Strojniški vestnik - Journal of Mechanical Engineering 54(2008)6, 385-397
UDC 658.5

Paper received: 28.2.2008
Paper accepted: 15.5.2008

Cognitive Product Development: A Method for Continuous Improvement of Products And Processes

Wim Gielingh
Delft University of Technology, Faculty of Civil Engineering, The Netherlands

In current engineering practice, designers usually start a new project with a blanc sheet of paper or an empty modeling space. As a single designer has not all knowledge about all aspects of the product, the design has to be verified by other experts. The design may have to be changed, is further detailed, again verified and approved, and so on, until it is ready. But only the final product, once it exists, will prove the correctness of the design. Given the complexity of modern industrial products, the intermediate verification and change processes require substantial time. This has a major negative impact on the development time and costs of the product. Cognitive Product Development, as proposed here, approaches design as a scientific learning process. It is based on a well known and successfully applied theory for Cognitive Psychology. In stead of relying solely on the experiences of a single individual, CPD makes the combined knowledge of multiple disciplines, acquired throughout the life of existing products, available through generic design objects. CPD thus approaches design as the configuration of existing and verified knowledge. It is expected that this accelerates the product development process and results in designs of higher quality and reliability without affecting the creative freedom of the designer.

Keywords: product development, cognitive engineering, continuous improvement, parametric modelling

1 INTRODUCTION

1.1 The High Costs and Risks of Product Development

The development of complex systems such as buildings, plants, infrastructures, off-shore structures and aircrafts, has a high risk of budget and time overruns. In the construction sector, for example, budget overruns between 10% and 30% happen frequently. But overruns of 80% or more are not exceptional [9]. Also the aerospace, automotive and railway industries are often plagued by serious budget and time overruns. These costs and risks make many enterprises reluctant with the introduction of new products or the investment in new projects.

Although many different factors may contribute to these overruns, two factors appear to be essential for most cases: (1) problems caused by high complexity, and (2) the unpredictability of consequences of 'new' knowledge.

The complexity of a system can be defined as the total number of interactions or interdependencies between components of a system [13]. Complexity depends on the number of components, but tends to grow more than proportional to this number. Also the number of interaction- or dependency-types may increase complexity. Examples of interaction types are mechanical interaction (such as mechanical fixation), electrical-, chemical-, and control interaction. If a system has n components and i interaction-types, it may have maximally $i \cdot n \cdot (n-1)$ interactions with other components. Complexity can thus be reduced by reducing the number of components or by reducing the number of interactions or dependencies. The latter can be accomplished by modularizing a design such that each module behaves as a 'black box' that has minimum interactions with its environment.

On the other hand, the trend towards 'mass-customization', i.e. the offering of client specific solutions based on a generic design, increases product complexity because designers have to keep all variant-solutions and their consequences in mind.

*Corr. Author's Address: Delft University of Technology, Faculty of Civil Engineering, Section of Building Processes, Stevinweg 1, 2628 CN Delft, The Netherlands, wgielingh@tiscali.nl

A new product is the result of 'new knowledge'. The consequences of this knowledge are often unpredictable. That is why a design has to be verified thoroughly through modeling, analysis, simulation and testing, before the actual product is being realised. For the automotive sector it is estimated that design changes make up 75% of total product development time and costs [1].

Product development may thus be improved in terms of costs, risks and quality if the problems caused by high complexity and the consequences of "new knowledge" can be reduced. This subject will be addressed by combining principles for systems modelling with a theory on cognitive psychology that is generalized and extended for design, engineering and production.

1.2 Origin of This Theory

The methodology that is described in this paper finds its origin in a theory for product modelling developed by the author in the 1980-ies. After several implementations, applications and further refinements it evolved into a theory and methodology for the acquisition, organization and use of product and process knowledge. Milestone publications were: (a) the General AEC Reference Model [3] which became part of the Initial Draft of ISO 10303 STEP; (b) the IMPPACT Reference Model [4], which was implemented for integrated design and manufacturing of ship propellers at LIPS and the design and manufacturing of aircraft components at HAI; (c) the PISA Reference Model [5], which was implemented to support the early design process of cars at BMW; and (d) the Theory of Cognitive Engineering [6] which was partially applied in a large Design-Build-Maintain project in the oil and gas sector. This paper presents a comprehensive summary of the last - most recent - theory.

