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GENERAL SYSTEMS THEORY BASED INTEGRAL DESIGN METHOD

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ABSTRACT
The paper describes the Integral Design method, derived from the Methodical Design method developed at the University of Twente, the Netherlands, in the early seventies for applications in the Mechanical Engineering domain. The basis for the Methodical Design method is a combination of German and Anglo-American design approaches and general system theory. Integral Design method is proposed to help to cope with the growing complexity of building design. The Integral Design method was taught in workshops for professionals to test its value for the Dutch building design practice. This resulted in an Integral Design course which is now part of the permanent professional education program of the Dutch Society of architects. The focus in this paper is on the description of the roots of Integral Design: Methodical design and its relation to general system theory.

Keywords: Integral design, General systems theory, methodical design

1 INTRODUCTION
"Design aims at structuring the known data of nature in a way leading to an effective control of matter in relation to man's need and wants" (Van den Kroonenberg 1978).

This already somewhat dated definition of design by van den Kroonenberg is strongly related to the new definition by Krippendorf (2006): *Design is making sense of things.* This leads to the central theme of this paper: to make sense of design. History is always a good starting point, so to start a short historical overview of design. In the early sixties design became an international concern. The 'Conference on Design Methods' held in London in 1962 is generally regarded as the event which marked design methodology as a subject of enquiry (Jones & Thonley 1963). In the United Kingdom the Feilden Report (Feilden 1963) concluded that design was of paramount importance and asked for more effective design management, more attention to customer requirements and asked for more cooperation in design teams (Blessing 1994). The origins of new design methods in the 1960s were based on the application of 'scientific' methods derived from operational research methods and management decision-making techniques in the 1950s (Cross 2007). The first design methods or methodology books appeared – Asimow (1964), Alexander (1964), Archer (1965), Jones (1970) and French (1971).
However, in the 1970s came the rejection of design methodology by even some of the founding fathers themselves, such as Alexander and Jones. Fundamental issues were raised and design problems were characterized as 'wicked' problems, un-amenable to the techniques of science and engineering. This resulted in a proposal for a new generation of methods by Horst Rittel, moving away from attempts to optimize and towards recognition of satisfactory or appropriate solutions (Simon 1969). Herbert Simon (1969) is regarded as the founding father of 'a science of design' – establishing the foundations which would be 'a body of intellectual thought, analytic, partly formalizable, partly empirical, teachable doctrine about the design process.' There was a desire to 'scientise' design.
In the 1980s engineering design methodology of the systematic variety developed strongly. A series of books on engineering design methods began to appear; Hubka (1980), Pahl and Beitz (1984), Cross (1984) and French (1985). In fact, after the risen doubts of the 1970s, the 1980s saw a period of substantial revival and consolidation of design research. Since then there was a period of expansion through the 1990s right up to day: design as a coherent discipline of study was definitely established in its own right (Cross 2007). Still there is no clear picture (Finger & Dixon 1989, Horváth 2004,

Bayazit 2004) and many models of designing exist (Jones 1970, Cross 1994, Wynn & Clarkson 2005, Pahl et al. 2006). That makes it difficult to choose and implement design models in practice.
A fully proven method, acceptable to all designers and applicable to all design problems, is not available. Still designers in practice have produced many successful products, apparently without using a unified design method. Most of them have developed their own methods, often not even aware that they use them. As the complexity of the design tasks increases design process support is more than welcome. Such a newly developed design method should be an addition to the personal design approach of experienced designers and a good tool to support the education of design to students. It should be an easy method to work with otherwise designers will not use it in practice.
In year 2000, BNA (Society of Dutch Architects), TVVL (Technical Society for Building Services) and TUD(Technische University Delft) started the research project Integral Design. This project primarily aimed at the reduction of failure costs. The idea of the participants was that, by optimising the design process, fewer mistakes will occur and fewer unnecessary costs will arise. The project had to unfold ways to investigate and implement an integral approach for building design. This integral approach encompasses the built environment from initiative to design, construction and real estate management as a seamless whole. This seems to contradict with the subdivision of the construction industry in phases, in which parties operate with opposing interests, resulting in disintegration and waste of time, knowledge and resources. The coordination of various independent phases, scales, decision-makings and disciplines is crucial to the creation of a built environment in which the people concerned feel comfortable. This is the core of the integral approach. Integral design is meant to overcome, during design team cooperation, the difficulties of the complex design tasks through the structures early involvement of consultants. This is achieved by providing methods to communicate the consequences and possibilities of design steps between the different disciplines on areas such as construction, costs, life cycle and indoor climate at early design stages. The aim is to support all disciplines with information about the tasks and decisions of the other disciplines. This will improve understanding of the combined efforts (den Hartog 2003).

