latter are delivered as tier 4-deliveries installed on-site (on tier 0). Being a one-of-kind project of a limited size, *Ellepilen* does not use integrated tier 1 toilet and bathpod chunks. In the present case these have been built up by pieces (tier 3 and 4 deliveries) directly in the chunks. The small batch size combined with project specific circumstances concerning lead time and vacant staff in the factory has probably determined this choice where Scandi Byg in other cases – as, for example, in the *Almenbolig+* production – use finished tier 1 bathpods procured from an external manufacturer. Such deliveries can either be supplied on-site or be nested into the tier 1 chunks.

Industrialised and automated production line: The Almenbolig+ case[10]

With point of departure in a large contract comprising approximately 650 dwellings constituting a first phase of the social dwelling concept *Almenbolig+*, Scandi Byg is presently working on enhanced industrialisation and automation of their production line. The idea is that the specific production planning for the delivery of this contract subsequently should be transferred and adapted to Scandi Byg's general production line that is mainly producing one-of-a-kind or few-of-a-kind projects. A particular focus is to what extent such a production line can be automated. As it is today, the production is mostly manual although assisted by craning and power tools while pulling the product through a production line rather than – as on-site – building in a fixed location. The considerable batch size of, in this case, almost identical dwellings forms a good basis for developing and optimising the general production line as well as for implementing robotics for automation. The goal is that almost any of Scandi Byg's projects can be built on such an automated

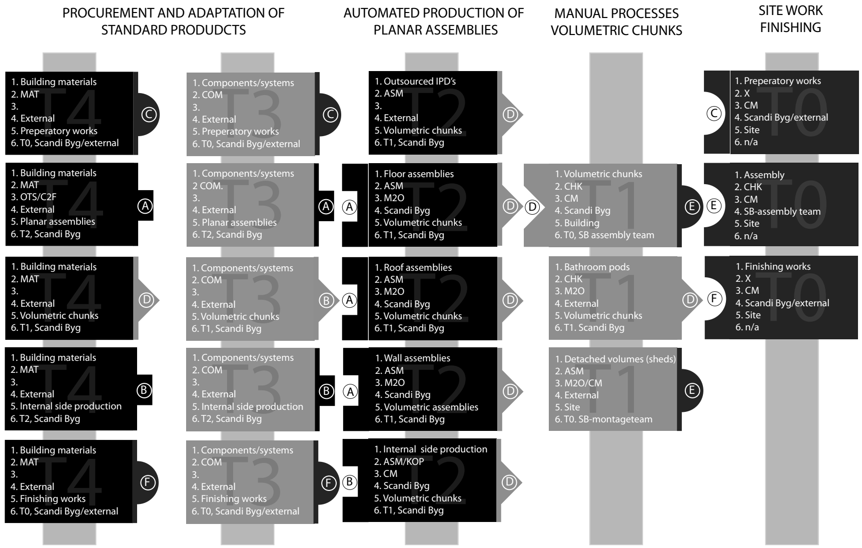


Figure 11.7 System structure of Scandi Byg's future general production line [Author's drawing]

or semi-automated production line – *Ellepilen* could be such a project in the future. Based on the *Almenbolig+* production line, Figure 11.7 displays an attempt to code such a general production line as a system structure within the model.

The production is – by Scandi Byg themselves – split into three general parts that each of them has a certain number of work stations. Apart from the production line in the factory, the on-site assembly as well as supplementary initial and final works are also included. The total number of work stations in the factory is ultimately defined by the size of the facility. The three parts are:

1 procurement and adaptation of standard materials and components
2 production of planar assemblies (floor slabs, wall and roof elements)
3 production of volumetric chunks.

In the *first part* (1) tier 4 and 3 materials and components are procured as standard off-the-shelf – OTS products, i.e. sheets, timber, insulation, fittings, etc. Adaptation is handled manually with use simple machinery. A semi-automated scenario is also considered in order to regulate the flow rate. By keeping processes in-house the point of product variance (here the specific measures of sheets and timber) are brought closer to the final customer resulting in a more flexible production line.[11] Alternatively, sheets and timber can be ordered directly cut-to-fit – C2F – from the supplier which reduces processing in the factory but also increases procurement costs by leaving a larger part of the value creation (or supply chain) outside the factory. Another drawback of the outsourcing scenario can be enhanced inventory needs.[12] In general, suppliers in the building industry are not geared towards supplying small customised batch sizes. The most important, however, is a steady flow through all the general parts and each of the work stations. Less important is the achievement of the fastest possible production within each of the work stations seen isolated. This will only lead to relatively useless sub-optimisation and can even distort the overall flow.[13]

In the *second part*, the production of planar assemblies, the production line is split into three parallel sub-lines for respectively producing tier 2 floor, wall, and roof assemblies. In this part, the vision is that all processes are pure assembly. All adaptation or processing of the components should be located before (upstream), beside (parallel) or after (downstream) these parallel sub-lines that are the primary objective for automation through the integration of robotics. On the three planar assembly lines both surface finish (i.e. painting) as well as the nesting of different technical systems (i.e. electrical cabling, heating and ventilation ductwork) is sought maximised – again however with the main focus on the steady flow of the entire line.

In the *third part*, the production of volumetric chunks, the three sub-lines from the second part are joined into one single main line leading to the final tier 1 delivery leaving the factory. In this part the planar assemblies are joined into volumes, that are finished and fitted out through the integration or nesting of various supplementary deliveries on different tier-levels (1–4). These are bathroom chunks, kitchen assemblies, windows and doors, stairs, fixtures, etc. In some case, these supplementary tier 1 and tier 2 deliveries are produced partly in-house by Scandi Byg on a kind of side lines thus creating a ‘fishbone’ production structure. Within the *Almenbolig+* production, the bathrooms are outsourced and arrive as finished volumetric chunks while the kitchen assemblies are delivered to the factory as a tier 3 kits-of-parts, and joined as a finished tier 2 assembly on one of these side lines before they are inserted into the volumetric tier 1 chunks. The same is the case for the waste pipes, the circuit breaker panels and others, if they are not outsourced – partly or completely. The flow and the price determine the ideal solution. The tier 2 installation shaft used in the laboratory project as referenced above is an example of this. On the last work station of the line, the finished tier 1 delivery is wrapped in plastic for transportation and subsequent tier 0 assembly on the building site.

The lead time for the present *Almenbolig+* production line is 6 to 7 days from stock to finished and wrapped volumetric chunk. A primary bottleneck of the present production line is the initial joining of the planar assemblies into a volumetric chunk on the last main line. Through enhanced automation of the second part, the planar assembly lines, this problem will be further accentuated. However, it is difficult to speed up this particular process if not two parallel work stations are established – or even two parallel lines for the entire third and final part. This is not possible within the present production facility. Other processes like drying time for fillers and paint are also potential bottlenecks but can often be distributed over several work stations thus tuning the general flow. Alternatively, processes from the chunk line can be moved to parallel lines on the second part or to side (fishbone) lines but the issue of space in the facility limits the flexibility to make such changes. The main philosophy is to move as much as possible down to parallel processes (second part parallel sub-lines or third part side lines). Installation of windows and doors is presently done from work stations on the last main line (third part). If these are moved upstream for installation on the wall assembly line (second part) it will put higher demands on the tolerances of the wall assemblies in order not to have windows and doors sticking to the frame. With the presently available technology in the facility this has so far been turned down, but things can change. Another alternative concerning bottlenecks at some points and overcapacity at other points can be to exploit the overcapacity for other purposes. This could be to produce planar assemblies or other parts for Scandi Byg's second production facility, that is located only a few kilometres away. However, even this small distance is not optimal with regard to internal road transportation of the relatively big planar assemblies (floors, walls and roofs). They could also be sold externally as discrete tier 2 assemblies. Scandi Byg does normally not provide this kind of product for direct sale, but it could be a scenario to consider in order to maintain a steady flow while maximising the use of the production facilities.

Explanative power of the model

The system structure model is created drawing on initial inspiration from the very industrially conceived – and perhaps not quite as industrially produced – Cellophane House™ by KieranTimberlake.[14] In this project, the discussion of prefabrication vs. on-site construction is an explicit an integrated part of both concept and process. This suggests that the explanative power of the model is good in relation to Scandi Byg and their specific focus on off-site manufacturing (being a building manufacturer). Compared to the theoretical scenarios advanced in the beginning of this Part III – 'Model' – Scandi Byg can be located somewhere between *traditional prefabrication* and *future industrialised architecture*.[15] The internal production line and its logic is clearly expressed through the model and its system of deliveries on different tiers defined by their integrated complexity. However, the model also shows that there still is – and probably always will be – a considerable number of project and context specific circumstances, that require deliveries that break with the linear logic of a traditional industrialised production line as known from mass production in parts of the product industry. The need for flexibility and product variance late in the process (delayed differentiation), even within a heavily standardised housing concept as *Almenbolig+*, works against the completely standardised production line and process that is normally the object for an automated production.

A weakness in the model can in the present case be that the clarity and visual perceivability on the less integrated tiers (3 and 4) is partly lost due to the relatively high number of different deliveries on these tiers. The high number of deliveries can, as mentioned, partly be explained with the manufacturer viewpoint chosen for the analysis. An architectural viewpoint would probably have less upstream deliveries in the model coding. Again, it becomes a question of the level of detail – or the 'zoom' of the analysis chosen for the analysis. A way to enhance the clarity and reduce the number of deliveries expressed in the model could be to concentrate on the deviations from the standard solutions provided by the manufacturer. This would better match the viewpoint or perspective of the architect, where e.g. standards floor or wall assemblies just would figure as tier 2 integrated product deliveries (assemblies) with no nested upstream tier 3 and 4 deliveries. They would be implicit in the delivery as integrated complexity with no particular need for attention from the architect.

One of the advantages of working with maximised off-site integration is that by nesting deliveries as early as possible in the building process (into tier 1 and 2 deliveries) there is more time available to accommodate possible delays or errors occurring throughout the process. This can have huge advantages if the deliveries are highly project specific, that is, made-to-order – M2O towards bespoke – BSP solutions where the finished result is perhaps not fully known up until the moment of delivery. The alternative, to procure e.g. tier 2 deliveries directly for integration on the building site probably works better, if these deliveries are well established and more standardised i.e. made-to-order – M2O towards off-the-shelf – OTS solutions. The model seems to display such issues in a way that facilitates discussion.

Notes

1 Scandi Byg contractually mainly acts as turnkey contractor in building projects. A limited number of fixed and ad hoc subcontractors deliver solutions in the factory as well as preparatory and accomplishing works on-site.

2 For a definition of flexible structuration see 'General systems thinking', Ch. 4.

3 *Integrated complexity* and *total integrated complexity value* are expressions of the degree of integration of a delivery and gives an indication of how much design work that potentially can be 'saved' by using this (product) solution. See Integration Taxonomy in 'Architectural systems terminology', Ch. 5.

4 The tier 3 and tier 4 deliveries will always be present as nested at some point of the entire supply chain. A tier 5 of raw materials is equally inherently present. The modelled system structure, however, seeks to display the particular viewpoint in focus chosen for the coding – in this case the manufacturer perspective at Scandi Byg.

5 This quality of the system structure is linked to general systems theory and is elsewhere referred to as *isomorphism* (similar forms or structures). See 'General systems theory', Ch. 4.

6 Scandi Byg does not normally deliver planar tier 2 assemblies for on-site installation. In this case, the assemblies are simple non-insulated constructions that are not to the same extent sensitive to temporary weather exposure during installation.

7 These innovative deliveries are particularly interesting in the context of the present research as representing new possible paths for enhanced complexity integration in architectural design.

8 For an introduction to the theoretical scenarios elaborated using the system structure model, see 'Model presentation', Ch. 9.

9 Product structure or product architecture can be seen as a product internal system structure.

10 Based on the interview with Head of Production Planning, Allan Pedersen Kjølner, Scandi Byg.

11 Cf. responsiveness, economies of scope and delayed differentiation, see 'Industrial production theory', Ch. 3.

12 Standard materials and component are easier to store and handle and take up less space.

13 This way of looking at the system as a whole of interconnected parts and processes is a distinct property of systems approaches. In this case what is at stake can be classified as systems engineering – a hard fact systems approach. See 'Industrial production theory', Ch. 3.

14 See KieranTimeberlake case, Ch. 10.

15 See 'Model Presentation', Ch. 9.

12 NCC

An office building concept

Introduction

This analysis is founded on material retrieved during a study at NCC Construction Danmark. The study draws on a general concept for office buildings as well as a specific built office building related to this concept although this is rather as being the outset for, than as a result of the concept. After an introduction to the company and the focus of the analysis follows a description of the cases – the concept and the particular project – before moving to the establishment and discussion of the system structure which here represents a special version reflecting the conceptual nature of the cases and NCCs particular focus on process. The model coding in this case somehow challenges the definition of the system entities (the *deliveries* as the constituent elements) and the way they are related to each other. In a final paragraph the explanative power of the model as applied to this particular case is discussed.

From NCC, direct contributors to the study have been Chief Advisor of IT and Business Development/Industrial PhD student Anders Kudsk (AK), Head of Concept Planning Lars Henrik Hansen (LH), and Head of Project and Process Planning Claus Schmidt (CS). Direct references to meetings and interview in the text will be followed by the initials of the person cited in brackets.

The company and the 'zoom' of the analysis

The concept and the specific project are in this case primarily seen from the perspective of a (turnkey) contractor. NCC Construction Danmark is one of the major Danish contractors and was established in the late 1990s as a subsidiary of the big Swedish contractor and developer NCC AB. NCC also does roads and other infrastructural projects. Although mainly concerned with the execution and construction of designs initiated by other parties, in the present case NCC acts as both contractor, consultant and developer (the latter role undertaken by NCC Property Development), and has thus been in charge of all design phases in both concept and project. The integration of the different roles has made it possible to integrate design concepts and solutions more directly with the way they are subsequently executed on the building site (bridging concept and construction) which also means that the concept from the outset has been based on a highly pragmatic approach making use of existing knowledge and well-known technology and construction solutions. The visionary aspects of the concept thus rather lies on the contracting side than on the architectural side as well as in the idea of developing an (all-encompassing) building concept that is meant to be sold as a product thus exceeding the project level that mostly characterises the construction sector.

Project type: Description of the case(s)

The project type is a building concept for office buildings that, based on a collection of well-known and tested solutions, claims to offer customers high quality at a competitive price. The concept, called *Danske Kontorhuse* (Danish Office Buildings), is meant as the first in a series and is, according to NCC themselves, probably too narrow seen in the light of the present state of the market where it is only estimated to hit around 5 per cent of the Danish office market (LH).

By engaging in the concept a lot of basic features both process and product wise are already defined while others – with core value for the clients in focus – are left open as specific configurations of the concept in each project. A specific office building project was used at the outset for the development of the concept. This project was developed for NCC's own developer division – NCC Property Development – that focuses on property development within office, retail and logistics. The project – *Vallensbæk Company House* – is a four-storey development in two phases located in the outskirts of Copenhagen. Phases were finished in respectively 2009 and 2010 as office

Figure 12.1 Vallensbæk Company House [Author's photo]

decks for later tenant-specific fit-out combined with fully outfitted common facilities as lobby and reception area, canteen, circulation and service areas. This equals to some extent, as we will see, the Arup case following this chapter although addressing another segment of clients (see Figure 12.1 and 12.2).

The general concept, *Danske Kontorhuse*, is defined as a three-to-six storey *company house*[1] in the shape of a single wing building with a fixed depth of 18 metres gross and a variable length between 66 and 110 metres gross according to specific client needs. Among other standardised features are fixed storey and clearance height as well as standard cores including staircases, lift, installation shafts, handicap toilet, kitchenette, cleaning repository and general storage. Equally, remaining toilets cores are standardised but variable in number while the basement as standard includes mechanical room, and changing rooms. Other common facilities as canteen and fitness room are optional. Different façade claddings can be added to the standard building envelope thus forming what is termed different *models*. All models meet the European Green Building Programme requiring an extra 25 per cent reduction in energy consumption compared to current national standards.[2] The developed concept was meant to be sold directly to external clients both as domiciles (client = occupant) as well as tenanted properties (client = owner/landlord). The concept material can be handed out to external consultants, i.e. architects, as the base for the development of specific projects within the concept. Both the specific project analysed and the general concept are primarily

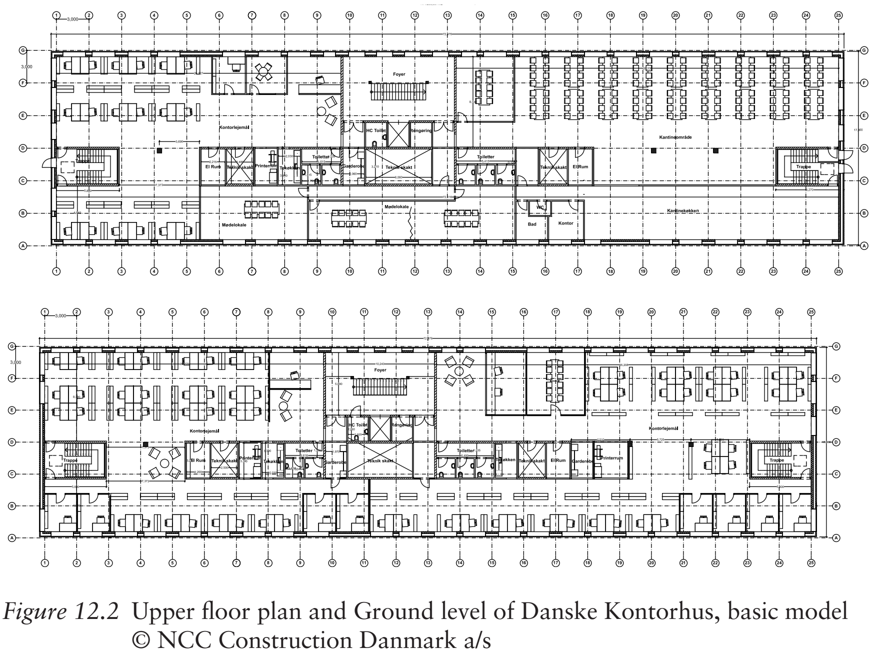


Figure 12.2 Upper floor plan and Ground level of Danske Kontorhus, basic model © NCC Construction Danmark a/s

based on conventional construction methods with no particular focus on prefabrication or integrated product deliveries. However, conventional construction in Denmark – if not *all* construction – usually encompasses some degree of prefabrication i.e. concrete slabs and panels, window sections or even bath or toilet pods. The specific solutions will be treated more in detail below.