1.3 Structure of This Paper

This paper starts with an introduction of the Theory of Cognition which is founded on a well known theory for cognitive psychology (chapter 2). Next, this theory is generalized and extended for design, production and product lifecycle support (chapter 3). Chapter 4 discusses in brief a Theory of Systems. It addresses in particular the principles of modularization of systems. Subsequently chapter 5 combines the theories unfolded in 3 and 4 into a theory for cognitive design, production and support of complex systems. Chapter 6 describes one of the cases where these principles are applied: a large design-build-maintain project for the oil and gas sector. Chapter 7, finally, draws conclusions.

2 KNOWLEDGE CREATION AND CONTINUOUS IMPROVEMENT

2.1 Continuous Improvement

Continuous Improvement (CI) is a widely used concept with a variety of meanings. For many it is synonymous to innovation, for others it is a corner stone of total quality management.

CI is a basic element of Lean Manufacturing, where it is known as the *kaizen* principle [16]. In this context CI aims primarily at quality management. It is implemented here as an organizational solution, by making teams of people responsible for improving their own part of the production process.

Bessant and Caffyn [2] define CI as 'an organization-wide process of focused and sustained incremental innovation'. Lindberg and Berger [8] propose a model, identifying five types of CI organization, which is based on two dimensions. The first dimension addresses whether CI is part of ordinary tasks or not, the second makes a distinction between group tasks and individual tasks. In practically all studies, focus is on the human aspect of Continuous Improvement.

2.2 A Theory of the Learning Organization

Also theories about learning organizations are human centered. Probably the most well known one is the SECI model of Nonaka et.al. [11] and [12].

According to this theory, design knowledge within an organization is developed according to a spiraling process that crosses two arrays of apparently opposite values, such as chaos and order, micro and macro, part and whole, implicit and explicit, body and mind, deduction and induction, emotion and logic. According to these authors, the key for successful knowledge management is to manage dialectic thinking in order to resolve apparent conflicts in design objectives.

The spiral develops in an interaction between implicit (i.e. residing in the heads of human individuals) and explicit (i.e. recorded, transferable and shareable) knowledge.

Four stages of knowledge transformation are recognized: Socialization, Externalization, Combination and Internalization, to be abbreviated as SECI.

Socialization is a process in which individual implicit knowledge is transformed into shared implicit knowledge, for example through (informal) meetings, discussions and other forms of human interaction.

Externalization is the expression and/or recording of knowledge with the objective to become a shared resource for the organization.

Combination is a process aiming at unification, integration and/or generalization of individual pieces of shared knowledge, which results in knowledge of higher value for the organization.

Internalization, finally, is the process in which individual members of the organization pick up shared explicit knowledge, for example through reading, learning, training and experiencing.

The process of sharing depends heavily on the existence of a platform of common experiences, values and concepts. Such a platform provides context that is necessary for the understanding of words and gestures. It forms the 'commonality' of a shared domain. This platform is called 'ba' by Shimizu [14]: 'ba' is the Japanese word for 'place' or 'location'. 'Ba' can be a physical or a virtual place, and represents not only a location in space but also a location in time.

Nonaka's theory comprises further the notion of Knowledge Assets (KA's): the different

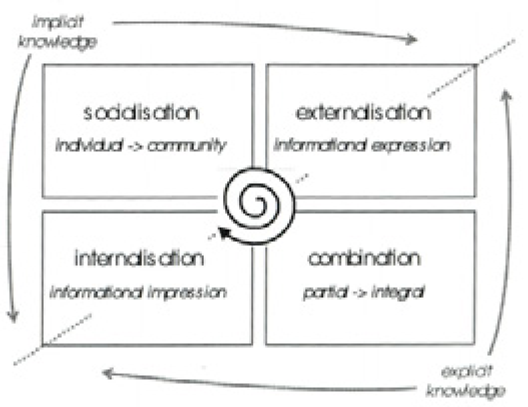

Fig. 1. *The SECI process as proposed by Nonaka et al.*

forms in which knowledge is encapsulated. Examples of KA's are experiences (implicit knowledge developed through practicing), routines (business practices that may exist in implicit or explicit form), concepts (common ideas) and systems (explicit knowledge, recorded in the form of documents, databases and models).