2 METHODOLOGY: METHODICAL DESIGN, THE BASIS

A specific design approach was developed at the university of Twente in the Netherlands in the late sixties, formalized in the seventies into 'Methodical Design' (Van den Kroonenberg 1978) and elaborated theoretically by de Boer (1989) and Blessing (1994) Methodical Design is based on the combination of ideas and characteristics of the German design school and the Anglo-American design school.
Most prescriptive German/Swiss models (Matousek 1962, Hansen 1968, Koller 1976, Roth 1972, Hubka 1980, Pahl 1984, Beitz 1985) focus on the design process as executed by the mechanical designer, and on a systematic generation of solutions (from abstract to concrete). They consist of stages leading to the final design concept, and include detailed steps in all the stages of the prescribed design process. These approaches can be characterized as discursive and problem-orientated, i.e. the process of concept generation focuses on abstraction and reconsideration of the problem, rather than on the analysis of the initial product idea. The abstract design problem is transformed into a concrete concept through a stepwise concretization involving functions, physical principles and working principles. The approach could be characterized as process-oriented. Typical example is VDI-2222, the first normalized description of the design process (Blessing 1994).
The English and American approaches of the Anglo-American school (Hall 1962, Asimov 1964, Archer 1965, Greogory 1966, Krick 1969, Jones 1970) generally extend the design models to other parts of the product life-cycle, including the context in which the design process is executed.
When developing his design method van den Kroonenberg took only the most essential elements of the many different design methods that were proposed at that time. He focused on the need for a methodical ordering of the design activities in an overall design framework and looked at the difference between research and design in analogy with a general sytems theory, see figure 1.
With the increasing complexity of technical systems a unified principle for science and a common ground for interdisciplinary relationships needed in the study of complex systems was being sought (Blanchard & Fabrycky 2005). General systems theory was conceived by Ludwig von Bertalanffy in the 1940s to provide a systematic framework for describing general relationships in the natural and the human-made world. Bertalanffy (1956) saw it as a theoretical and methodological program, aimed at

seeking principles common to systems in general that may allow scientists and researchers to think more clearly about the goals of any possible system and about the methods for reaching them.
The problem of communication among the various disciplines involved in the design complex of technical systems results in difficulties to communicate across disciplinary boundaries although the scientific methods used brings similarities between the methods of approach independent of the discipline itself. Concepts from one area seldom carry over to another discipline where they could lead to significant forward progress (Blanchard & Fabrycky 2005).

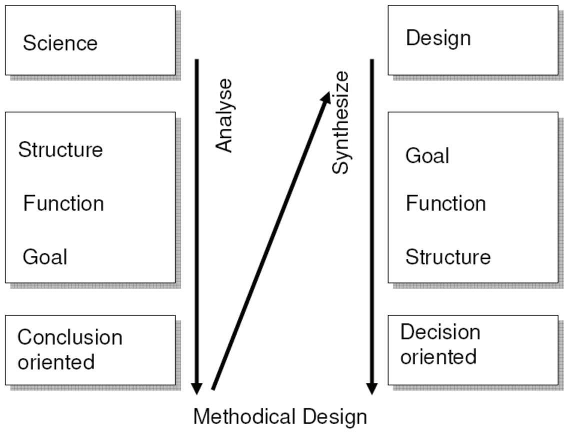

Figure 1. Analogy between science and design

General systems theory is useful for conceptualizing phenomena as design, which did not lend them selves to explanation by mechanistic reductionism of classic science. One approach to a supportive orderly framework is the structuring of a hierarchy of levels of complexity for basic elements in the various fields of inquiry. A hierarchy of levels can lead to a systematic approach to systems that has broad application and was formulated by Boulding (1956).
This framework of levels according to the general systems theory was transformed into the decisions model as presented by Hall (1962), see figure 2.