System structure: Coding and special project-specific features

As a (turnkey) contractor, NCC is naturally focused on the execution and construction phases or stages of a building project. Project design and design development are, if in-house, mostly limited to the technical engineering disciplines as mechanical systems and plumbing and are based on proposed layouts from external architects and structural engineers. NCC generally bid on turnkey contracts which are subsequently internally split up on a number of (domestic) subcontractors that mainly deliver on-site tier 0 solutions. This means that the detail design is often fairly well-defined and fixed when NCC takes over whereas the way this design is split up into subcontracts and then built is defined by NCC as a weighing of factors like time, price, availability and quality. This post fact translation is tedious and time consuming and leads, apart from cost-cutting measures, to uncertainty in what is with a production term called ‘lead time’ – the time it takes to produce an object. In the studied case(s), a main idea for NCC is to take command over *all* phases which are then directly accommodated to and restricted by a more streamlined construction phase. The ‘modularisation’ of the construction process into its constituent elements is at the outset based on the company’s conventional procedures and thus mainly follows the traditional craft based divisions (the subcontractors) although in a contemporary more specialised version with a relatively large number of subcontracts. However, NCC has also worked with the question of product development in a more ‘physical’ sense, for example, through the development and marketing of an integrated installation shaft for multi-storey housing projects. Such ideas could be integrated as a further *physical* commoditisation of the concept.

Subcontracts as parallel deliveries

Following the above mentioned subcontracting division, the system structure of both *Danske Kontorhuse* (DKH) and the specific *Vallensbæk Company House* (VCH) project can then be modelled according to the different trades or crafts involved in each project. Seen from the perspective of the main or turnkey contractor, NCC, the project is physically delivered by these different subcontractors according to the descriptions elaborated by NCC themselves. How these individual subcontracts are actually produced and delivered as specific mixes of more or less prepared, standardised, and serviced sub-deliveries has in principle little importance to NCC as long as they meet the requirements of the description and as long as the price and suggested delivery time is satisfactory.[3] This means that the primary system entity of the system structure at first becomes the subcontracts as a number of *parallel* deliveries that theoretically, each of them, encompasses sub-deliveries on various tier levels (T4–T1). These sub-deliveries, however, remain mostly opaque to the main contractor. Each subcontractor delivers and in most cases also installs a final part of the building on-site corresponding to a delivery on tier 0 with a relatively high level (INS) of the service dimension. A subcontract as painting (MAL) combines simple tier 4 deliveries with tier 0 processes into the final building integrated paint on the walls whereas the Concrete Assembly delivery (ELM) combines tier 4 materials (i.e. concrete, mortar, and reinforcement), tier 3 components (columns, couplers and other embedded parts), and tier 2 assemblies (insulated concrete panels and reinforced concrete slabs) into the tier 0 assembly (on-site) of the structural building system. If, however, we go further down in detail, these parallel deliveries (the subcontracts) can each of them be divided into a combination of sub-deliveries on different tiers. Some of these can be nested into each other. See Figure 12.3.

Differences in the subcontracts between concept (DKH) and project (VCH) are few. Where the DKH includes 20 contracts, the specific VCH project encompasses 19: in VCH, carpentry (TØM), joinery (SNE), window sealing (FUG) and some of the building envelope (FAC) has been joined into one single contract while plumbing (VVS) on the other hand is split into two:

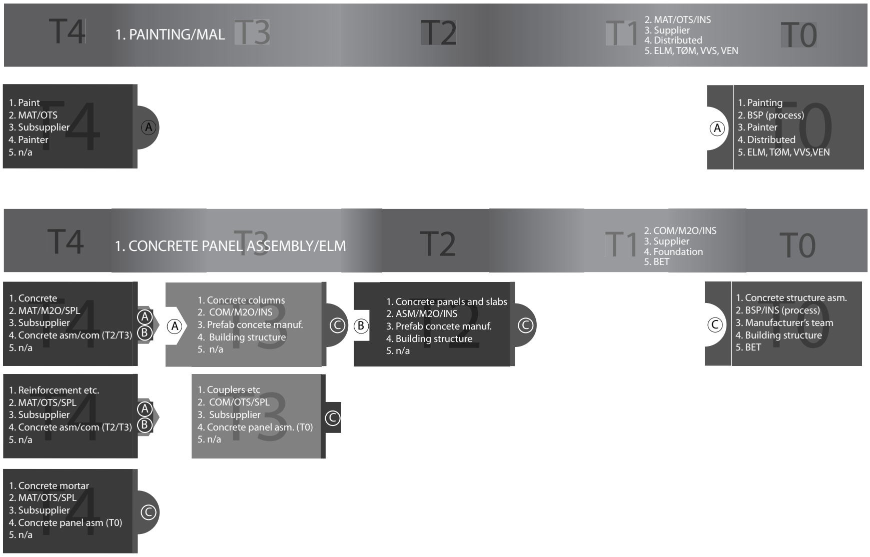


Figure 12.3 Parallel opaque deliveries – a question of viewpoint. Further detailing reveals serially nested subsystems [Author's drawing]

plumbing and air condition. Other minor subcontracts such as fire insulation (BRA) and NCC's own miscellaneous work (NCC) has been omitted in the specific VHC-project (see Figures IV.4.4 and IV.4.5). Miscellaneous work could be to install (INS) a delivery supplied (SPL) by a subcontractor.

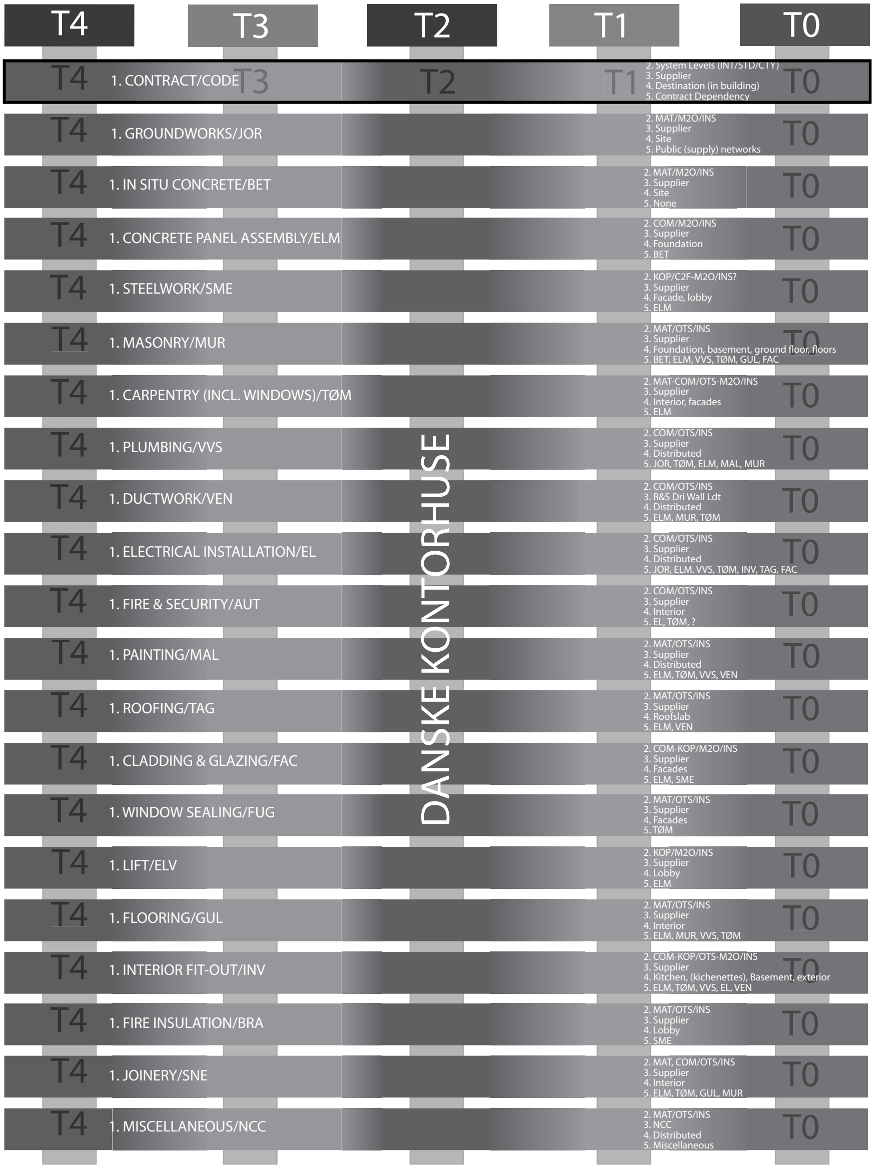


Figure 12.4 The system structure for Danske Kontorhuse expressed as parallel subcontracts [Author's drawing]

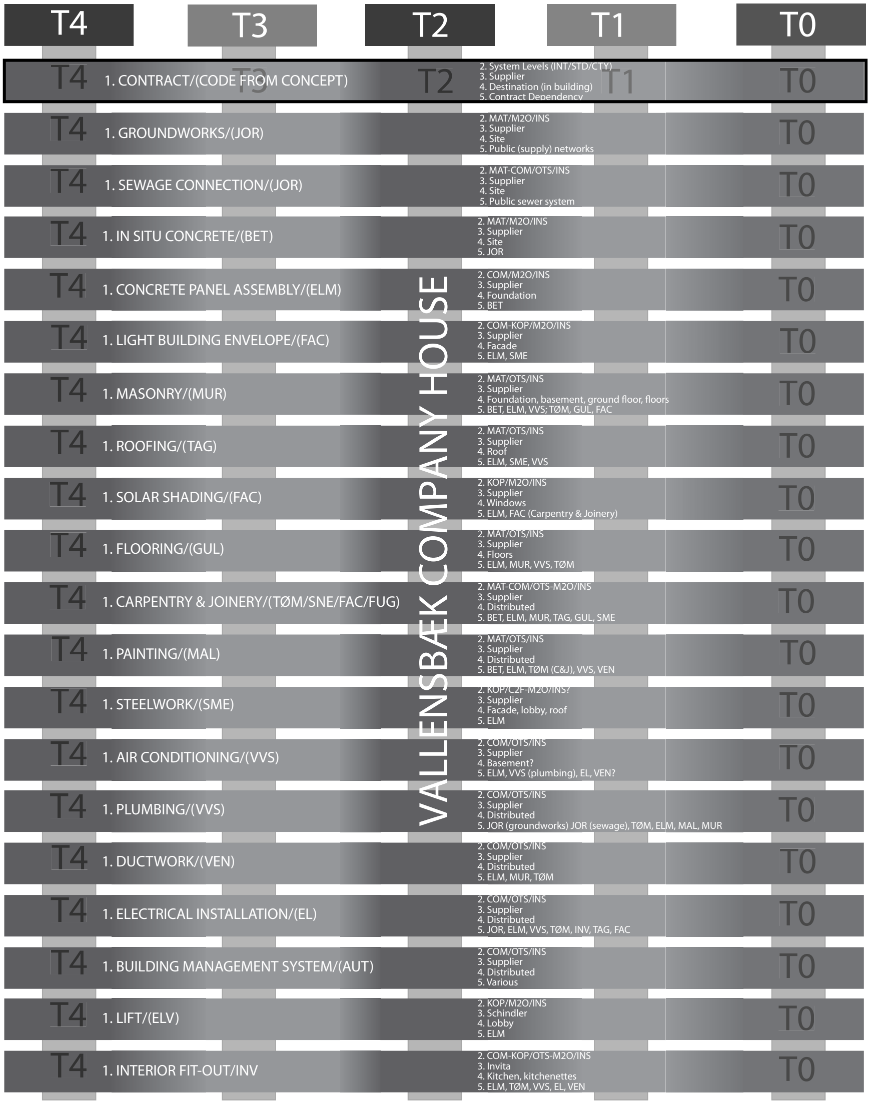


Figure 12.5 The system structure for Vallensbæk Company House expressed as parallel subcontracts [Author's drawing]

However, the apparent indifference towards the more detailed system structure is only theoretical. On-site construction requires coordination between the different trades and subcontractors both time- and workspace-wise and this can in this case only be done efficiently by the turnkey contractor, NCC.

This coordination could be fairly simple if – as in traditional construction a century or more ago – trades were few and the physical interfaces between these were simple both process- and space-wise. This is not the case even in a relatively standardised concept like DKH. Construction has, as argued earlier, become considerably more complex and most subcontracts such as masonry work, flooring, painting, plumbing, ventilation and electrical installation are highly distributed deliveries meaning that they are integrated in the building as a whole rather than constituting clearly perceivable and physically distinguishable integrated modules. This means that all on-site processes connected to each subcontract require considerable coordination with other subcontracts and their sub-deliveries that consequently demand attention from the turnkey contractor. This complexity is a very common problematic in turnkey contracting and one of the main incentives for moving processes to off-site sub-deliveries – at least in the form of 'construction-under-roof' where site conditions are neutralised by a more controlled production environment as seen in the Scandi Byg analysis.

Connecting client decisions and construction schedule

NCC does not adapt an off-site strategy and generally – as a turnkey contractor in a more traditional sense – sticks to an on-site scenario and focus. In order to control and desirably reduce the complexity in focus, emphasis is put on the elaboration of a sophisticated and dynamic scheduling tool that can help coordinate the different dependencies among the subcontracts and among the different phases or stages that each particular project goes through in order to prepare for a smooth final delivery on tier 0 (on-site). The scheduling tool as a kind of advanced project stage model aims at 'packaging' and connecting client decisions (within the framework of the concept) with subsequent design development tasks, procurement, delivery and finally construction/installation according to standardised packages and contractual divisions.[4] This in such a way that any change within one phase or package will have direct influence on subsequent downstream phases or packages ultimately changing the entire schedule. For DKH, the tool divides client decisions into 11 decision packages (BPs), 9 design packages (PPs), 16 procurement packages (IPs) and 16 delivery packages (LPs) that are ultimately connected to 20 different subcontracts (UXs) and all put into one single schedule – (BPILU) (see Figure 12.6).[5]

> What is special about that [BPILU-]schedule which we have spent considerable time on working out is that it is one big coherent schedule. You get five different [sub] schedules out of one file. If you move a delivery, all the rest will move as well. This is new.
>
> (LH)

Theoretically the packages and their connections express exhaustively where the client has influence on the project (through the decision packages)

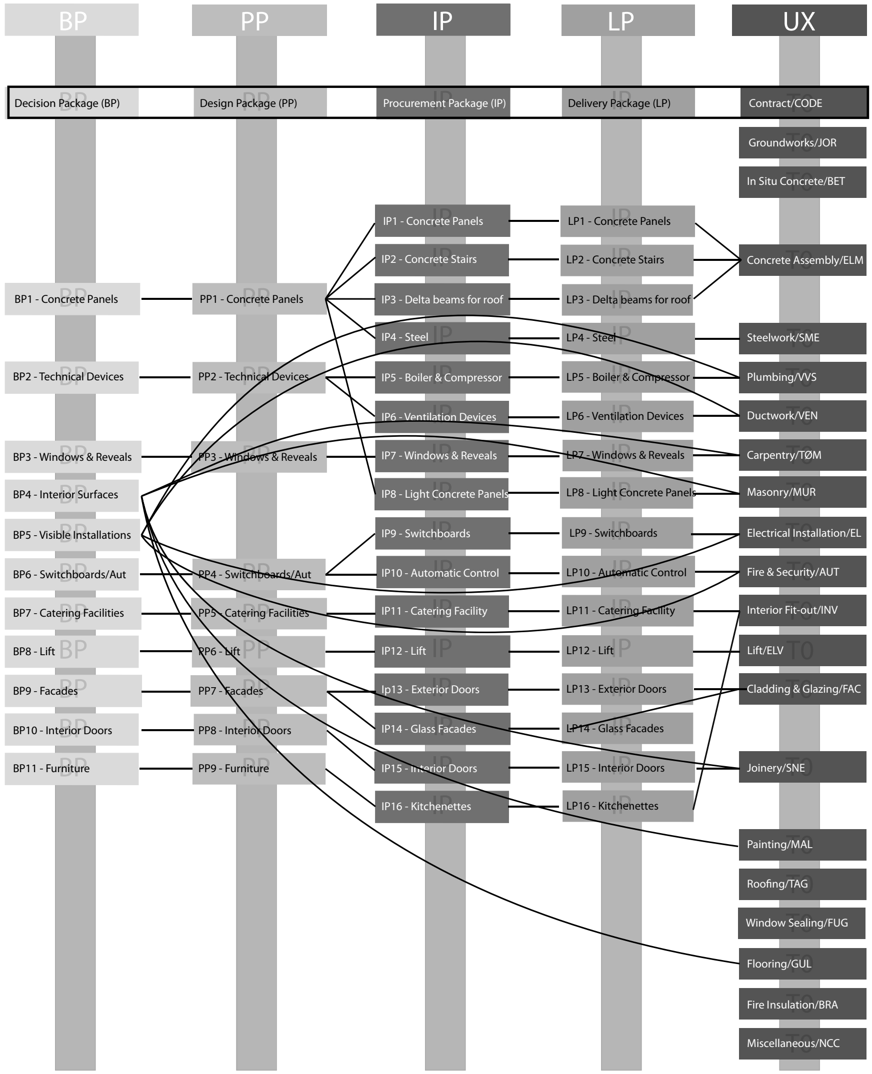


Figure 12.6 NCC's BPILU-structure showing the different decision packages (boxes) and their interconnections (lines) [Author's drawing]

whereas all other decisions and subsequent tasks (of design, procurement, delivery and construction/installation) are standardised within the concept. The different packages are thus ideally an expression of all tasks to be performed on the specific *project* level while all other tasks already has been accomplished (and standardised) on the *concept* level. In the construction/installation phase (UX), the standardised concept tasks and the project-specific tasks merge into one unified construction/installation plan.