2.3 An Assessment of the SECI Model

Nonaka's theory focuses largely on (a) the interaction of human individuals with other individuals through socialization and (b) the sharing of knowledge in explicit (i.e. documented) form. It does not incorporate feedback from real world experiences. Also, it does not address the possible role of more advanced forms of knowledge representation, such as in the form of product models.

Product models that are used for simulation, such as structural analysis, virtual reality and the digital mock-up, may play an essential role in the learning cycle of a design and engineering team.

Product modelling requires a paradigm shift in industrial production, because its nature is so different from document based working. A product model is a near-to-reality 'image' of a product that may exist on different levels of concreteness and completeness. Product models result in (virtual) experiences for the human beings that work with them. In contrast, documents must be read in order to provide knowledge for the reader and are hence only accessible for those who master the language in which they are written.

Consequently, there is a need to make KM theory consistent with modern scientific principles, including feedback from virtual or real experiences.

2.4 Theory of Cognition

The missing link between KM theory and feedback from reality is provided by a modern theory on cognitive psychology [10]. Neisser defines Cognition as ' the acquisition, organization and use of knowledge'. As his theory originated in the context of psychology, it is focused on the human individual. This part of the theory will be discussed first; in section 3 it will be generalized and adapted to learning organizations for design and engineering.

Experiences in the immediate and remote past influence human cognition. Experiences are memorized and organized by the human brain. Similar experiences confirm and reinforce each other, and result in abstract structures in the human mind that are called *schemata*. For example, a person who has seen dozens of dogs will develop an abstract idea that combines the observed features that all dogs have in common. This abstract idea becomes a *concept* [15]. Concepts may become independent sources of knowledge. By associating concepts with symbols such as words, knowledge can be communicated to other people.

Concepts and conceptual structures have a biological origin: they enable a human being to anticipate and act more effectively in new situations. A child that has touched a hot stove once or twice will associate the two concepts 'stove' and 'hot', and will be more cautious in next encounters with stoves. Similarly, once we have eaten many apples, we associate the shape and colour of apples with their taste: we know that small green apples can be hard and sour, and that yellow or red ones are mostly sweet and soft.

The human senses provide an enormous amount and a continuous stream of sensory stimuli. Only some of these are really of importance. The extraction of useful stimuli from the irrelevant ones is called *perception* [10].

As the life-experiences of individual people differ, the understanding and interpretation of sensory stimuli, in the form of new experiences, will also differ. Hence, two people may act and react differently if they are confronted with one and the same situation. For example, a person who is once attacked by an aggressive dog will have a different concept, and may act differently, than a person who never had such an experience.

From the above it can be concluded that 'old knowledge' plays an essential role in human perception, an thereby affects the creation of 'new knowledge'. Existing knowledge determines how new information is interpreted and valued. The entire process of sensing and the interpretation of sensory stimuli by a human being will be called *impression*.

Learning is not just a passive process that is based on the observation of physical reality. Much can be learned by exploration and experimentation. Baby's learn by touching things, by putting them in their mouth, and by throwing them away. Children learn by playing, which is a combination of action and observation. Action partially affects and changes the physical reality that surrounds us. The whole of activities performed by human beings that affect physical reality will be called *expression*.

The learning process of human individuals can thus be depicted by a circle that is intersected by two orthogonal axes (Fig. 2). The vertical axis represents physical reality (top) versus knowledge about reality (bottom). The horizontal axis represents *impression*, which includes processes such as sensing, observing, interpreting and perceiving (left) and the process of *expression*, which includes various forms of acting (right).

The cognitive process that is depicted in Figure 2 applies to individual people but it can also be applied to organizations, such as industrial enterprises. For enterprises, physical reality may form a market. Market analysis, or the interpretation of client needs, is a form of impression. To serve this market or these clients with products and/or services is a form of expression. Once these products and/or services are consumed or applied, physical reality has changed. These changes may form input for product or process innovation.