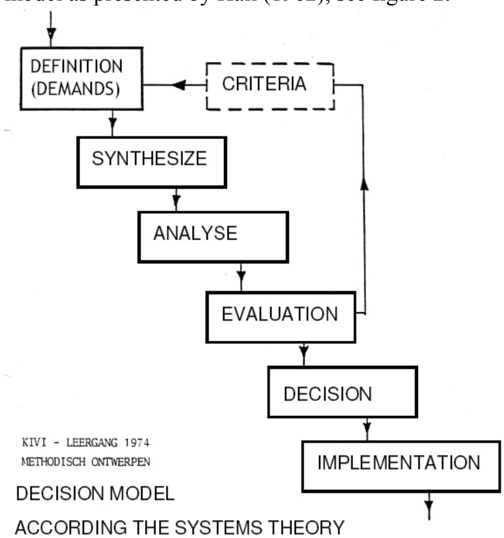

Figure 2. Decision model General Systems theory according to Hall (1962)

Using the analogy with Systems theory van den Kroonenberg thought of a design process as a chain of activities, which starts with an abstract problem and results in a concrete solution. Methodical Design is problem oriented and distinguishes, based on functional hierarchy, various abstractions or complexity levels during different design phase activities. The essential element in this model is the design process. Methodical Design makes it possible to link these levels of abstraction with the stages and steps in the design process itself (Van den Kroonenberg 1992, de Boer 1989, Blessing 1994).
Stages have been defined as a subdivision of the design process based on the state of the product under development. Dividing a design process into stages is important to structure and split the process in easier tasks. The transition between stages provides decision points forcing review and evaluation of the results so far. Stages, therefore, are not only important for efficient progress but also for planning of a project (Eekels 1973).
A step or is a design activity defined as a sub-division of the design process related to the individual problem solving process rather than to the state of the product under development as reflected in the stage division. Compared to stages, activities are specific design steps e.g. generating, synthesizing, selecting and shaping (Blessing 1994). This framework can accommodate the different subjective interpretations of the requirements, inherent to the different members working together on the design process. The design process is divided in three main phases or stages: the problem definition, the selection of the working principle and the detailed design. An important feature in methodical design is this distinction of levels of complexity, see figure 3.

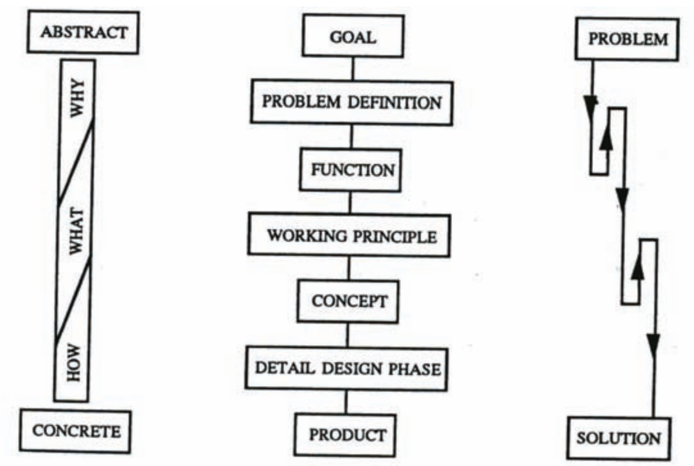

Figure 3. Methodical Design by van den Kroonenberg (Blessing 1994, p.154)