The decision packages (BP) are divided according to entities and themes that make sense for the client while the subcontracts and the construction schedule are divided according to the focus of the main contractor, NCC. The scheduling tool *translates* these client entities or themes into subcontractor entities and sub-tasks while assuring consistency time- and solution-wise throughout the different phases. This means that, for example, the client's response to BP4 – *Interior surfaces* or BP7 – *Catering Facilities* at the end are combined with the standards of the concept and translated into specific sub-deliveries and construction tasks within several subcontracts, that is, *Carpentry (TØM), Masonry (MUR), Joinery (SNE), Painting (MAL), Flooring (GUL)* or *Interior Fit-out (INV)* (see Figure 12.6). The client is more interested and skilled concerning the service 'Catering Facility' than preoccupied with the specific trades involved in delivering this service. By packaging relevant decisions – and *only* these – in categories relevant to the client, reduction of complexity in focus is obtained both for the client and for the contractor where the latter can both focus the interaction with client and reduce the amount of design work required in each project by drawing on standardised solutions (= *integrated complexity*) that exceed the project level. Information is *timely and accurate* as in an optimised supply chain (Hugo 2006: 6).[6]

Process schedule and system structure

The system structure and the model as defined within this book concentrates in its present state exclusively on deliveries or systems than include some physical element to be inserted in the final building. It focuses on the (primary) material supply chain whereas (secondary) pure service deliveries have been left out.[7] These physical deliveries can be combinations of materials, components, assemblies *and* the processes and knowledge to produce, deliver, or install them on a subsequent tier (i.e. tier 0) but the final result of the delivery remains physical. The system structure is physical although resulting from different processes just like the product architecture of an industrial product. NCC's packages above are rather concerned with *processes* as system entity. The structure expressed in the BPILU-model is the structure of a process whereas the specific *physical* division results from the way the process is divided into contracts and their sub-tasks and deliveries. Moreover, client decisions and design development work are also processes but have no direct physical content. They are immaterial information or *knowledge*. However, the system structure also expresses some aspects of process in the form of simplified supply chains. When it, as used in this book, divides into different tiers and the deliveries become nested into each other from the less complex upstream deliveries on tier 4 and tier 3 over the more complex and integrated deliveries on tier 2 and tier 1 to the final tier 0 deliveries on-site, it is both displaying structure and process – a combination of product architecture and supply chain (management). Figure 12.7 shows an attempt to relate the two different models showing how aspects of process cross over with aspects of (physical) system structure.

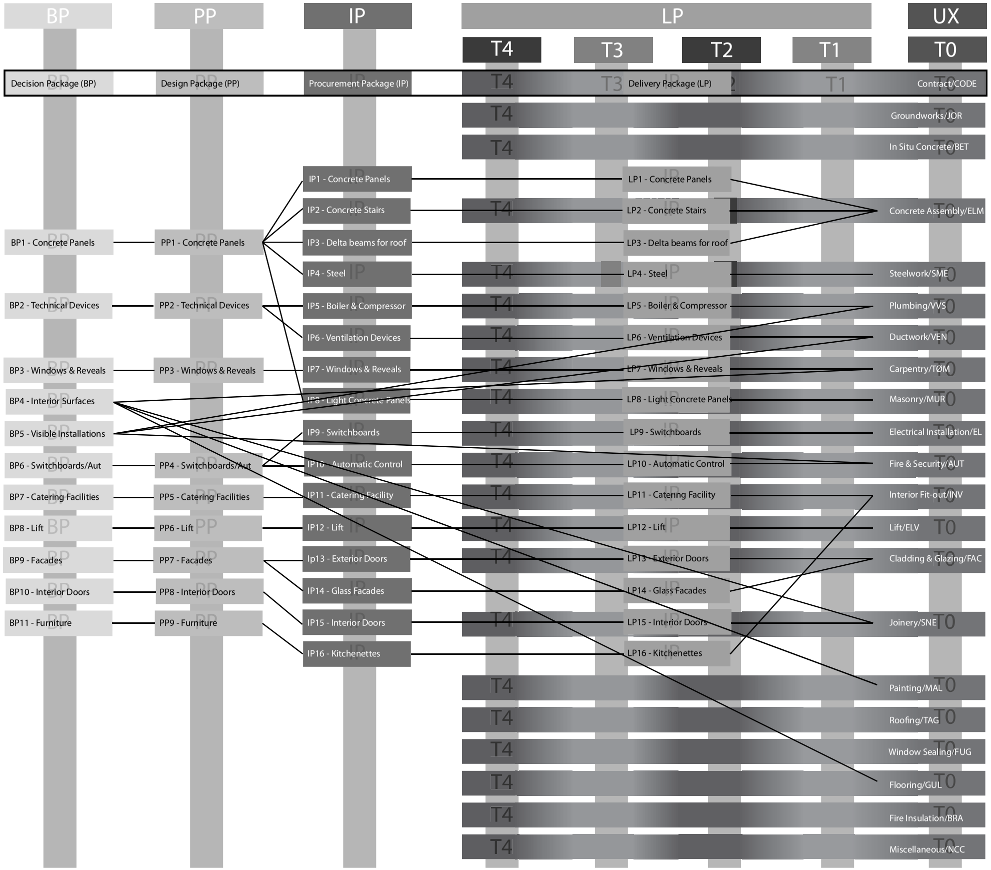


Figure 12.7 BPILU and system structure merged – BPILU is more detailed on process and the system structure more detailed on physical delivery [Author's drawing]

Integrated product deliveries: Examples

As main contractor, NCC mostly does not have explicit focus on how different upstream deliveries are combined before they arrive for installation on-site as tier 0 deliveries – they remain opaque to the main contractor. If specified, in most projects this would be the job of an external architect or engineer. In the *Danske Kontorhuse* concept NCC are in control of the entire value chain from conceptual design over design development to procurement, delivery and construction and have actually made the descriptions. However, the choice of sustaining traditional trade divisions as the main system structure does not necessarily encourage the (traditional) subcontractors to make intensive use of more integrated off-site produced solutions – even if there could be both short-term (time) and long-term (quality) benefits from the use of such solutions. If the descriptions provided by NCC or external consultants do not point towards or at least to some extent are open towards alternative contractual divisions and/or physical solutions, the final choice of subcontractors will almost exclusively be about choosing the lowest bid – not necessarily the best solution from an architectural point of view.[8] Opening up for new solutions requires other incentives, other ways of describing and perhaps an earlier active involvement of the subcontractors in finding the best solution. *Early procurement* is an example of such a strategy.[9] The paragraphs below list some of the few more integrated deliveries that are actually used in the specific office project and assumed for the general concept. Other *potentially* suitable integrated product deliveries are also discussed.

Concrete panels and slabs

Both *Vallensbæk Company House* and *Danske Kontorhuse* are based on a prefabricated concrete structural building system consisting of insulated façade elements, pre-stressed hollow core slabs and columns. This kind of structural system is very common in a Danish context where intensive in-situ work is seldom applied due to high labour costs on-site. Furthermore, the Danish prefabrication concrete industry is very dominant on the market compared to other structural systems such as wood or steel based versions. In the system structure terminology both façade elements and slabs as planar elements represent tier 2 assemblies while the columns as more simple structural 'lines' figures as tier 3 components. Concerning standardisation level, all three can be characterised as made-to-order deliveries (M2O) based on a standardised production method and material composition and, within the concept, furthermore with fixed construction dimensions. The façade elements (approx. 3.5 m high × 6 m long) are prepared as sandwich constructions with insulation between an exterior and an interior layer of concrete. The interior part is prepared for electrical wiring and communication cabling while the exterior accommodates a later added tier 3 solar shading or other additional tier 3 façade claddings (according to the different models). Window location and window size is flexible within the structural constraints of each panel assembly that has a 'column' in the middle thus subdividing the basic façade module to 3 metres. The hollow core slab-assembly is one of the most standardised precast tier 2 products on the market. Although perhaps not literally an off-the-shelf delivery (OTS), such slabs often have standard lengths and can to some extent be delivered/installed as cut-to-fit (C2F) assemblies or be accommodated on-site.

Glass façade, doors and windows

The Vallensbæk Company House consists, contrary to the general concept (or module), of two concrete wings connected by a lighter glass section with reception and service facilities thus forming a 'H' plan. The connecting glass section is clad with a tier 2 façade delivery made by Schüco – one of the major cladding manufacturers worldwide. Schüco delivers both stick-built solutions as a kit-of-parts and unitised panel assemblies (ASM) to be mounted on brackets and joined only by gaskets on-site. In this case a unitised solution was chosen. The entrance door including weather porch as a separate delivery was a stick-built kit-of-parts delivery due to the relatively limited size of the contract that made off-site production less cost-effective. The general concept (DKH) exclusively encompasses concrete façades although the façade modules in the lobby and reception area can have larger openings giving a vertical impression crossing over several floors. These and all other openings in both cases are fitted with tier 3 window and door deliveries.

Other integrated product deliveries

Most other sub-deliveries in the subcontracts are installed in quite traditional ways based on materials (MAT) and components (COM) delivered on-site and often require a considerable amount of adaptation and use of labour. This way of delivery closely corresponds to the theoretical scenario of 'contemporary on-site construction'.[10] However, some of the sub-deliveries are already established standardised and marketed products with high preparation and standardisation levels. Solutions for both the catering facilities and the kitchenettes come as made-to-order (M2O) tier 2 assemblies based on projects elaborated by or in collaboration with the supplier and are based on highly standardised modules and measures. Another example is the lift delivered by Schindler, who also design, deliver, and install lift solutions based on relatively few design inputs from NCC (as client/consultant) concerning available area, load requirement, surface design, etc., while most design information already is embedded as standard configurations in their products. Equally, as in many office designs, tier 2 suspended ceiling systems, DEKO and Rockfon, are used. These systems have the advantage of giving easy access to hidden installations above each office floor, i.e. electrical wiring, data cabling, ventilation, heating and plumbing installation and often integrate fittings for lighting, ventilation, sprinkler and other fixtures. Suspended ceilings mostly arrive to site as stick solutions. Finally, the applied drywall solution by Danogips has characteristics of an integrated product delivery by comprising a completely designed system solution. It is, however, not prepared and delivered as such a coherent system but rather as various discrete tier 4 deliveries based on standard measures and with considerable adaptation needed on-site. Both service and preparation levels are low.

Potential use of IPDs in the DKH concept

The DKH concept includes, as described above, standard cores including staircases, lift, installation shafts, handicap toilet, kitchenette, cleaning repository and general storage. Although plan sizes vary, the core layout is fixed. Equally, optional additional toilet cores are standardised. These cores would be an obvious target for more integrated deliveries that could even become further commoditised if sales volume of the concept went up or if they were sold as separate products for other contexts. As for the toilets, many products already exist on the market (bathpods) – mostly as made-to-order solutions (M2O) with considerable design flexibility offered to the client. For the residential sector most solutions are tier 1 volumetric elements fully fitted and often sealed upon arrival to site. For larger toilet areas in offices and public buildings, volumetric elements are in some cases replaced by modular tier 2 wall assemblies that literally can be plugged together on-site.[11] When the volumes get bigger and installations per m2 get relatively lower, tier 2 solutions can be a wiser choice. Although toilet and bathpod systems seldom represent high degrees of automation production wise, the controlled factory environment combined with the fact that they are known as established products on the market often makes both tier 1 and tier 2 solutions very cost-effective even for small batches. Concerning the installation shafts of the concept, NCC themselves have already developed a prefabricated tier 1 shaft system for residential projects. This system could evidently be adapted for use in office projects like the DKH concept, where the project economy would not only benefit from the semi-automated configuration of the individual shaft solution but also could gain from the advantages of mass-production by having larger batches of exactly or almost the same solution. Equally, mechanical rooms could be delivered both as volumetric tier 1 chunks or panelised tier 2 assemblies whereas general storage and cleaning repository most obviously could form panelised solutions due to the high amount of 'empty space' in these if delivered as volumetric tier 1 chunks.[12]

Explanative power of the model

The coding of the DKH-office concept as a system structure is quite different from the two earlier cases of KieranTimberlake and Scandi Byg, that distribute deliveries over all tiers and display several chains of nested deliveries (from upstream tier 4 to downstream tier 0). Seen from the viewpoint of the contractor, NCC, the DKH concept and the specific VCH project on the contrary sustain a structure close to the theoretical scenario of 'contemporary on-site construction'[13] with a relatively large number of parallel deliveries (or subcontracts) all present on the final tier-0 level (on-site) and mostly with opaque upstream sub-deliveries (on tier 4 to tier 1). Furthermore, even if zooming in on these sub-deliveries, only few of them are nested upstream into more integrated product deliveries (tier 2 and 1). The bulk of deliveries is rather brought directly into tier 0 deliveries as relatively simple tier 4 materials or tier 3 components nested on-site. An explanation of this apparently quite traditional system structure can, as mentioned above, be found in NCC's focus on process rather than on product(s). As a contractor, NCC works mostly with the implementation of (design) ideas of others and is less concerned with a complete reframing of the constituent elements of these ideas. In turnkey contracts, NCC bids on already established designs and subsequently divides them into a number of subcontracts corresponding to their usual (domestic) subcontractors. Although NCC within the office concept tries to bridge between the architectural idea and its execution (construction), they do not move out of the established subdivision even if other initiatives within the firm actually support this, that is, the development of the prefabricated configurable installation shaft. The reason should probably again be found in the process focus where the development and test of the dynamic scheduling tool (BPILU) has been pivotal. However, AK points out that when working on the design aspects of such concepts as the DKH, the product view – such as expressed in a system structure – becomes interesting:

> Where I find this [system structure] interesting for us [at NCC] is in relation to the design of such concepts and on a planning level. [It is] when we start – not on a single project but as here – on a building as a product. How would we like the model to be?
>
> (AK)

The system structure coded for this case expresses the need for considerable on-site coordination between the different (opaque) parallel deliveries. By furthermore displaying (traditional) trade based divisions rather than functional or performance based (integrated) divisions many of these deliveries are highly distributed and thus integrated into the building as a whole rather than into clearly delimited functional modules. This structure inhibits subcontractor incentive for enhanced prefabrication by producing an immense amount of on-site interfaces between dominating deliveries, i.e. plumbing (VVS), electrical installation (EL), flooring (GUL) and painting (MAL) instead of establishing alternative delivery divisions like, for example, fully fitted toilet units, technical rooms, installation shafts or kitchen modules that each of them integrate several of the former trades. However, some generally established integrated deliveries as Concrete Panel Assembly (ELM), Cladding and

Glazing (FAC) and the lift (ELV) does show the general but weak market-based tendency towards new divisions. However, NCC's focus is primarily on process. This process is internal and specific to NCC and consequently runs the risk of sub-optimisation seen in a wider industry perspective.