A basic three-step pattern, the so called basic cycle, can be recognized within each phase of the methodical design process: diverge-systemize-converge (de Boer 1989 p 43). In this three-step pattern each step consists of a characteristic operation, which leads to a 'basic design cycle' of: generate-synthesize-decide. When discussing the origin of this step pattern, Van den Kroonenberg refers to the General Systems Theory (de Boer 1989, p43). The framework of the methodical design process phases and the three-step pattern of design activities can be put into a matrix, the design matrix see figure 4.
This way the characteristics of the design process can be split up into those related to: strategies, stages and activities. The strategies are related to the phases of the design process, with their focus on specific aspects of generating, synthesizing, selecting or shaping. The stages are related to the different abstraction levels in which the design process is divided. Methodical design is an approach with typical and exceptional characteristics (Blessing 1994):

1. it is a problem-oriented approach;
2. it is the only model emphasizing the execution of the process on every level of complexity;
3. it is one of the few models explicitly distinguishing between stages and activities.

activity		GENERATE	SYNTHESIZE	DECIDE
problem definition phase	problem	describe needs and influential factors	devise problem descriptions	choose problem description
	requirements	list demands, constraints, wishes, etc.	arrange and quantify list of requirements	decide on program of requirements
	function	derive functions to be fulfilled	compose function block diagrams	choose best function block diagram
working principle phase	working principle	list various working principles	arrange working principles according to relevance	select most feasible working principles
	combination	compose combinations of working princ.	arrange compatible combinations	select most promising combinations
	structure	sketch several structures of combination	vary layout by moving, fusing, etc.	choose most suitable structure
detail design stage	components	list ideas for realization of the elements of the structure	devise different options	choose most suitable option
	make or buy	examine different suppliers & cost	arrange possibilities for make-or-buy	decide on making/buying the components

Figure 4. Design matrix from de Boer 1988 (Blessing 1994, p.157)

3 THEORETICAL CONTEXT

A meta-theoretical framework for design theories is presented by Horváth (2004) to bring epistemological and ontological clarity and also bring in a philosophy of practice. For such framework for design philosophy research he proposes: design science, design history, design policy, design ethics and design axiology, see figure 5.

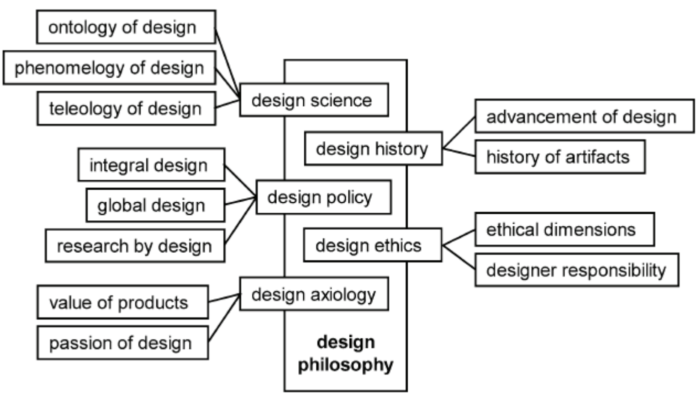

Figure 5. Research in design philosophy by Horváth (2004)

Our interest is on design policy: research concerning the executions of complex design projects, knowledge about planning collaborative design processes, and outsourcing strategies for design projects. Within the field of design policy our focus is on the integral design trajectory to explore the application-independent principles and forms of current implementation of a majority of product development activities. The methodical design process of van den Kroonenberg is such a framework application-independent principle with its connection to the general system theory.

4 EXTENSION TO INTEGRAL DESIGN

A framework of application-independent principle is the basic three-step pattern (generate, synthesize and decide), combined with the 3 different design process phases that can be recognized within the Methodical Design process. The concept of open system in the domain of General System Theory, as it was developed and employed by Ludwig von Bertalanffy (1976), means to think interaction in every aspect of life and also in every aspect of humankind. As such it is meant as an integral approach in which nothing is lacking. When essential factors are disregarded, or are not recognized, the operation of the system risks to be wrong or sub optimized. It could be said that the same thing applies to the design of buildings, where the aim is to find ways to incorporate all relevant knowledge from the involved disciplines in order to get integral results. As decisions about the results of the different design steps determine whether or not all aspects are dealt with, decisions are essential for the integrality of the approach. The basic three-step cycle of methodical design is extended by us to stress the importance of the decision making in the design process. The steps are confirm to the universal description of the design process steps from the general system theory, see figure 6.