One could say that, by having all subcontractors delivering and installing on-site, the service level is apparently relatively high. This, however, is opposed by the low preparation and standardisation levels of these deliveries that lead to very project-specific solutions that are hard to warrant as products. As buildings are seldom designed down to each single detail and interface the innumerable and fuzzy contract interfaces on-site leave the turnkey contractor with much of the quality control and responsibility – and this on a *project* basis. Warranty periods of more than a few years are unusual within construction projects even though buildings are often built to last virtually for ever. Fewer assemblers on-site through earlier serial nesting into integrated product deliveries produced off-site would enhance the possibilities of proper *product* warranty.

Notes

1 Defined by NCC as a multi-storey office building containing one or several separate companies with shared facilities.
2 See http://www.eu-greenbuilding.org/ (accessed 11 July 2011).
3 For an introduction to the three dimensions of *preparation*, *standardisation* and *service* see Ch. 5.
4 For a presentation of different commonly used project stage models see 'Classification systems in construction', Ch.2.
5 The applied abbreviations refer to the corresponding Danish terms (*Beslutning, Projektering, Indkøb, Leverance and Udførelse* = BPILU).
6 For a short introduction to supply chains and supply chain management see 'Industrial production theory', Ch. 3.
7 See definition in 'Architectural systems terminology', Ch. 5.
8 A similar view is also introduced in the KieranTimberlake case; see Ch. 10. The following Arup Associates case, Ch. 13, introduces several alternative contractual divisions in a high-end project where quality is primary to price.
9 See 'Classification systems in construction', Ch. 2.
10 See 'Model presentation', Ch. 9.
11 For an example of this kind of toilet core delivery see the Arup case, Ch. 13 and the Podwall product in Ch. 7.
12 KieranTimberlake's Lobolly House described in Ch. 10 includes volumetric chunks for mechanical rooms.
13 For a description of the theoretical scenarios, see 'Model presentation', Ch. 9.

13 Arup Associates

The Ropemaker Place project

Introduction

The following analysis is based on a study at Arup Associates in London. Particular focus is put on the external façade cladding that is used as a main example for discussion of different issues concerning the system structure of the analysed case. After a short description of the case and the company the system structure model is established and its particular attributes subsequently discussed. In a final paragraph the explanative power of the model as applied to this particular case is discussed.

From Arup, direct contributors to the study have been Associate at Arup's Milan Office, Mikkel Kragh (MK), Project Director, Paul Dickenson (PD), Architectural Director, Mick Brundle (MB) and Project Architect for the latter project stages, James Ward (JW). Direct references to meetings and interview in the text will be followed by the initials of the person cited in brackets.

Project type: Description of the case

The project type in this case is a bespoke high-end 22-storey office building erected in a centrally located business area in London. The building, Ropemaker Place, was finished in 2009 and was commissioned by British Land, one of the largest property companies in the UK that develops, owns and manages retail and office properties. It was delivered to British Land as a so-called 'shell-and-core'-project where reception, lobbies, infrastructural and other common areas are fully finished while the individual office decks are passed over to the tenants before fit-out. Although Arup Associates provides the necessary general documentation needed for the tenants to accomplish the individual fit-out of the decks, they are not directly involved in this part that runs on separate contracts with the developer and landlord, British Land. The scale of the project and the budget for this kind of development combined with a demand for short and precisely scheduled construction time in order to hit the market at the right moment address a special category of contractors and suppliers which often have only few equals on the European or even on the World market.

Figure 13.1 Ropemaker Place, London by Arup Associates © Christian Richters Photography

The company and the focus of the analysis

The building, Ropemaker Place, and the coding of the corresponding system structure model is in this case seen from the perspective of Arup Associates who designed the project and as consultant in construction integrates architecture, structural engineering, environmental engineering, cost consultancy, urban design and product design within one studio.[1] As a subsidiary to Arup that was originally founded as an engineering consultancy in London in 1946, Arup Associates have been formed as exclusively dedicated to what they themselves term '*Total Architecture*'. The idea is that an integrated multidisciplinary design approach enhances the ability to work with the building as a whole from the start.[2] This makes it possible even on an early design stage to work closer with the question of how the building is procured, produced and erected and to let this impact directly on these early design decisions. Arup Associates, as opposed to Arup in general, only engage in projects where they are responsible for all consultancy disciplines. One could say they act as a kind of 'total consultant'. Their project portfolio encompasses mainly corporate architecture, cultural institutions and university buildings. Arup Associates employs approximately 150 employees at the time of writing.

The perspective of this analysis is thus that of the consultant but not limited to the architectural consultant which in this case forms part of a larger team that coordinates internally. As subsidiary of Arup, the company also draws on a huge amount of technical knowledge and experience within construction in general. Particularly relevant here is Arup's expertise and experience with the building envelope seen as a separate and highly prefabricated delivery. The building envelope was the most expensive single delivery (contract) of the Ropemaker Place building. The choice of a procurement route for the Ropemaker Place, following a so-called *construction management* approach, puts keen emphasis on the contractual divisions that in the British system seem to be more open for negotiation than in the previous NCC case.[3] The present analysis of the system structure for the Ropemaker Place deals with these different contractual divisions as pointers towards emerging integrated products and their interfaces.

System structure: Coding and special project-specific features

Ropemaker Place was organised around a relatively large amount of individual trade contracts directly between the client, British Land, and different contractors. This particular project-specific split was established already during the design development stage (PD) within the Arup Associates' design team in collaboration with Mace, the construction manager of the project who controlled the bidding process/procurement and the later management and coordination of these different contractors each delivering their particular bit of the building (PD). This form of procurement is called *construction management* and the individual contracts are called trade contract packages or simply: *work packages*. The principal difference between the traditional (British) system of procurement and the construction management system is that in the former the final building design is divided into subcontracts by a contracting body (a main or turnkey contractor) often using own subcontractors without involving the designers and consultants (i.e. Arup Associates) in the choice and divisions whereas the latter, construction management, from the start is procured as these different work packages thus potentially bringing closer the way architecture is conceived and the way it is subsequently produced. This gives in this case Arup Associates as well as the client, British Land, enhanced control over the specific division into contracts and the choice of individual contractors, who engage in a direct contractual relation with the client. The contract manager, Mace, does not control this division – they manage it.

The interesting thing about this in a discussion of system structures is that it facilitates a way of splitting up the construction job that, as opposed to traditional craft based divisions, in some instances are delimited as performance based deliveries that simultaneously transgresses and encompasses several of these traditional crafts or trades. In the analysis these work packages become the primary elements of construction – the elements of this particular system structure.

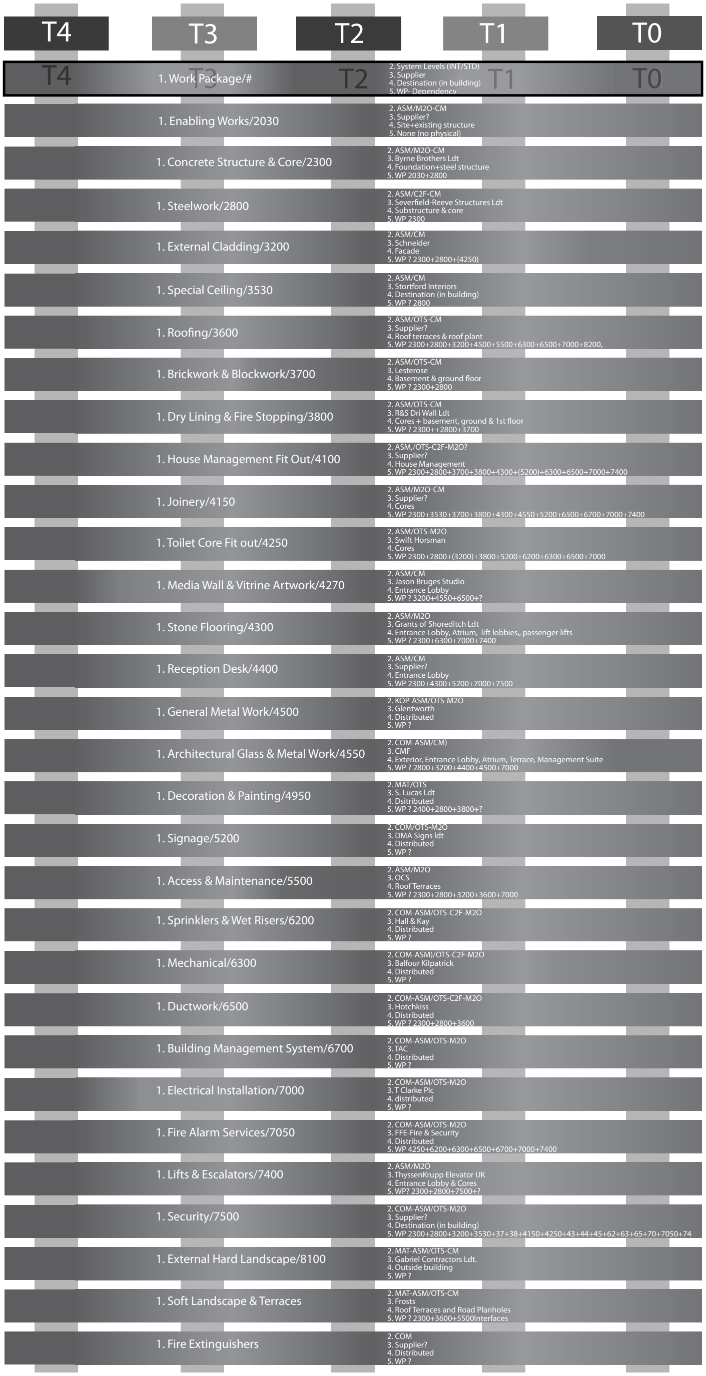


Figure 13.2 System structure of Ropemaker Place, parallel trade-based contracts as work packages [Author's drawing]

Work packages

Some of the actual work packages found in the project fall outside this system structure analysis. Examples are introductory site investigations and archaeology, movement monitoring or logistic features on-site as tower cranes. Work packages seen as system elements (deliveries) can have varying degrees of focus on *thought, process* and *matter*.[4] Most will contain shares of all three, but in order to be reflected in the system structure they need as a *minimum* to figure in the final building as a physical entity. In the Ropemaker Place project this definition brings out 30 different work packages that together make up the entire shell-and-core building. Individual office deck fit-out is not, as mentioned earlier, part of the construction project. From Arup Associates the work packages are prepared as a specification and a 'scope-of-work' description (PD).

The work packages behind the trade contracts are system structure wise thought as parallel, as opposed to serial, in the way that they generally all deliver physical matter installed on-site in the building itself (tier 0). Within each work package and based on the project elaborated by Arup Associates the trade contractor is responsible for the entire supply chain from design to commissioning. This 'internal' supply chain can contain various suppliers, manufacturers and subcontractors and may consist of elements with varying integration (tiers) with varying preparation, standardisation and service levels. This substructure of the individual work packages is, however, in most cases opaque to the consultant and the client and thus not reflected in the system structure. The deliveries in all work packages span from and include any sub-delivery from tier 4 (T4) to tier 0 (T0). Arup Associates describes the work packages in the following way:

> The Works to be undertaken by the Trade Contractor shall be the design, co-ordination, procurement, supply, fabrication, manufacturing, delivery to site, assembly, installation, supervision, inspection, testing and commissioning of the Works. The Works shall be deemed to include all materials, components, assemblies and finishes together with all associated fixing devices, fittings and fixtures required to complete the Works in compliance with the Trade Contract.[5]

The work package perspective combined with the construction management approach creates the specific system structure of parallel deliveries spanning various tier levels (See Figure 13.2).

However, these parallel work packages also express that interfaces *between* the system elements (the different deliveries of the system structure) are primarily found in tier 0 (T0) – the building site. Here, the deliveries are no longer parallel in the sense that some deliveries evidently depend on the prior execution of or the simultaneous coordination with other work packages. The concrete substructure (WP 2300) comes before the steelwork (WP 2800), the reception desk (WP 4400) comes after and upon the stone flooring (WP 4300), the security system (WP7500) has to be coordinated with the access doors of the cladding contract (WP 3200), etc. The system structure of Ropemaker Place becomes a series of specific contractual interfaces that are all present as processes on-site and only interface physically there.

Divisions and interfaces

Although the (sub) supply chain of each work package in principle is opaque to Arup Associates certain ways to control their execution is indirectly introduced through several means: The initial work package structure, their descriptions (i.e. interfaces, performance, available production time, etc.) and through the selection criteria of each sub-contractor which is not exclusively based on the question of cost. Through the descriptions and in order to comply with the requested performance, the trade contractors of each of the work packages are encouraged to use techniques of off-site production as much as possible although in some cases restrained by the assembly sequence on-site and the coordination with the other work packages: The concrete substructure (WP 2300) and the structural steel structure (WP 2800) set up constraints on the size of prefab elements that can be lifted in. Likewise, the scheduling of the façade cladding montage is decisive for the delivery of larger elements or 'flatpacks' to decks by the tower crane. Some work packages still follow quite traditional lines of division corresponding to old crafts or fragments of these. An example could be the 'Brickwork and Blockwork' package (WP 3700) or the 'General Metalwork' package (WP 4500). Others like the 'Toilet Core Fit-out' package (WP 4250) or the 'House Management Fit-out' package (WP 3530) transcend these traditional divisions – in the first case as a mainly off-site produced integrated and modularised kit-of-parts solutions, in the second case as a primarily site-based adaptation and joining of lower integration level items. Both packages contain elements and processes stemming from many different trades or skillsets/crafts. Thus, a work package that does not follow traditional divisions along crafts or well established trades does not necessarily result in more integrated products or more off-site fabrication. If the work package encompasses building parts that are physically and/or functionally clearly delimited either as single parts (as e.g. a bathpod) or modularised systems (such as façade cladding panels) it is, however, more likely that integration and off-site fabrication will take place. If, on the other hand, they are distributed and interface with many other packages it is less likely. However, the structure of parallel deliveries can provide for high levels of the service dimension thus compensating for low preparation levels. Some of the specific integrated product deliveries found in the work packages will be described below.

Changes or negotiations of interfaces

Even though the division into work packages of the Ropemaker Place is project-specific it does not mean that it has been made from scratch for this particular project. Arup Associates developed the base for an internally used standard division of construction works into work packages about 30 years ago from a specific factory construction project developed together with the big construction company Bovis (PD). A general (work) breakdown structure was established assigning four digit numbers to each work package. The number of different work packages has decreased since then due to the fact that construction managers, as Mace in this case, prefer a reduced number of contracts that require less coordination between the packages (which is the construction manager's responsibility) and more coordination within the packages (which is the trade contractor's responsibility) (PD). Mostly, the original packages are simply merged, that is, piling, concrete basement construction and 20 floors concrete core (WP 2300) or external cladding, entrance doors and atrium (WP 3200) in the case of Ropemaker Place. In some instances, parts of some of the original work packages are put into several different work packages; although Ropemaker Place still contains an 'Electrical Installation' work package (WP 7000), many of the other packages equally contain electrician work. The 'Electrical Installation' work package contains the general installation and is distributed all over the building while the electrician tasks moved to other packages are either physically clearly delimited as in the 'Toilet Core Fit-out' package (WP 4250) or the 'Reception Desk' package (WP 4400) or functionally clearly delimited as in the 'Security' package (WP 7500) or the 'Access and Maintenance' package (WP 5500).

In a way the 'ideal' number of work packages is a weighing of direct control vs. integrated complexity. A reduced amount of packages also reduces the control of the construction process seen from the point of view of the client and Arup Associates as consultant. In the extreme, as with the traditional (turnkey contract) model, one contractor is in charge of all construction work.

The external cladding work package – an example

Although work package divisions and the resulting interfaces tend to follow a semi standardised internal system defined by Arup Associates themselves there are, however, always project-specific negotiations of the interfaces between the packages. Apart from the physical and functional delimitation as well as the coordination issues, as mentioned above, reasons can also have to do with economy. The external cladding delivered by Schneider (WP 3200) is an example of various aspects at a time pointing out both expediency and problems. The cladding contract was the highest value work package of the project (JW). The building type (both high-end office and green building) demands a high emphasis on the façade solution allocating a considerable percentage of the total budget to get this right. This means that the primary focus here is not the price, but rather the capability of the contractor to combine high quality and smooth installation.

The German façade construction company Schneider was chosen for the job. Schneider plan, manufacture and install bespoke façade solutions and have specialised in off-site produced unitised systems. The 'External Cladding' work package (WP 3200) included in this case all vertical external cladding on all façades including recessed main entrance doors and ground floor retail façades. It included furthermore external soffits (over ground floor recess), an internal glass vitrine for ventilation and artwork in the reception area and internal and roof glazing for an atrium. However, the external cladding for the roof plant on the top roof was, with exception of the louvres, transferred to the 'Roofing' work package (WP 3600). This transfer was, apart from advantages in sequence and interface coordination issues, also an economical disposition considering that the conventional skillset of the roofing contractor was more than sufficient to solve that task and thus avoided paying Schneider a premium for 'a bit of tin cladding' (PD) which is not their speciality.

Unitised solutions, the speciality of Schneider, are very common for buildings with larger glass façades such as Ropemaker Place. These prefabricated façade units are easy to lift onto the decks on tall buildings by tower crane and are subsequently installed by the use of a special robot that moves around on the floors, takes the glass out, rotates it, lifts it and drops it into position (JW). The on-deck robot further streamlines the process by saving tower crane time thus being released for other tasks. However, ground floor cladding, atrium glazing and in particular the main entrance doors are not equally suited for unitised systems, that tend to be less slim than stick based systems. Schneider ended up with a hybrid solution of unitised and stick based for these parts. The main entrance doors caused problems due to the electrical controls interface. Schneider are strong in engineering but they are not electricians and the electricians do not understand the cladding business (JW). An alternative would have been a separate work package – and delivery – for the access doors taken home by a contractor specialised particularly in these issues thus displacing the interface to the physical border of the entrance doors and letting Schneider concentrate on what they do best – unitised façade cladding.

Integrated product deliveries: Examples and innovation in commoditisation

Due to the work package focus of Arup Associates, selected as viewpoint in this analysis, mostly the system structure does not as mentioned, display any sub-deliveries within the work packages. Generally Arup Associates do not have direct focus on these upstream tier levels; they divide and describe the content of the work packages through the scope-of-work and the description and thus only indirectly control how each package is actually produced by each of the contractors before they deliver on-site. Still, Ropemaker Place contains several examples of different degrees of integrated products. A manufacturer focus, as in the Scandi Byg case, within each of the work packages would alternatively have revealed the detailed system structure of the many parallel supply chains. This paragraph brings in some of the more integrated sub-deliveries 'hidden' within the opaque parallel work packages.

Unitised façade cladding

The unitised façade cladding used from first floor and upwards is an example of a bespoke (BSP) high-end industrialised solution where the client is ready to pay a premium to get the best possible quality on the market. The specialisation in façade cladding crosses various traditional crafts and skill-sets and has gradually become established as a separate discipline based on considerably specialised knowledge drawn from several fields. In the present system structure terminology the unitised façade delivery represents a tier 2 delivery – an assembly 'by system'. However, the degree of commoditisation – the façade solution seen as a product – is so far low or not very developed for solutions with this degree of sophistication and customisation. While the preparation and service level might be high, standardisation is low (BSP).[6] Although Schneider, as cladding manufacturer, in the specific solution draw on several standardised products, that is, the Schüco-produced gaskets, each solution is rather a *project* delivery than a *product* delivery. Most of it is specifically designed and produced to the building project and not (simply) based on configuration of an already existing system (product). It is, however, Schneider, and not Arup Associates, that designs all junctions (MB) and follows what JW terms as the European school of cladding as opposed to the American school of cladding. In the European system, mainly developed by Schüco, the profiles of each façade unit (assembly) are structurally independent and are only connected by the rubber gaskets in between that create the weather seal (JW). In the American system the profiles from each unit (assembly) interlock and become one structural entity with the rubber gaskets only as sealants – not connectors (see Figure 13.3):

> The fundamental [difference] is that the [European] is a symmetrical profile with a non-structural link where [the American] is a metal to metal link and an asymmetric profile.
>
> (JW)

Although the American system is structurally the most efficient because the connected profiles can borrow structural capabilities from each other, the European system is so tied into Schneider's supply chain that Arup Associates, by choosing them, do not have influence on the choice of cladding school. The Shüco produced gaskets define the solution space of the profiles but also ensure that by following the prescriptions of use for these gaskets the product liability can be placed with Schüco.

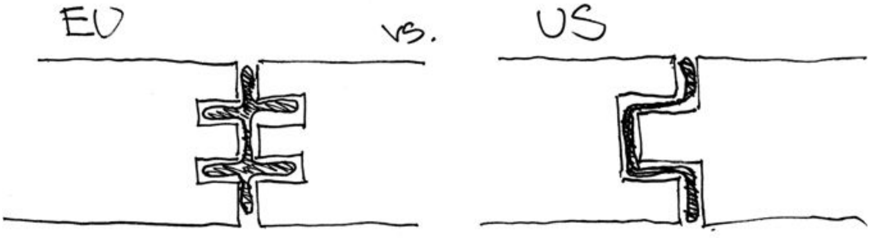


Figure 13.3 European vs. American façade cladding [Author's drawing]

Toilet core fit-out

When toilets or bathrooms are made for residential units it often makes good sense to produce them as tier 1 deliveries (T1) – chunks or 'assemblies by zone' – even if the rest of the building is produced as conventional on-site processes or partly as flatpack prefabricated deliveries based on planar tier 2 elements (T2). This has partly to do with the limited size of private bathrooms. In the case of Ropemaker Place, the toilet cores on each floor were much larger and furthermore divided into ladies', men's and handicap spaces. The manufacturer and contractor, Swift Horsman, chosen for the 'Toilet Core Fit-out' work package (WP 4250) market a specific product under the brand 'Podwall'. According to their homepage Podwall 'is a fully prefabricated modular walling system incorporating finishes and services all of which are manufactured completely off-site in a dedicated controlled environment'.[7] The modules (or assemblies) are brought to site as a tier 2 delivery (T2) and are literally plugged together and into the building with minor on-site preparation. Swift Horsman is, according to PD, one of the few companies able to deliver the required quality. Generally the companies who deliver prefabricated toilets originate from the joinery business rather than being grounded in skills around the services such as plumbing, ductwork or electrical installation. Off-site joinery is generally good but the quality often fails in the service systems. The origin of a company is not irrelevant. It defines the basic skillset and somehow even the fundamental mindset they work from. Swift Horsman provides joinery but has, as one of the few developed, a sophisticated product that is not just a matter of 'putting some stuff together in a factory' (PD). As a made-to-order (M2O) kit-of-parts of assemblies with a high service level the Podwall represents a highly industrialised integrated product delivery. One of its major qualifications in this sense is being both functionally and spatially clearly delimited. Still here there are some interface issues: due to the requirement of a unified solution in order to certify the systems of the 'Fire alarm services' and 'Security' work packages (WP 7050 and 7500) Swift Horsman had to coordinate with these packages doing their part of the installation on-site.

Special ceiling

Also the 'Special Ceiling' work package (WP 3530) integrates various trades or crafts delivering a clearly delimited part of the building both physically and functionally speaking – a special ceiling in the entrance and lobby area, that apart from integrating the lighting solution for this area also facilitates easy service access to lighting fixtures and to the technical installations above. In this package, delivered by Stortford Interiors, Arup Associates did have specific focus on some of the underlying supply chain (see Figure 13.4). The solution was designed as a bespoke solution (BSP) by Arup Associates and produced as a combination of bended perforated metal, produced as a sub-delivery by SAS Ceilings and sockets and special acrylic diffusers produced as a sub-delivery by the German lamp manufacturer Zumtobel. The sub-deliveries were assembled off-site as ceiling assemblies (ASM) and later installed and connected on-site (T0) – both steps by Stortford. (MB). After installation each of these 'gullwing'-shaped modules can be flipped down for service access. The ceiling solution brings two tier 3 deliveries (T3) together in a tier 2 delivery (T2) modular system that could perfectly be marketed as an integrated suspended ceiling solution. This is not, however, the case so far. A similar although not identical solution has later been applied in the reception area of Arup's main office in London. The creation of a solution like this is a typical expression of the course of product development in the building industry. A specific project with enough budget to develop a bespoke solution (BSP) becomes the launch pad for a new commoditised product. A condition for a successful implementation as a more standardised product (either OTS or M2O) is a business setup where the involved parties either engage in a consortium or where one of the stakeholders takes on the role as system owner – possibly through buying the others out or by paying them royalties. Many well-known industrial design objects have been established this way.

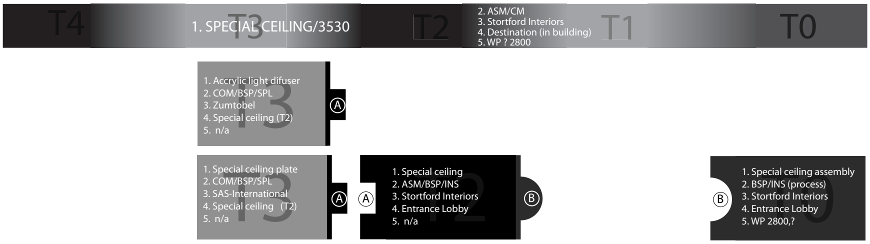


Figure 13.4 For the 'Special Ceiling' work package Arup coordinated nested subsystems [Author's drawing]

Other integrated product deliveries

The 'Stone Flooring' work package (WP 4300) delivered by Grants of Shoreditch Ltd. actually covers a slightly more sophisticated product than just the work of a tiler on-site. Arup Associates strive towards prefabrication and dry construction (MB). In this context advanced office flooring has developed into integrated systems that preserve the aesthetics and durability of traditional stone flooring that is the background of Grants of Shoreditch. The installed 'Technik Floor' is, as a tier 2 (T2) delivery, a prefabricated screedless raised dry assembly product that furthermore integrates functions as underfloor heating and in-floor lighting. The floors were installed in the entrance lobby, the atrium and in the lift lobbies all the way up the building. According to PD there are probably only three companies in the UK that can deliver a solution on that level and only the scale of the Ropemaker Place project makes it possible to choose one of these (PD). Apart from quick installation and reinstallation the cavity below the raised floor makes it possible to run supplementary or later added cabling in a flexible way and without having to hack up the floors. Flooring in the toilet cores and in the house management area were extracted from the 'Stone Flooring' work package and installed under these fit-out work packages.

The vertical service risers are often, in projects of the scale of Ropemaker Place, delivered as complete volumetric tier 1 (T1) solutions that sometimes span several floors and include all vertical service routing as sprinkling, water supply, ductwork, cable trays and man access for later re-servicing and supplementary installation. These assemblies are simply dropped into place as the building goes up and secondary pipework and cabling are connected from here.[8] However, in Ropemaker Place this vertical riser work package lacks and pipework and cabling were instead located together with the secondary installation under the different more craft rooted packages as 'Sprinklers & Wet Risers' (WP 6200) 'Mechanical' (WP 6300), 'Ductwork' (WP 6500), 'Electrical Installation' (WP 7000), etc. Ropemaker's slightly unusual design with the many setbacks of the roof terraces made the volumetric prefab strategy untenable because of the enhanced need for transfers. Instead a whole series of tier 3 (T3) flatpack components were brought and hooked into an equally flatpack delivered steel carcase (PD and MB).

Ropemaker deliveries as 'haute couture'

In some way the façade cladding, the toilet cores, the ceiling system and the stone flooring in the Ropemaker Place project, can be seen as a kind of 'haute couture' or 'formula 1' that, as in the clothing or car industries, points out certain tendencies that subsequently diffuse into the more conventional commodity market (read: become commoditised). The construction industry has, apart from materials and smaller components, only sparsely been able to develop well established building products. The enhanced complexity to handle in contemporary construction, as pointed out elsewhere,[9] combined with the demand for short installation time, however, seem to push the general development towards more advanced system solutions with high levels of standardisation, preparation as well as service.[10] 'Haute couture' markets like external cladding of office buildings or some of the other examples given above could show the way for development of new 'off-the-shelf' or 'made-to-order' (OTS/M2O) products in the building industry. In that sense product development within the building industry, as pointed out under the ceiling paragraph above, still, as has always been the case, takes place on a project basis and is not, as in the product industry in general, an activity detached from the production itself. The new aspects here, however, are that product development, as in the case of the façade cladding, is on the one hand more integrated than simple materials or building components and, on the other hand, points towards the emergence of a new product *type* through the redefinition of the contractual, physical and functional interfaces expressed in the work packages. New integrated product deliveries do not just come out of a good (design) idea; they are equally tied to the way construction is organised.

New divisions equal new elements in construction

The construction management approach used by Arup Associates in the Ropemaker Place project brings them, as consultants, quite close to a contractor perspective but still with a point of departure in the architectural design rather than the later production of it. The partly project-specific division into work packages is not only driven, it seems, by construction issues. The architectural design also plays a role here. By bringing in the division and thus also the form of procurement and indirectly even the way particular parts of the building will be produced at the design development stage, the distance between the architectural design as idea and the way it is produced seems to decrease. The way Arup Associates practise what they themselves call 'Total Architecture' somehow suggests *one* way – not necessarily the only way – to bridge the gap between architectural idea and the way it is actually realised or produced.

Explanative power of the model

The coding of Ropemaker Place as system structure is considerably different from the KieranTimberlake case(s) or the Scandi Byg examples and closer to the NCC cases. This is mostly due to the structure of a large number of parallel deliveries (the work packages) that each of them at least potentially span all of the different tiers while ending as tier 0 deliveries (T0). In the previous cases, these 'supply chains' are divided serially into sub-deliveries on the different tiers, that in the case of Ropemaker Place as well as the NCC cases become opaque from the viewpoints analysed. The general system structure model has, as it is thought, two functions that are, however, closely related:

one is to show how the final outcome, the building, production wise is constructed or assembled by different constituent elements. Another is how these elements sometimes are embedded in each other forming supply chains that lead to more or less integrated product deliveries to be installed or nested into the building.

Compared to the theoretical model scenarios introduced in the model presentation, Ropemaker Place seen from the selected viewpoint is actually closest to the scenarios of 'traditional on-site construction' or 'contemporary on-site construction' by having these parallel lines of delivery from upstream tier levels (T4 and T3) to on-site delivery (T0) and many 'assemblers' on-site.[11] This is, however, as mentioned above, partly explained by the general opacity of the supply chains within each work package as seen from the viewpoint of Arup Associates but could also be seen as a weakness of the model regarding the ability to express the actual system structure. These work package internal supply chains and their much more detailed system structure could have been established through a more intensive in-depth study of the individual work packages. This would possibly show a (system) structural picture closer to the scenario of 'future industrialised architecture' with a tendency towards more tier 1 and 2 deliveries. The complexity of the model would have been high. However, in order to fulfil the overall goal of helping to reduce the complexity of the design process it is not necessarily the aim to establish a view of the entire supply chain. It is rather a question of showing the architectural design complexity *in focus* and equally to show where this complexity in focus has been reduced through the integration into 'opaque' work packages or industrialised deliveries, where each contractor is directly responsible for the complete delivery and installation according to the description, the scope-of-work and the drawing material elaborated by Arup Associates. This project material can of course be very complex in itself, but the point is that the internal coordination of the production of each work package is mostly outside the focus and attention of Arup Associates, the client and Mace, the construction manager that is hired to coordinate between work packages. Furthermore, the early introduction of these work packages already in the design development phase and Arup Associates' internal 'total consultancy' work facilitates better correspondence between 'project-as-thought' and 'project-as-built'. As mentioned above: contractors are only indirectly encouraged to use techniques of off-site production through means such as the overall work package division, the choice of work package contractors, the project material and its performance requirements. This strategy does not in itself guarantee but can potentially lead to an enhanced commoditisation of construction solutions and the emergence of more integrated product deliveries in construction. New work package divisions along lines that cross traditional craft based tasks that are typically distributed all over a building and towards divisions of simultaneously physically and functionally well-defined entities – as here the façade cladding or the toilet core fit-out packages – present an interesting way of promoting new specialised contractors and manufacturers that develop integrated deliveries encompassing the entire supply chain. These new as well as traditional divisions are reflected in the system structure analysis of Ropemaker Place. Equally, it points out the particular work packages where Arup Associates as architects or 'total consultant' have had special focus on the supply chain in order to get the right solution. These more focused views correspond to the focused discussion of system structure changes in the previous Scandi Byg analysis.

A disadvantage of the specific system structure for Ropemaker Place, such as compared to the theoretical scenarios of 'future industrialised architecture' as well as 'conventional customised prefab' or 'conventional standardised prefab', is the relatively high amount of tier 0-suppliers that furthermore also install on-site. This requires a different kind of coordination than if only one or few assemblers did the on-site job. Additionally, the tier 1-dominated prefab scenarios, as in the Scandi Byg case facilitate an earlier integration and give more time or possibilities to correct possible faults in the upstream subdeliveries. The advantage on the other hand is the high service level in terms of the enhanced possibility of product guarantee and later servicing provided by the supplier which after all ought to be the expert within a particular field as opposed to a general assembler.

Notes

1 See http://www.arupassociates.com (accessed 2 April 2011).

2 See http://www.arupassociates.com: '"Total Architecture" implies that all relevant design decisions have been considered together and have been integrated into a whole by a well organised team. This is an ideal which is well worth striving for, for artistic wholeness or excellence depends on it' (accessed 2 April 2011).

3 An explanation of the *construction management* approach will follow below.

4 The distinction between systems of *thought*, *process* and *matter* is introduced in 'General systems theory', Ch. 4.

5 General on 'Scope of Works' cited from Arup Associates's project material on Ropemaker Place.

6 On component level many façade products exist as simple standardised plates or sheets with or without matching systems for attachment. Even though standardisation level might be high they oppositely often represent low preparation and service levels.