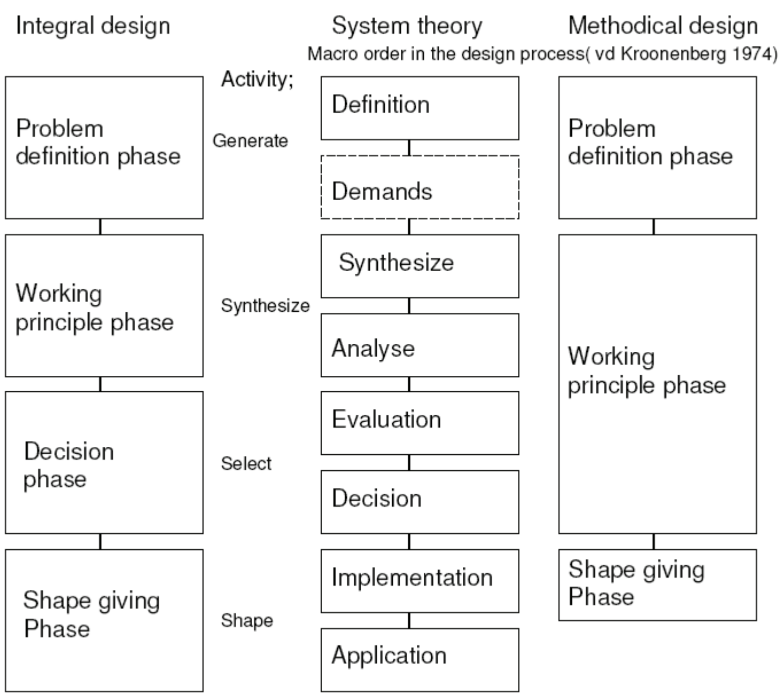

Figure 6. Comparison between system theory steps (design activities) and methodical design by van den Kroonenberg (1974) and integral design

The design matrix represents the recursion of the design steps, the three-step cycle (generate, synthesize, shape) of a design process from high abstraction level to lower abstraction levels during the different design process stages. This design method, familiar in the Netherlands, (Blessing 1994) was extended into an integral design model by us by adding an evaluation step. Thus, a distinctive feature of the integral design model is the four-step pattern of activities (generating, synthesizing, selecting and shaping, see figure 7).

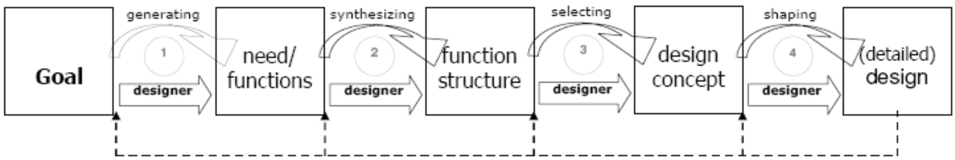

Figure 7. The four-step pattern of Integral Design with possible iteration loops

In contrast to other familiar models e.g. the basic design cycle of Roozenburg and Eekels, 1995 (analysis, synthesis, simulation, evaluation and decision), the ID model differs in its implementation and shaping of the design into a lower level of abstraction, and as such it places focus on the connection between the horizontal dimension and the vertical dimension of the design model. As such, the design process becomes more transparent, and this transparency increases the possibility to reach synergy between the different disciplines and/or designers involved in the design process.

On each level of abstraction the different steps can be described, see figure 8 for the example of the design steps in the mechanical engineering domain.

Throughout the different levels of abstraction the description of the design gradually becomes more detailed. The methodical design process therefore describes the path from an abstract problem to a solution. Though the path is described there is no telling what the results will be of the separated design steps, these depend not only on the problem solving capability of the designers involved but also on their creativity.