7 Available online at http://www.swifthorsman.co.uk/companies/swift-horsman/products/podwall (accessed 1 April 2011). See also 'Product catalogue', Ch. 7.

8 On the Danish market NCC Danmark recently lauched a configurable installation shaft for residential construction. The product has also been adapted to a pharmatech project. See 'Product catalogue', Ch. 7.

9 See 'Introduction'.

10 These three dimensions of *integrated complexity* are presented in the 'Architectural systems terminology', Ch. 5.

11 See 'Model presentation', Ch. 9.

Part IV

Reflection

14 Findings

Discussion of perspectives of system structure and use of the model

This book has as the main contribution to knowledge suggested the introduction and use 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 principal and essential outcome has been the elaboration of an analytical tool in the form of a *system structure model* that seeks on the one hand to strategically grasp and on the other hand to make it possible to practically work with system structures as part of architectural design. Such endeavour has roots in the main question of the book about bridging an 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.[1] Although this split between idea and execution historically, as indicated in the theoretical exploration of the book, can be traced all the way back to the Renaissance,[2] the pronounced specialisation during the industrial era as well as the recently emerging and fast-developing information technology have further accentuated this tendency. Architectural design and construction have become a hugely complex matter and fragmentation of the knowledge needed to comply with the task produces risk of incoherent results. On the other hand, this information technology has also strongly enhanced the ability to deal with complexity through data processing in quantities that were unimaginable just a few decades ago. New advanced management tools within all fields based on information technology are introduced on a daily basis and both processing speed and storage capacity are doubled within only a few years – while the devices that run these software based tools gets smaller and smaller. The notion of system structure and the proposed system structure model is *not* an attempt to keep up with this development and follow this track. On a much more basic level, it offers a qualitatively new way to look as this complex reality of construction and architectural design through a different kind of lens that detects and describes coherent wholes of interdependent elements rather than seeking to describe each of these in their outmost detail. In line with the so-called systems sciences the present research rejects the prevalent scientific view that the degree of detail 'automatically' enhances understanding and explanative power. Pivotal in the present research endeavour has been that the concept 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 facilitates discussion about how architectural wholes are appropriately put together as assemblages of what the current and future building industry is capable of producing. Such a systems view has – it has been asserted – the potential of reducing design complexity in focus by enabling more qualified decision-making concerning where to apply the 'precious and limited inventive power' or resources available in a building project.[3]

Furthermore it is asserted that by conceptually as well as practically drawing on existing and emerging *integrated product deliveries* when conceiving and realising buildings, design work – and thus design complexity – can strategically be outsourced from an individual project and be reused over several projects. In the present book this phenomenon has been termed *integrated complexity* and its use and related concepts are considered a second pivotal contribution to knowledge within the field of architectural creation in a contemporary industrialised context. This is not a reinvention of architecture and architectural creation – it is not in itself an attempt to establish a new architectural paradigm and even less a different style. It does however represent a new way to *look* at what is already there – an industrially produced architecture – and argues that this new view and methodological approach can help facilitating a more active practical use of the present and future building industry in order to create *architecture* – not just construction – that is specifically attached to time, place and cultural context – not just the expression of smooth processes or cost efficient solutions. Important to note is that such a systems view is *epistemological* rather than *ontological*: a system such as the proposed system structure with its constituent elements will always be an abstraction chosen or unconsciously adapted with the emphasis on either structural or functional aspects that can be associated with, not identified with the real world physical embodiment of the phenomenon it seeks to describe – in this case buildings or physical structures.

The current chapter should be seen as an attempt first to evaluate on the result of this research endeavour and second as well presenting a selection from the more general findings about industrially produced architecture and construction – which to some extent comprises all architectural creation today. Much of the relevant discussion in this book is located in the earlier chapters of the different parts. Particularly the four case studies contain many points that cannot just be summed up here shortly in any meaningful way.[4] The ambition is, however, that the present chapter should pick up the most important of these in relation to the main question, as referred above, and to the stated goal of the research about proposing 'an analytical structure . . . for clarifying the potential of industrialised construction as positively enabling rather than limiting the architectural solution space'.[5] A hope is that this will invite people to dive deeper into the preceding parts and chapters. Even here, the first two of the following paragraphs concerning the *system structure* *model* and the *integrated complexity* are primary for understanding the main contribution to knowledge of the research. Particular attention is also given to a discussion of the role of the architect in a traditional vs. an industrialised context. Subsequent paragraphs recapitulate the inherent tension between *industrial* and *architectural* expressed in the notion of *flexible solution space* as well as the problem of clearly distinguishing *product, process* and *project* – or the closely related triad of *thought, process* and *matter* which has led to the use of *delivery* as the embracing system entity in the proposed system structure model. The final paragraph points out some of the future perspectives of working with system structures in architectural creation.

The system structure model

So what does the proposed system structure model actually show at the present stage of development? What are its limitations? And can qualitatively (new) knowledge about architecture and architectural creation be produced through development and use of an intermediary model as this system structure model?

Limitations of the model

The model at its present stage is – despite constituting the principal outcome of the research – not meant as definitive in the way that in order to become a directly applicable proactive tool in the process of architectural design it still needs considerable elaboration and preferably more external qualification and further tests. The reiterative abductive nature of its conception dictates continuous successive approximation towards a satisfactory explanation and the model is in this sense only satisfactory seen as a step-on-the-way. Another potentially limiting issue would be whether it would have benefited from being turned into a digital piece of software.[6] Such work lies outside the scope of the present book – a choice that, however, does limit the model's actual capacity for handling real world complex scenarios on a directly operational project level. Still, the model in its present state can be used for analytical purposes as suggested in the previous four case analyses. However, comparability between different system structures is still limited as will be resumed further below.

Chains of physical deliveries as a system view

On the strategic level, the system structure model provides a possible definition of systems in a building as physical systems and their related processes as they are delivered and inserted into a building (as deliveries) which inherently also touches upon the organisational set-up. The coding of the different cases display considerable differences in system structures that can be explained in – or can itself be used to explain – both the different viewpoints chosen for the cases and the different characteristics of the particular projects that have been analysed. The model does have explanative power in this sense and seems to support the value of the notion of system structure as applied to industrialised architecture in particular as well as to architectural creation in general. The case studies generate and facilitate through the model discussions about the way the particular architectural solutions have been conceived and subsequently produced and constructed as buildings and touch important issues about the means of production, the contractual set-up as well as their combination and the resulting pros and cons. The angle and sub-concepts around the system structure seem to provide qualitatively new knowledge in the form of a supplementary systems view on architecture and construction. This view can be used to talk about and regard the process of architectural creation as *chains of (physical) deliveries that are nested into each other on various tiers with different levels of integrated complexity* all ending on the building site where the building is assembled and constructed as combinations of these different integration levels. The model is particularly useful for explaining and analysing industrialised production scenarios that are based on a considerable share of off-site produced products. Integrated product deliveries as a new emerging type of delivery in construction have been described and are in the model clearly distinguished from more conventional material or component deliveries while the idea of integration is nuanced through the three dimensions of preparation, standardisation and service. One of the main points of using and discussing integration in architectural design which is facilitated by the system structure model is in its sense of integrated complexity – that is, the possibility of reducing and handling design complexity in focus. Integrated complexity as the second pivotal conceptual contribution of the research will be discussed further below.

Comparability and objectivity

Important to point out is the fact that the model displays considerable variance in system structures when applied to the different case studies in this book it does not automatically mean that the cases are directly mutually comparable as system structures. Each system structure with its division into a number of deliveries is – at least at the present stage of the model – an interpretation that depends highly on both the particular viewpoint (architect, contractor, manufacturer, etc.) as well as the choice of detail when it comes to, for example, nested subsystems of the more integrated deliveries in the structure. This means that the discussion of a particular system structure presently is mainly project-specific and can be used for a comparison of different possible production scenarios within a project rather than fitting into non-ambiguous universal categories of scenarios to pick from and align along. This is seen, for example, in the Scandi Byg case, where several project changes result in different changes to the system structure that can be compared. On the other hand, the previous establishment of a collection of theoretical scenarios has served as a base for some degree of comparison also between cases particularly when it comes to the contractual issues. Overall contractual issues have considerable influence on the system structure – and for the possibilities of changing a system structure if used as the proactive design tool it potentially could become. All four cases represent different contractual set-ups which have more or less resemblance with one or several of the theoretical scenarios and, as the analyses show, the contractual set-ups can provide for new organisations as well as remedying the traditional organisation that, as pointed out, seems out of step with the current means of production of the building industry. In the case of NCC, the development of a streamlined internal process seems to remove focus from its possible mismatch with external efficiency that through a more appropriate selection of subcontractors perhaps could deliver more integrated solutions thus reducing the need for complex on-site coordination. The Arup case shows a more conscious use of contractual divisions as a driver towards new integrated construction entities but has, with the parallel and relatively opaque work packages, still a distinct trade and process focus that does not necessarily provide for the development of products of a more commoditised character as well as resulting economic and qualitative advantages of enabling a more industrialised approach.[7] This will also be discussed below. The Scandi Byg case, as being seen from the viewpoint of an off-site manufacturer, naturally expresses the wish for industrialised off-site production where the superior (lean production) goal of a steady flow of the production line encourages new ways of balancing bottlenecks and overcapacity through outsourcing and product sale. This can give incentives for development of more clearly delimited and discrete integrated product deliveries made of serially nested subsystems and support the establishment of new market niches. Finally, the KieranTimberlake case shows how the same development can be substantiated ideologically through projects that are on the one hand *discursively* constructed as assemblages of integrated product deliveries and on the other hand *operationally* both makes use of existing as well as seeking to develop new products within this category. As the primary case constituting the initial inspiration – or *abduction* – for the system structure model, this case comes closest to the theoretical scenarios of a *future industrialised architecture* as presented in the model presentation.[8]

Feedback from industrial participants

Direct feedback from the contributors during the case studies has worked as *one* of the means of iteratively modifying the system structure model and the related concepts and thus potentially also for improving its practical applicability. As for the primary case study (at KieranTimberlake), the relatively long and 'stretched' duration of the study has provided the possibility for an extensive but continuous feedback on the initial elaboration of the basic concepts and the earliest abductions of the model. Feedback was received from the various persons involved through the performed interviews, the two formal presentation sessions (kick-off and wrap-up) as well as during informal discussions during the work day. Having a point of departure in KieranTimberlake's own theoretical as well as practical work with supply chains and integrated products in construction,[9] the system structure model (at its early stages) was generally received as relatively easy to understand among most of the people who got involved. Both the idea of enhancing the number of tiers as well as of mirroring the model for displaying disassembly scenarios were considered as useful elaborations of the office's own theoretical work. However, in order to further improve the practical applicability questions were raised about how the model could equally encompass parameters – or *dimensions*! – such as time and economy.

The secondary case studies have, as described, been conducted in a much more condensed format posterior to the primary.[10] In these cases, the model at its stage of development at the time of the studies was presented initially as the author's approach to the main research question and as the suggested way of examining the selected cases. This provided a better initial understanding of what material was needed in order to conduct the analysis. The 'best match' was clearly found in the Scandi Byg case, where the manufacturer's perspective with focus on *production* rather than *construction* made the model an excellent basis for communication during the stay and provided useful feedback concerning the conceptual division lines and overlaps between the different tiers in the model. As for NCC and Arup, the more trade-based system structures – as opposed to more product-based system structures in the former cases – made it harder to get the relevant delivery information and led to the abduction of *parallel* as different from *serial* system structures. The distinction was partly conceived through dialogue with participants concerning available project material. All analyses have passed through review and acceptance by the industrial participants.

Integrated complexity: Reduction of design complexity in focus

As the second main contribution to knowledge, and as stated in the introduction, a main concern in the present book has been the question of handling increased complexity and knowledge fragmentation. The problem of complexity seems to further widen the claimed gap between architectural ideation and the way it is realised thus causing translation problems and incoherence of the final architectural result. The atomistic knowledge paradigm of the dominating scientific tradition has not provided good answers to this problem and clashes with the general integrative character of architectural design concerned with the creation of wholes. The system structure model seeks to introduce a systems view where wholes and relations *between* entities can be considered while (temporarily) disregarding their individual characteristics. Choice of different viewpoints and complexity in focus keeps parts of the model opaque according to the purpose of the modelling. This is necessary in order not to get lost in the abundance of, for example, technical, legislative and economical detail that – although not irrelevant – can blur the conception of the whole and result in sub-optimisation according to more or less arbitrary parameters. The research suggests that fragmented knowledge can be gathered around new – and preferably flexible – constituent elements of construction that are serially nested into gradually more integrated deliveries. In this way a levelled complexity can arise where each nested delivery while contributing to the overall complexity and integration of the whole (building) it forms part of, simultaneously reduces the complexity that is needed to be handled design-wise at the level of the whole. On delivery level this *integrated complexity* has tentatively been expressed along three dimensions of respectively preparation, standardisation and service that can be seen as qualitatively different means of integrating complexity. *Preparation* is close to what often in construction is termed as prefabrication – although here it is more nuanced as various levels that correspond to the different tiers of the system structure model. *Standardisation* integrates complexity through deliberate (or forced) limitation of an otherwise broader solution space while *service* compensates for complex processes of supply, installation or maintenance by including these as integral parts of a delivery.[11] This means that even an only loosely prefabricated delivery can have a relatively high degree of integrated complexity. Acknowledging that products are more than just the physical substance delivered, integrated complexity expressed as a combination of the three dimensions thus gives an overall valuation of the delivery as a commodity. The total integrated complexity value is parallel to what we could call the *degree of commoditisation* of a delivery.

Important to point out here is that the present book does not agitate for a highly commoditised building industry on the building level which, while it would heavily reduce complexity in focus by limiting design choices, would equally reduce the ability to respond to single and context-specific design tasks. Through the levelled integrated complexity of series of nested deliveries an overall context-specific complexity of a unique architectural solution can – if market choices of the subsystems are sufficiently manifold – be created through combinations of existing more or less mass customised products thus combining the advantages of economies of scale with those of economies of scope. The levelled complexity can furthermore provide the basis for industrial ecologies by clearly distributing knowledge (and responsibility) of material cycles over a range of sufficiently simple subsystems and suppliers while maintaining these as discrete (and disassemblable?) elements. However, while common data standards within information technology aim at reducing translation work between systems thus simplifying the process of data processing and facilitating more complex results, the standard and prefabrication attempts in construction has so far mainly simplified the architectural result.[12] These systems have not been made for handling the complexity of unique context-specific solutions – they are not properly translating between systems of thought (ideation) and systems of matter (result) but rather reduce the former to already existing categories (products) of the latter. Like the classification systems in construction introduced in the theoretical part, industrialised construction has tended towards an over determination that freeze the division of constituent elements rather than setting it free through the enhanced capacity of handling complexity by the introduction of a systems view – a general level to mediate between the specific idea and the specific realisation of it. Many new design drivers have joined the cacophony of parameters to consider and integrate such as energy performance, design-for-disassembly, emergy and life-cycle assessment, indoor climate and health or user involvement. All these make obsolete the traditional or fixed divisions into constituent architectural elements by dealing with the overall performance of the whole rather than the constituent parts. If these are to be included in early design phases, oscillation between the whole and (its) flexible constituent parts is necessary. The system structural view and the concept of integrated complexity of wholes potentially provides for such a process.

Bridging the gap

The point furthered here is that we *should* use the existing industry and its products as more active design drivers already from the early design phases. This is not the same as a subsequent translation of an architectural concept into existing standard elements. By thinking up-front how to build but simultaneously – and through the levelled complexity – choosing where to respectively locate design attention and where to maximise integrated complexity through the choice of integrated solutions, the architectural solution space can be negotiated on a project basis while still making use of highly industrialised solutions. Through what has been called *flexible structuration* the system structure model can (potentially) support the elaboration of project-specific balances between opaque highly integrated parallel deliveries, specifically designed or mass customised serial nesting of different subsystems and simple building materials and components delivered directly to and installed on the building site. Again it should be stated that the model in its present state is not a finished design supporting tool. However, even used as the present stage analytical tool it enhances as a minimum the understanding of this interweaving of systems on different integration levels and nuances the stereotypical picture of buildings being either off-site produced (prefabricated) or on-site constructed (traditional construction). Any building – and any of its subsystems or deliveries – is a specific combination of these two poles and the understanding of this can, it is asserted, help bridge the gap between architectural ideation and building production. The idea of integrated complexity as a means of actively controlling this balance and focusing design attention points towards several new roles of the architect. These will be treated in the following paragraph.