Design phase activities;steps →

Design focus ↓

Stages	Abstraction level stages	generate	synthesize	select	shape
Problem definition stage *Focus Problem*	Need	Descripe needs goals etc.	Compose problem description	Select problem description	Task to fulfill
	Design problem	List demands, requirements, wishes	Structure and quantify list of requirements	Determine programme of requirements	Specification
Functional design stage *Focus Working principle*	Functional specification	Determine functions to be fulfilled	Combine functions to function block diagram	Select best function diagram	Function structure
	Physical solution process	List various physical processes	Arrange according to importance	Select most feasible working principles	Principle solution
Conceptual design stage *Focus evaluation concept*	Module structure	Generate combinations of working principles	Arrange compatible combinations	Select most promising combinations	Structure
	Prototype structure	Sketch lay-out of the selected structure	Vary lay-out by mixing moving fusing etc.	Select preliminary lay-out optimum	Preliminary form
Detail design stage *Focus detail design*	Engineering aspects	Generate different forms	Vary form	Select best form	Definite form
	Material properties	List possible materials	Make alternatives with different materials	Select material	Product

Figure 8. The integral design matrix as an example for the mechanical engineering domain indicating the phases, abstraction levels, focus and steps

The process can be seen as a series of activities with an iterative process step where designers must reconsider decisions about different issues all the time, due to new available information and use different design tools to solve problems or generate possible solution through creativity techniques, see figure 9. Through iteration cycle of interpretation-generation steps the set of design requirements is continuously refined, and with it also the design solution proposals become more concrete.

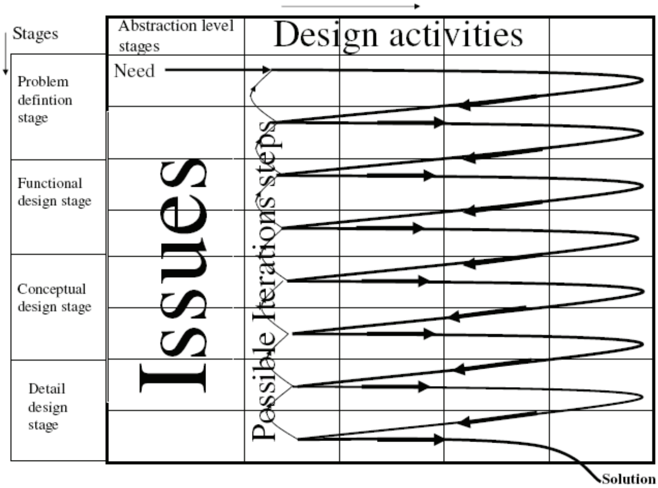

Figure 9: Iterative process of activities concern different issues in the methodical design matrix

An essential difference between the methodical design model and the integral design model is the shaping phase after the decision phase, in which the transformation to a lower level of abstraction takes place: the design object is modified, developed and further shaped. Still as such this in line with a similar approach presented by van den Kroonenberg (1974) himself in a proposal for micro ordering of the basic design process, see fig. 10.