The (new) roles of the architect

Drawing on design knowledge and design work already embedded in industrialised systems that are delivered as parts of buildings seem to challenge the traditionally perceived role of the architect as the central 'auteur' in the architectural design process. However, the architect seen as a specifier in detail has perhaps only been present for a short and possibly transitory period of time while moving from established crafts into new integrated but yet more flexible partitions of the deliveries in a building project – the integrated product deliveries as they have been sketched and exemplified in the present book. The traditional crafts embedded huge amounts of (tacit) knowledge of materials and their connections in local vernacular building styles. The internationalisation of building styles and techniques combined with the explosion in the number of available building materials has, as mentioned among other factors, distorted the coherence of these knowledge systems. In this context an industrialised architecture based on knowledge partly embedded in integrated product deliveries as sketched above seems a more plausible path for handling the complexity of contemporary construction and for providing a more holistic approach for creating integrated architectural wholes. Much valuable material knowledge from the crafts (e.g. on material properties and jointing) can and should be reused in industrialised systems but as bits from many disciplines simultaneously in each product.[13] An important issue becomes how to transfer and integrate this often tacit knowledge from crafts to industry – if it is not already lost! This will need further treatment elsewhere.

In the scenario sketched above the architect can still be seen as an important and central, though not exclusive, creator of a building.[14] However, in order to make this creation possible today it is here argued that architects *need* to rely on knowledge integrated in industrialised systems – as they equally relied on knowledge integrated in the crafts. A future industrialised architecture based on assemblages or configurations of discrete integrated product deliveries could represent an opportunity of getting out of the work overload of over-specification and (again) rather concentrate on architectural wholes. Architectural design focus is moved towards interfaces and interaction between systems (performance) rather than the detailed design of the systems themselves. The architect would to some extent, but not solely, become a configuration manager of existing systems. As KieranTimberlake state: architecture is rather the employment of collective than singular intelligence and the architect is (just) one of the stakeholders in a dynamic interplay of forces and competencies. The architect in this role does not represent a detached creative force but work in a team particularly concerned with the creative selection, organisation, integration and articulation of systems.[15]

Architects on various integration levels

But this is not the only possible role of the future architect. As more integrated solutions probably will become commoditised as integrated product deliveries, architects can equally work with or within companies delivering these upstream deliveries – just as industrial designers today work with product development within the product industry. While architects in an architectural office perhaps today would sketch on and even fully design a balcony solution, a bathroom plan and a kitchen layout, this design work could be outsourced to companies specialised in these assemblies or chunks of a building but could still be designed by in-house architects of these companies. Alternatively – and perhaps in some cases more architecturally viably – such in-house architects could be in charge of developing, defining and qualifying the architectural solutions space of such integrated product deliveries thus introducing a system level with a flexible solution space that could be applied for configuration by the architect working with the building as a whole and choosing the particular product as a means of integrating complexity. Even companies delivering further upstream systems such as building materials and components could make use of architects for the development of their products. Such in-house architects could be concerned with product development both concerning the possible preparation for nesting of these deliveries into other industrialised subsystems as well as into final buildings and – as architects – still have the particular training concerned with architectural wholes that makes them capable of qualifying such products beyond their mere technical performance. Although architects today are not only found working in architectural offices, they are only seldom found in such building product companies. Combined with the fact that the architectural office is often one of the smaller stakeholders involved in a building project, this has diminished the overall role of the architect in construction processes whereas large consulting companies with roots in engineering, large turnkey contractors also heavily founded in engineering and construction management, and huge investor and developer companies form the core stakeholders in present day construction projects – at least seen from an economic point of view. If this picture is to change it will probably have to be addressed already at the level of educational training programmes which are today mostly directed towards the traditionally perceived role of the architect as the central 'auteur' of buildings and furthermore often support a generalist approach that excludes early specialisation already at university level. Such a specialisation could broaden out the scope of new roles of the architect and contribute to the development of coherent solutions over several tiers or integration levels and facilitate the active use of such subsystems during the architectural design process. A stance in the present book is that both the 'black-box' design process represented by the traditionally perceived role of the architect as well as the turnkey contractors' traditional internally controlled tender process is problematic for the coherence of the final architectural result. Both can be seen as kinds of sub-optimisation that do not bring in all relevant factors. What Simon (1996) calls 'satisficing' as opposed to optimising, and which is the true goal of architectural design, requires collective intelligence as suggested by KieranTimberlake.

The need for flexible solution space

As it has been shown, in the Renaissance, Alberti pointed out the importance of variety (*varietas*) in architecture.[16] Although he – as did Vitruvius – sought to establish clear guidelines for the design of our built environment, his directions were prescriptions rather than demands; they were not meant to lead to a specific solution but sought to establish a frame within which architectural alternatives should be kept open. Architecture was not to be seen as a free art, but neither was it to become a mechanical application of rules leading directly to a solution. The newly established architectural *createur* extracted and detached from the craftsman was a man of thought and creation – not a technician. Only he could combine (divine) prescriptions and context-specific conditions and requirements thus introducing *concinnitas* into buildings. Although our 'rules' of building today are not ascribed to any divine force but rather have roots in the mechanical sciences and their breakthrough in the nineteenth century, the need for balance between constraining rule application and artistic interpretation and synthesis is basically the same. The negotiation of such a balance becomes even clearer when architecture is partly produced through industrialised means of production. The need for a flexible solution space needs to be (re)considered.

The notion of industrialised architecture should, as stated in the introduction, not be seen as a direct promotion of organisation, processes and results falling within this category as being particularly conducive for the architectural result. Industrialised architecture as it has been treated particularly within the framework of the current book has rather concentrated on providing a critical discussion of developments and tendencies which are already there. As the gap in society in general, in Frampton's Arendt-inspired version, is enhanced between the *what* and the *how* – the thought or idea is removed from the task of its realisation.[17] For architecture this means that its meaning loses the connection to culture and society it earlier had through its physical embodiment in the building. Although pessimistic however, Frampton, as mentioned, sees conscious architectural practice as a potential resistance that can mediate between *work* and *labour* (the *what* and the *how*) by sustaining a combination of rationalised production and more traditional craft-based practice. This is the core message of his so-called *critical regionalism*. Using this idea of a hybrid situation in the present context, an industrialised *architecture* as summarised above could – as opposed to mere industrialised *construction* – represents such a combination of rationalised production and craft-based practice. In other words, in order to become true architecture and (re)claim the connection between thought and process/matter – between idea and its cultural manifestation – an industrialised architecture needs to provide space for this mediation thus resisting 'being totally absorbed by forms of optimised production and consumption' (Frampton in Hays 2000: 359). This somewhat resembles what is tentatively suggested in this book through the concepts of flexible structuration and levelled complexity that by means of industrially produced integrated product deliveries integrate complexity while simultaneously keeping open the possibility to decide where to focus the architectural design attention – or using Chermayeff and Alexander's words: 'just where to apply the precious and limited inventive power'.[18] The industrialised means of production used in the right way, it is here proposed, can actually contribute to the solution of singular and context-specific architectural design tasks by freeing resources and directing design attention towards selected parts of the whole.

For example, when NCC as described in the NCC case study integrates the different roles of architectural designer, technical consultancy and turnkey contracting within one single company it provides a good outset for bringing the idea and its realisation together and in a way bridges the gap that has been pointed out as a main problem in present day architectural creation. Crucial, however, is that the architectural solution space is kept sufficiently flexible and that the architect is constantly able to challenge the highly pragmatic approach of the particular office building concept that obviously has roots in contracting (read: execution) rather than architectural ideation for example. The design work (or thought) should seek to make use of the logic and efficiency of NCC's process system as an active design driver but not become subordinate to it. A company internal system like NCC's produces risk of sub-optimisation both concerning (process) *labour* over (result/idea) *work* as well as concerning company internal over general efficiency.

Product-process-project continuum

The book has in the first place drawn up a theoretical division between systems of thought, process and matter. However, it has also been shown that this distinction is used purely theoretically or *epistemologically* in the sense that it might help to describe different aspects of a continuum while the architectural result or its constituent elements mostly are a mix of all three. The different classification systems introduced in the theoretical part express different attempts to establish clear divisions between processes and products but get into the same problem of distinguishing between a product delivered to a construction project and the work results on the building site implying work processes.[19] A product is, as discussed in the introduction to the different types of integrated product deliveries, not just a physical entity but can equally encompass elements of process (supply, installation, maintenance) and even thought, being all the (design) knowledge integrated into such a product.[20] The system structure model suggested in this book seeks to integrate the three types of systems into one single system entity, the *delivery*. Although in the first place, for simplifying reasons, concentrating on deliveries that contain some kind of physical matter to be inserted into the final building, deliveries without physical content can equally potentially be included into the model. The process software tool, *U_build*, was used as an example that points out a potential need for integrating pure systems of process into the system structure.

Product vs. project (deliveries)

The lines between thought, process and matter become particularly blurred when introducing more complex deliveries as the integrated product deliveries.

As mentioned in the Arup case study, some of the high-end solutions used in the Ropemaker Place building are almost completely bespoke solutions (BSP) although delivered as discrete work packages by a subcontractor specialising in delivering this particular kind of solution. The façade cladding is a prime example where the system level – or commodity aspect – of such a delivery is physically reduced to patented gasket and bracket solutions while procedurally and knowledge-wise drawing heavily on experience from earlier similar deliveries. Such deliveries are equally *projects* in themselves as well as having elements of general *products*. As introduced earlier, such bespoke integrated *product* deliveries should perhaps rather be termed integrated *project* deliveries. However, acknowledging that products equally encompass knowledge and process makes it easier to see deliveries as the façade cladding as a product as well. Using the three dimensions of (complexity) integration from the taxonomy, the high preparation and service level of the façade cladding compensates for the lower standardisation level and the result (the 'sum') still is a relatively high value of total integrated complexity. Another aspect is, as mentioned, that such high-end bespoke solutions very well can turn out to work as the *haute couture* or *Formula 1* of integrated product deliveries thus pointing out new market niches for development of more standardised or mass customised integrated product deliveries. These can be marketed for more mainstream architectural projects and contribute to the provision of a flexible solution space for these kinds of projects by making it possible to focus the limited design attention available on other aspects that perhaps are considered more important in a particular project-specific context. They can reduce complexity in focus without necessarily reducing the complexity of the final result itself by integrating complexity into the (opaque) product solution. The development of such established integrated product deliveries requires engagement from the industry as well as from architects – the latter perhaps, as mentioned above, also operating directly within the industry as integrated product developers.

Off-site fabrication is context specific

An important statement coming out of the present research is that maximising off-site fabrication is not necessarily the same as optimising the use of it. Off-site fabrication – or prefabrication as it is often termed – vs. site-built tends to be regarded as an either/or choice. However, as the previous case analyses show, there are many versions and degrees of such off-site fabrication and any building project is *always* a context-specific combination of off-site and on-site processes. Any product made off-site has at some point to meet the site and here lies some of its complexity.[21] The service dimension of the elaborated taxonomy grasps some of this complexity by showing that integrated service as supply, installation and maintenance (SPL, INS and MNT) equally (to preparation and standardisation) reduce complexity around the application of an integrated product delivery in a specific architectural solution. One could say that while the preparation dimension has to do with the physical interface of the delivery towards its surroundings, the service dimension has to do with the procedural interface of the delivery: is the delivery simply handed over at 'factory gate' or dealer, is it delivered on-site but handed over to an assembler – or is the supplier responsible for the entire installation and perhaps even later servicing? The standardisation dimension has to do with internal organisation of the delivery or a company's production line or product family and can also externally be about interfacing with legislative demands, national or international standards.

By zone and by system – chunks and assemblies

Finding the right interfaces (of constituent elements) and optimising the use of off-site fabrication is a design task in itself and can – as suggested in this book – become an integrated part of the architectural design from early design phases. The system structure model with its different tiers and the individual deliveries with their respective dimensions form (so far) a conceptual framework for the system structure as a complementary design driver – particularly when the design strategy is to move towards a higher degree of off-site produced or integrated product deliveries as theoretically reflected in the scenario of a future industrialised architecture.[22] The system structure model is meant to help reduce complexity in focus rather than augmenting it.

The integrated product deliveries are, as explained in the model presentation, divided into two basic categories each representing a tier in the system structure model: the assemblies and the chunks (respectively tier 2 and tier 1). A fundamental difference between these is that whereas the chunks are always volumetric spatial deliveries thus constituting actual finished space of the final buildings, the assemblies are a singular or an integration of various systems that rather serves these finished spaces; a wall assembly closes and supports, a kitchen assembly provide for cooking, etc. Assemblies are functional 'by system' deliveries whereas chunks are spatial 'by zone' deliveries. In some chunks, such as a bathpod or a lift, 'by zone' and 'by system' widely coincide thus making the system boundary definition clearer than in other cases. Assemblies can form part of the more integrated chunks whereas the opposite is not the case. In some cases, a smaller chunk – such as a bathpod – can form part of a larger chunk such as an entire apartment floor. A single assembly can constitute an entire system such as a one storey staircase but often these 'by system' deliveries are modularised into a number of assemblies and delivered as a kit-of-parts that can be plugged together on-site – or off-site as nested into chunks. However, as partly reflected in the cases, off-site strategies tend to be either 'by system' or 'by zone'. As expressed by the theoretical scenario of *conventional prefabrication* many manufacturers offering off-site solutions maximise off-site fabrication by producing volumetric chunks but these are often produced predominantly as conventional construction under roof where simple building materials and components are joined together by use of manual labour and relatively simple power tools like circular saws and nail guns. Others again produce assemblies such as wall, floor and roof panels, façade systems, finished attics, or installation walls (e.g. Podwall) that are mostly delivered for site installation and only seldom become nested subsystems of the chunks. Exceptions exist and the development described in the Scandi Byg case points towards a more nuanced evaluation and use of the pros and cons of each of these two integrated delivery types and their possible combination as a hybrid strategy of 'by zone' and 'by system' deliveries. Such a strategy in a more elaborated form could, for example, combine relatively simple volumetric chunk frames with modularised system assemblies comprising both local and distributed systems of a building. Another rationale behind a combination of assemblies 'by system' and chunks 'by zone' could, as pointed out in the NCC case, be that when the chunks get bigger and installation 'intensity' per square metre gets relatively lower, tier 2 assemblies can depending on the specific situation be a wiser solution both cost and quality wise.[23]

Higher standardisation level

Off the shelf (OTS) or cut-to-fit (C2F) products are only seldom found on higher integration levels as the integrated product deliveries (assemblies and chunks). The use of more standardised products in general requires earlier integration in the architectural design process in order to avoid expensive on-site adaptation. Particularly standardised versions of the more complex integrated product deliveries will, as mentioned in the KieranTimberlake analyses, often have considerable impact on the selection and location of other elements or features as plan solutions of the rest of the building. If markets are to be created for more standardised integrated product deliveries it calls for changes in the architectural design process as it is practised in most offices. Early procurement where some of the (detail) design work is moved to sub-consultants, suppliers or manufacturers representing such deliveries is a possibility that, however, often is inhibited by the contractual set-up or procurement rules. Early procurement blurs the linear logic of most existing stage models used in the construction sector where conceptual design and design development stages and stakeholders normally are located prior to production and execution stages and stakeholders.[24] Scenarios based on such blurred stages are in this book estimated to potentially benefit hugely from the use of the notion of system structure and a design process supported by a system structure model. The system structure integrates the way the integrated product deliveries and entire buildings are produced and assembled from their constituent elements – subsystems and components – into the way these products and buildings are designed. The system entities are not connected to particular stages of a process model but to tiers (of integration) that rather express their degree of integrated complexity.

Whether using stage models, classification systems, data interchange standards or the suggested concept of system structure it is, as also pointed out in the Arup case, essential to have clearly defined interfaces (between different entities comprising thought, process and matter) in order to know who is doing what. When interfaces are not clearly defined – as they were between the traditional crafts – things fall between stools and the resources used to fix these misfits are most probably out of proportion with the size or amount of what is missing. However, as illustrated in the Scandi Byg case, it is (almost) impossible to plan for any unforeseen problem that can occur – even if the final result is completely defined before the production and/or construction process starts. Solutions and products change, production plans and delivery times are rescheduled and all of this causes changes that can – at least partially – be picked up and visualised by use of a dynamic system structure model.

Parallel and serial structures

Apart from more or less resemblance to the theoretical scenarios introduced in the model presentation, another significant system structural feature has been revealed through the analytical application of the system structure model to the four case studies. While the KieranTimberlake and the Scandi Byg cases display what has been termed as serial system structures, the NCC and the Arup cases rather display what has been termed as parallel system structures. The serial system structure is characterised by a series of upstream subsystems often nested into other more integrated downstream subsystems before these (with varying levels of integration) are installed in the final building. This corresponds closely to the theoretical scenario of *future industrialised architecture*. The parallel system structure on the other hand is characterised by so-called opaque deliveries (called work packages in the Arup cases), where a number of subcontractors deliver finished solutions – often as installed (INS) directly into the final building. The term opaque means that the viewpoint of the system structure analysis does not reveal possible nested subsystems of these deliveries and is rather concerned with the parallel division and coordination of these deliveries on-site. Superficially seen this corresponds to the theoretical scenarios of traditional or contemporary on-site construction thus representing a division along (traditional) crafts or trades that each with their particular tools, materials and processes deliver an often distributed solution in the final building. In both the NCC and the Arup case, this is only partly correct. Several of the old crafts such as plumbing, masonry and carpentry can be found as separate (parallel) deliveries. However, particularly in the Arup case, several of these parallel deliveries also represent new, more performance-based entities such as external cladding, toilet cores, reception desks, house management fit-out or special ceilings that cross over and incorporate elements and processes from several of the traditional trades within one single delivery (or work package). Such deliveries, although their specific internal supply chain and production method remain predominantly opaque, can – as with the tier 1 and tier 2 integrated product deliveries – be seen as highly integrated deliveries that considerably reduce the complexity of the design task by, for example, having clear physical and functional interfaces to other deliveries while internally integrating the coordination of many different materials, tools and processes formerly belonging under traditional crafts distributed as deliveries over the building as a whole. This last special kind of integrated product delivery is tentatively termed a tier 0 integrated product delivery as it is assembled on-site (low preparation level) but still to some extent can be standardised and often represent a high service level, that is, installation (INS) or maintenance (MNT).

The parallel tier 0 integrated product delivery is a different way to comply with the demand of variation while still maintaining a delivery around a clearly defined product – a part of a building – and not as earlier around trade or craft and its related tools and processes. As well as the development of industrialised assemblies and chunks requires engagement from both industry and architects (the latter as specifiers), this is equally the case for this particular strategy of industrialisation. There need to be companies like Arup Associates in collaboration with construction managers like Mace that specify in alternative ways, that do not follow the traditional divisions thus establishing the basis for new more performance based deliveries (or work packages). Working with what Arup themselves term as *total architecture* and being able to exclusively choose high-end projects where they can furthermore do all consultancy work put Arup Associates in a special position for influencing the building industry towards the development of this special kind of integrated product deliveries. The system structure of NCC reflects, as mentioned earlier, a much more traditional division of trades and somehow fixes this craft/trade-based culture among their subcontractors. Their innovation stays company internal and consequently probably has much less impact on the sector as a whole. A weakness of the system structure model in its present state is its inability to show visual difference between on the one hand a predominantly traditional division into parallel deliveries and on the other hand a more innovative division around new more performance based deliveries. The model has to be interpreted in detail in order to make such differences perceivable.

A future industrialised building industry

The point of departure and the main problem treated in this book was an apparent growing gap between how architecture is conceived and how it subsequently is or can be produced. This combined with a pronounced specialisation of the society in general and the construction sector in particular results in fragmentation of knowledge and in problems of handling the increased complexity related to the integration of relevant design knowledge into architectural wholes. Contemporary creation and modification of our built physical environment seem to be lacking adequate tools to handle this integrative task properly. The stance of the present research is that a more systematic and conscious but also critically well-balanced application of industrial logic in construction and architecture potentially can influence the building industry. This requires – it has been argued – that architects more actively use the possibilities of the industry and through the insight in this field can make qualified demands on how the industry should be able to perform in the future.

Inspiration from the product industry

As has been presented in earlier chapters, the product industry has been through a development that could be of inspiration for the building industry. The introduction of modular design and the subsequent forming of modular industrial clusters from the 1970s and on, as described by e.g. Baldwin and Clark, has led to the establishment of completely new industries and products which again subsequently become the building blocks or constituent elements of new integrated products.[25] The microchip and the LED technology could be examples. The building industry has so far only experienced true product development on building material and component level but the appearance of a number of gradually more commoditised integrated product deliveries points towards possible new areas for industrialisation that does not – as the first wave of industrialisation in construction in the 1960s and early 1970s – subordinate architectural creation and inventiveness to the straitjacket of all-encompassing closed industrialised building systems with roots in efficient technical execution and cost optimisation rather than in softer architectural parameters as well-being, comfort, experience and self-realisation. As mentioned earlier, more complex systems as e.g. bathroom pods and façade cladding are beginning to form networks of sub-suppliers but they can so far not be characterised as modular clusters.

An open question – too big for the scope of this monograph to answer – remains whether such a new product-byproduct structure of the built environment can be created to replace the passing traditional trade-by-trade structure of the crafts formerly involved in construction. The issue of creating sufficient market volume for such new products is probably one of the most important obstacles for a further commoditisation of integrated product deliveries today. National and even regional differences of both geographical/ climatic as well as legislative character today seriously limit the possibility of forming stable markets that can provide sufficient critical mass for a true industrialised production. The international 'haute couture' of construction can perhaps to some extent lead the way. Equally, as pointed out in the Arup case, the (trade) origin of a company engaged in development of more integrated product deliveries is not irrelevant. It defines the basic skill-set and somehow even the fundamental mind-set they work from.[26]

System structures

On the operational level, the present monograph has set out to examine how architecture and construction can 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. The system structure model, its systems view and its related concepts constitute the practical contribution in this regard. The scope and the applied methods of the research carried out throughout the research have given opportunity to iteratively test, modify and qualify the model. However, although the explanative power of the system structure model has been substantiated by the case analyses much work still remains in order to make it a fully functional proactive tool for use in the process of architectural design. If the model, as intentioned, should truly bridge the inexpedient distinction between product and process – or even between matter, process and thought – and effectively handle the complexity of a contemporary industrialised architecture, it will probably need extension of the current system boundary definition that as a start and for simplifying reasons has been set to include only deliveries with some kind of physical elements to be inserted in the final building.

Industrial ecology

In the chapter 'Industrial ecology' it is suggested that integrated product deliveries can provide for better controlled material cycles in construction.[27] Through a commoditisation of these more integrated deliveries the information and documentation needed about the building materials applied as well as the establishment of an infrastructure to recollect them into closed material cycles can move from a project level into a product level that as a non-project-specific system level can benefit from economies of scale that do not exist on a project basis for each singular building. The economies of scale – the economic benefit made from repetition – can in the first place make elaboration of such documentation and infrastructure economically plausible. If commoditised integrated product deliveries are furthermore put together by a series of subsystems, a hierarchy of nested deliveries each with their particular material cycles controlled and documented by each (sub)supplier can bring the issue down to a scale that seem manageable. It is however hard to see how such an initiative should come from the industry itself. It will most probably need legislative backup and official national or international support. The construction industry is one of the most resource- and energy-intensive industries – both concerning the production and construction of buildings as well as their later operation. The increasing demand for environmentally sustainable solutions makes it of utmost importance to control resource use and material cycles and here is perhaps the heaviest argument for introducing the system structure as an integrated part of the architectural design process as well as for the design of the following disassembly and recycling of the same system entities. As suggested in the KieranTimberlake case, system structures are equally suited to describe and analyse the disintegration of buildings into their constituent components on various levels of integration reusable in other specific contexts – as materials, as components or as recycled integrated product deliveries.

Notes

1 See ‘Scope’ in Introduction.
2 See second part of ‘Systems in Architectural Theory’, Ch. 1.
3 ‘Precious and limited inventive power’ alludes to the present stage of design as expressed in an initial citation by Chermayeff and Alexander. See ‘Introduction’.
4 See Chapters 10 to 13.
5 See ‘Scope’ in Introduction.
6 Mentioned in ‘Scope’ in Introduction.
7 By opaque is as earlier referred to integrated deliveries where nested upstream deliveries are not visible in the system structure.
8 See ‘Model presentation’, Ch. 9.
9 Ibid.
10 Ibid.
11 Forced standardisation is, for example, building code or established industry standard performances and interfaces. The establishment of standards exclude others and integrate the complexity implied in their definition.
12 See ‘Classification systems in construction’, Ch. 2.
13 The bathpod integrates mason, plumber, electrician, glazier and other traditional and more recent trades into one discrete industrialised delivery.
14 The scenario corresponds to that of a future industrialised architecture presented under theoretical scenarios found in ‘Model presentation’, Ch. 9.
15 See the KieranTimberlake case study, Ch. 10.
16 See ‘Systems in architectural theory’, Ch. 1.
17 Ibid.
18 See introductory citation.
19 See the description of the Omniclass tables 22 and 23, Ch. 2.
20 See ‘From construction of project to production in projects’, Ch. 6.
21 See the KieranTimberlake analysis, Ch. 10.
22 See the theoretical scenarios in ‘Model presentation’, Ch. 9.
23 See the NCC case, Ch. 12.
24 See ‘Classification systems in construction’, Ch. 2.
25 Modular clusters are groups of firms and markets that ‘play host’ to the evolution of a set of modular designs. See ‘Industrial production theory’, Ch. 3.
26 See Arup case, Ch. 13.
27 See ‘Industrial ecology’, Ch. 8.

15 Conclusions

Revisiting main problem, hypotheses and research questions

The previous chapter sought to recapitulate and discuss both the pivotal as well as more secondary findings of the present research. This last chapter is intended 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 the Introduction and in Part I ('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:[1]

> *How can systems thinking help bridge 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 clarify 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 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 multidimensional 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 ideas 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

In Part I – 'System' – four theoretical hypotheses are lined up as derivations of the main question of the research but with regard for the respective fields of exploration corresponding to each of the four first chapters.

The derived hypothesis for the exploration of *architectural theory* was:[2]

> *A gradually growing division has appeared between on the one hand how architecture is conceived as design (conceptual idea and form) and, on the other hand, how it can actually be produced (construction).*

The hypothesis was addressed through the following two research questions:

1 What are the main constituent 'elements' of architecture as expressed in architectural theory?
2 How can the apparent division between design and production/construction be substantiated and explained through architectural theory?

Much of the classical architectural theory such as that of Vitruvius deals with the search for universal laws or guidelines for architecture that can prescribe or suggest a certain combination of its constituent elements. These constituent elements seem up until the Renaissance to form a coherent whole or continuum from idea to realisation. Alberti's building types and elements are still closely connected to their realisation but, however, introduce *angles and lines* as products of thought as opposed to *matter* in the form of building materials. From this point and on conceptual idea/form and construction seem gradually to lose connection. While the former oscillates between pure artistic expression and political ideology, the latter becomes consolidated as a separate discipline expressed in the emergence of engineering and culminates (?) in present-day industrialised construction techniques and concepts like lean construction.

The derived hypothesis for the exploration of *classification systems in construction* was:[3]

> *The growing complexity of construction both as processes and as objects has produced a variety of classification systems that either split up or transcend the traditional crafts.*

The hypothesis was addressed through the following two research questions:

1. How has the construction sector conceptually systemised building processes and/or physical elements in order to facilitate clear interfaces of responsibility between a growing number of stakeholders and reduce the complexity of the construction process?
2. Do classification systems used in the construction sector reduce the complexity from the point of view of the architect and what implication does it have for the architectural result?

Different classification systems in construction have emerged as tools exclusively concerned with the execution of buildings. They seldom – if ever – have roots in architectural ideation and mostly work as posterior translations of architectural projects into construction projects thus rather enhancing than reducing complexity of a design task from the point of view of the architect. Classification systems in construction are mostly nationally based thus mirroring the construction sector in general. The introduction of new IT technology combined with enhanced internationalisation are beginning to trigger universal standards that, however, still rather *classify* (as 'type of') than *identify* (as 'part of') thus often freezing the constituent elements in fixed and interlocked categories of process, products (matter) or organisation (e.g. trades). This seems to work against the development and use of new more *integrated product deliveries* in construction that potentially could integrate complexity thus reducing design complexity in focus in individual construction projects.

For the exploration of *industrial production theory* the derived hypothesis was:[4]

> *Industrialisation within the production industry has moved from standardisation of products towards standardisation of processes thus extending the concept of 'the product' to include processes, techniques and business models that are equally applicable within construction – even when it comes to one-off building projects.*

The hypothesis was addressed through the following research question:

1 Which concepts from industrial production theory are applicable within the context of building projects and architectural design?

While on the one hand the project based construction sector has become more industrialised on the other hand the product industry has directed focus towards standardising processes rather than products. Processes have become products themselves! This enhances potential links between the two fields that intersect in new concepts like mass customisation and configuration. The somewhat – in an architectural context – misleading term of *product architecture* referring to the structural organisation of both physical and non-physical elements seems useful in architectural construction when brought to building *project* level as *system structures* that sustain the whole while simultaneously splitting up this whole into meaningful project-specific constituent elements (products, modules, product platforms, etc.) that can be designed and produced relatively independently, for example, as outsourced. Combined with the more process-oriented concept of *supply chain* and *supply chain management* product architectures/system structures point towards a possible enhanced commoditisation of architectural construction through new splits between a product level of more or less integrated product deliveries (economies of scale) and a project level where these are assembled into unique context-specific buildings (economies of scope).

Finally, for the exploration of *general systems theory* the derived hypothesis was:[5]

> *Widespread specialisation in construction caused by growing complexity has resulted in fragmentation into isolated fields of knowledge and has produced a need for intermediary models capable of grasping relations between these rather than their individual characteristics.*

This hypothesis was addressed through the following research questions:

1 How does (general) systems theory address the balance between specialised knowledge and wholes?
2 How can (general) systems theory point towards answers to the need for an intermediate model that can help combining specialised knowledge (of architectural construction) into coherent wholes?

General systems theory introduces *isomorphism* as a way of conceptualising structural or organisational similarity between systems or coherent wholes with potentially widely different specific content. In architectural construction this can be translated into equal system structures across different projects. On the other hand *equifinality* expresses structural or organisational difference leading to essentially the same system or coherent whole. Here – in architectural construction – different possible system structures (or construction scenarios) lead to equal end results. Furthermore the notion of *holons* as entities being both parts and wholes depending on the (selected) focus represents a useful input for the understanding of how a model of the constituent elements of architectural construction and its entities – such as the elaborated system structure model and appurtenant *deliveries* – can switch level, scale or focus point according to the specific purpose of modelling such a system structure. This *levelled complexity* of the holons – in the model: the deliveries – facilitates what in this book has been termed a *flexible structuration* that coded into a system structure grasps relations between entities (deliveries) of thought, process and/or matter rather than their complex and specialised individual characteristics. These entities span in the system structure model from raw materials over building materials and system components to assemblies and chunks with a high degree of integrated complexity which then culminates in the final building.

Future research and development perspectives

The present research has intentionally operated on three different levels of development:

1 a *methodological level* concerning method in architectural research;
2 a *model development level* concerning the development of the system structure model;
3 a *practical application level* aiming at using the elaborated model for specific analyses of empirical data.

The first and most general is the methodological level. A detailed methodological description and discussion has been omitted in this book. The intention was to contribute to an ongoing discussion and methodological development within architectural (an artistic) research and its relation to practice. Creative knowledge production through use of abductive inference is not new – and abduction is a relatively well-known term within the architectural research community. The present research as inspired by Pierce sought to apply abduction and a sequence of abduction–deduction–induction in a conscious and systematic way which seems to have yielded useful results (Peirce 1994). However, a more thorough examination of the implications of a conscious use of abductive inference for architectural research and knowledge production as well as its relation to the more established forms of inference seems necessary in order to possibly establish a proper (new) research paradigm.

The system structure model has, as dictated by the applied methodology, already been through several iterations of successive approximation thus seeking to qualify the initially abductively inferred version through both deductive inference of theoretical scenarios as well as inductive inference through exposure to real-world phenomena as expressed in the case studies as well as in the practical exploration of the building industry and its products as described in Part II – 'Product'. Although ideally the sequencing back to new abductions of the model was intentioned, the procedure has not always been that straightforward. What hopefully qualifies the model as robust although not definitive is its strong foundation in both theory and practice. However, the model should be seen as an open proposal rather than a finished tool. Future steps will obviously be to discuss and record what it actually shows in practical use and to what extent this gives new insight into both new cases and into the cases that have already been analysed. Relevant here will equally be to understand from a practical point of view what lacks, faults and problems can be pointed out in the current model version. This concerns not the least the use of the *delivery* as the system entity with its different degrees of integrated complexity. The future practical application of the model is evidently closely related to a continued model development and iteration as sketched above. Pivotal for a possible successful implementation of the model as a directly operational tool in architectural practice, contracting firms, and/or building manufacturers seems to be to obtain an enhanced understanding about where complexity – here expressed, for example, through workload and resource use – actually is located in the everyday practice of these companies. In order to make it plausible to integrate the use of the model in practice for more than just test purposes, heavy arguments are needed to make probable that it will actually, as suggested, reduce the complexity of the overall design work to be handled – or at least improve the end result to such a degree that resources can be meaningfully allocated for its use. Here is perhaps one of the keys: the resource aspect in a broad sense. As pointed out earlier, the increasing demand for environmentally sustainable solutions makes it of outmost importance to control resource use and material cycles. This is perhaps the heaviest single argument for introducing the use of system structures 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. As suggested, system structures are equally suited to describe and analyse the disintegration of buildings. If we are to understand and actively work with buildings as series of systems that can both be nested into each other (as integrated complexity) and disintegrated in order to form part of closed material cycles of an industrial ecology, we – and the architectural practice – need operational tools that bridge not only idea and realisation but the idea, the realisation as well as the *afterlife* of our built environment. It is the author's hope that the notion of system structure and future iterations of the thoughts around the proposed system structure model will take hold or inspire in the development of such future operational tools.

SYST-AINABILITY could be a new mantra!

Notes

1 See 'Scope' in Introduction.
2 See 'Systems in architectural theory', Ch. 1.
3 See 'Classification systems in construction', Ch. 2.
4 See 'Industrial production theory', Ch. 3.
5 See 'General systems theory', Ch. 4.

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