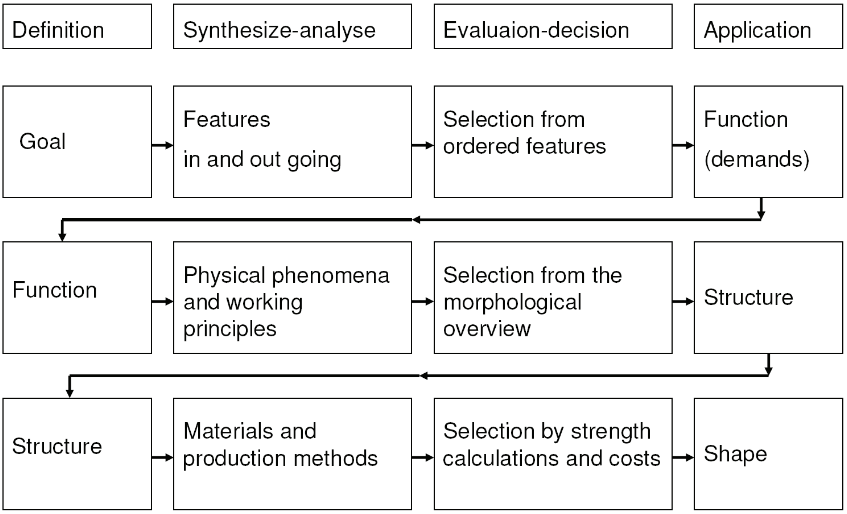

Figure 10. Micro ordering in the basic design process

DISCUSSION

Although the in this paper presented design model is of course only one of the many design models present in the field of design. Various overviews and comparisons can be found throughout the literature. One of the last examples can be seen in Table 1. The column headings used in Table 1 demonstrate the general agreement of design authors on common stages (often synonymously named), comprising the four major design phases (Howard et al 2008): ‘analysis of task’, ‘conceptual design’, ‘embodiment design’ and ‘detailed design’. Preceding these four phases is the ‘establishing a need’ phase, where the driver for the design is recognised. Following the four major phases is the ‘implementation phase’, which is included by several authors, explaining what happens when the final engineering ‘drawings’ and instructions are completed. The stages are usually defined as being executed sequentially (in principle only once), and are related to the states of the product.

In almost all models the stages relate to the design product as a whole. Besides stages, engineering design process can be sub-divided in design activities. A design activity is related to the designer’s problem solving process rather than to the state of the product under development (Blessing 1994, p.31); examples of activities are ‘generating’ and ‘evaluating’.

Models	Establishing a need phase	Analysis of task phase	Conceptual design phase	Embodiment design phase	Detailed design phase	Implementation phase
Booz et al. (1967)	X	New product strategy development	Idea generation / Screening & evaluation	Business analysis	Development / Testing	Commercialisation
Archer (1968)	X	Programming / data collection	Analysis / Synthesis	Development	Communication	X
Svensson (1974)	Need	X	Concepts	Verification / Decisions	X	Manufacture
Wilson (1980)	Societal need	Recognize & formalize / FR's & constraints	Ideate and create	Analyze and/or test	Product, prototype, process	X
Urban and Hauser (1980)	Opportunity identification	Design		Testing		Introduction (launch) / Life cycle management
VDI-2222 (1982)	X	Planning	Conceptual design	Embodiment design	Detail design	X
Hubka and Eder (1982)	X	X	Conceptual design	Lay-out design	Detail design	X
Crawford (1984)	X	Strategic planning	Concept generation	Pre-technical evaluation	Technical development	Commercialisation
Pahl and Beitz (1984)	Task	Clarification of task	Conceptual design	Embodiment design	Detailed design	X
French (1985)	Need	Analysis of problem	Conceptual design	Embodiment of schemes	Detailing	X
Ray (1985)	Recognise problem	Exploration of problem / Define problem	Search for alternative proposals	Predict outcome / Test for feasible alternatives	Judge feasible alternatives / Specify solution	Implement
Cooper (1986)	Ideation	Preliminary investigation	Detailed investigation	Development / Testing & Validation	X	Full production & market launch
Andreasen and Hein (1987)	Recognition of need	Investigation of need	Product principle	Product design	Production preparation	Execution
Pugh (1991)	Market	Specification	Concept design		Detail design	Manufacture / Sell
Hales (1993)	Idea, need, proposal, brief	Task clarification	Conceptual design	Embodiment design	Detail design	X
Baxter (1995)	Assess innovation opportunity	Possible products	Possible concepts	Possible embodiments	Possible details	New product
Ulrich and Eppinger (1995)	X	Strategic planning	Concept development	System-level design	Detail design	Testing & refinement / Production ramp-up
Ullman (1997)	Identify needs / Plan for the design process	Develop engineering specifications	Develop concept	Develop product		X
BS7000 (1997)	Concept	Feasibility	Implementation (or realisation)			Termination
Black (1999)	Brief/concept	Review of ‘state of the art’	Synthesis / Inspiration	Experimentation / Analysis / reflect	Synthesis / Decisions to constraints / Output	X
Cross (2000)	X	Exploration	Generation	Evaluation	Communication	X
Design Council (2006)	Discover	Define	Develop		Deliver	X
Industrial Innovation Process 2006	Mission statement	Market research	Ideas phase	Concept phase	Feasibility Phase	Pre production

Table 1. A comparison of engineering design process models (Howard et al 2008, p.163)

The Integral Design method is based on the methodical design model proposed by Van den Kroonenberg and as such includes a double cycle (Figure 11) linked to the levels of complexity, where all stages and activities are repeated for every product element (Blessing 1994, p.39). Blessing emphasizes that (the sequence of) activities are repeated many times during the design process.

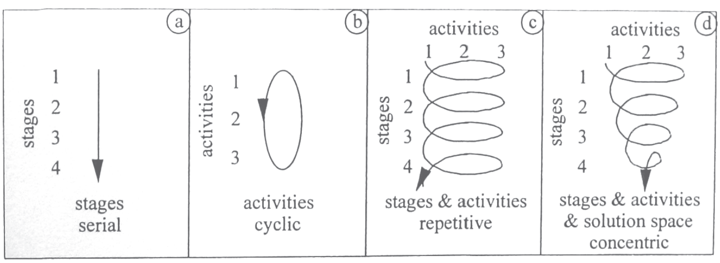

Figure 11. Main process flows design models (Blessing 1994, p.41)

The approach by van den Kroonenberg is similar to the Integrated Product Development (IPD) of Andreasen (Andreasen and Hein 1987, Buur and Andreasen 1989). This design model was chosen because it is one of the few models that explicitly distinguishes between stages and activities, and the only model that emphasises the recurrent execution of the process on every level of complexity (Blessing 1994). In particular, the horizontal dimension is not strongly represented in other familiar design models and thus tends to be forgotten (Roozenburg and Cross 1991, p. 216); "not so much by its authors (see for instance Pahl and Hubka) but by its users and, above all, its critics, leading to faulty arguments and wrong interpretations of the model."

In stead of comparing the integral design model further we focus on the practical application of the method. As that is often the problem of academic design models. Methodical design was although intended as a domain independent design method only rarely used in other domains than (bio)mechanical engineering. Still it is one of the few design methods used by professionals in theDutch industry (Zeiler 2007). The idea of the integral design method was that it should be more suitable for other domains. To test the hypotheses the integral design method was used in the building design domain, were the complexity of design processes demanded new design approaches (Zeiler 2005). The Integral Design method was used by the design of a office building in the Netherlands, and the project was awarded the status of IFD demonstration project (Savanovic et al. 2005). After is successful experiment in practice, the integral design method was used as a theoretical basis for structuring the design process in the Integral design project of the Dutch Technical Association of Building Services Engineers (TVVL), Royal Society of Dutch Architects (BNA) and Technische Universiteit Delft (TUD). If we consider relations between different disciplines within building design teams as a form of social system, rather than describing design as "fundamentally a social process" (Bucciarelli 1994), the question is if activities concerning design processes can be imposed on 'design-team-system' through external (meaning outside elementary design actions) management. Certain approaches suggest that each system, if we look at its constituting entities, can only organize itself (Baets 2006) – resulting in what is called emergent behaviour (Holland 1998). This self-organization is also systems' strongest point: it does not need any complicated prescriptive rules, at least if management is left to the system itself. External intervention is considered contra productive. The organization of building design activities is based on the assumption that all parties have the same notion of building (design) processes, the requirement acknowledged in the Netherlands more than a decade ago by the Dutch knowledge centre for housing and utility construction (Spekkink et al 1994). Based on the above considerations, 'design-team-system' could be structured through self-searching / self-organization.

Based on the integral design method, workshops were organized in which professionals of the mentioned organizations were taught how to use elements of the integral design model in design exercises (Savanovic & Zeiler 2007, Zeiler et al. 2008). The feedback of the professionals was so positive that the workshops were transformed in a design course which has become part of the permanent professional education program of the professional architectural organization since 2007 and is now also offered to building services engineers from the Netherlands.

CONCLUSION

Starting with a high level abstract description of elementary design activities, related to the structure of the general design theory, van den Kroonenberg developed the methodical design method for the mechanical engineering domain. Based on this methodical design method we developed an extended design method: Integral Design. We used the Integral Design method as a multi domain method, by applying the method for building design. The Integral Design method helps to make an abstract description of the building design as a process. Such a description helps to structure the building design process and to support designers in their daily practice. This was tested in workshops for experienced professionals, architects and engineers, and proved to be of value to them.

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