The cognitive cycle may also be applied to electronic knowledge processing systems. Knowledge about existing reality may be obtained via input devices, such as sensors or measuring equipment, or through human observations that are documented. And existing reality can be changed through output devices such as CNC machinery, process control systems or documented instructions.

The cognitive cycle forms thus the basis for a theory about learning enterprises and learning

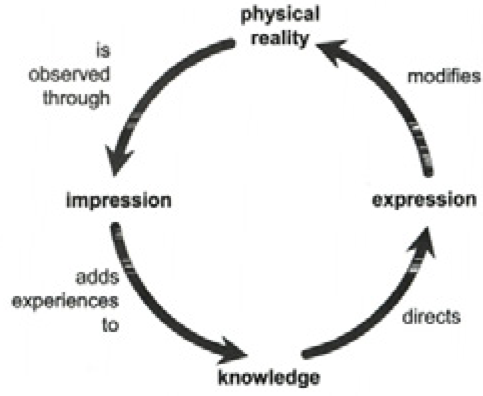

Fig.2. *The Cognitive Cycle*

information systems that, in contrast to Nonaka's theory, involves reality.

3 RETHINKING DESIGN AND PRODUCTION AS A SPECIAL FORM OF COGNITION

Concepts that result from experiences with real phenomena can be analyzed and decomposed into conceptual primitives. These primitives - or features - can be manipulated in the human mind to form new concepts. A simple but illustrative example is the mermaid, which originated in the mind of Hans Christian Andersen. This imaginary creature is partially a girl and partially a fish. The mermaid is an example of an imaginary concept: although mermaids do not exist and cannot be observed, it is 'assembled' from features that can be sensed. As a concept it can also be visualized in the form of a naturalistic expression, such as a painting or a statue.

A new product results also from imagination. Designs of new products are assemblies of features that are extracted from existing reality. These features comprise knowledge about shapes, materials, techniques and technologies, and are manipulated in the mind: they can be resized, reshaped or re-arranged.

If the cognitive cycle is applied to industrial enterprises, then "physical reality" includes physical products, clients and markets, "impression" includes analysis, "knowledge" includes technological and production knowledge as well as design, and "expression" includes production and servicing. The cognitive cycle for product creation is shown in Figure 3.

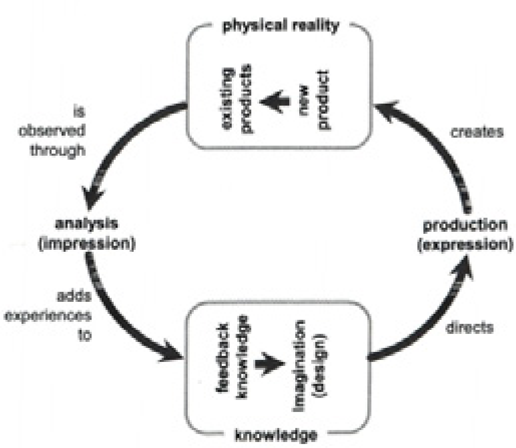

Fig. 3. *The cognitive cycle for product creation*

The design of a new product usually has to be verified before it can be produced. Such a verification can be done by making physical prototypes, or by asking experts to analyze and approve the design. With the advent of CA-technologies, it is now also possible to verify a design in virtual reality through product models and simulation technologies (Fig. 4).

As a model is an abstraction of reality, it is used to check some - but not all - properties of the anticipated product. In early design phases, only a few properties are checked, and the more design progresses into detailed design, the more properties are added.

Hence, the cognitive cycle is not traversed only once for the development of a product, but many times. Each successive traversal of the cognitive loop adds more detail to the product specification, up to a point where sufficient knowledge is acquired so that a safe, error-free production process can be expected, and the resulting product is likely to meet client and market expectations. This iterative process can be depicted by expanding the cognitive cycle into a spiral (Fig. 5).

In this figure, the design process is supposed to start with an initial idea (Product Concept L0), which is modelled and simulated in virtual reality through Model L0, and which is subsequently analyzed. Based on the outcome of this analysis a modified and/or more detailed specification is made (Product Concept Ln), modelled and simulated, and so on. This process ends once the final specification

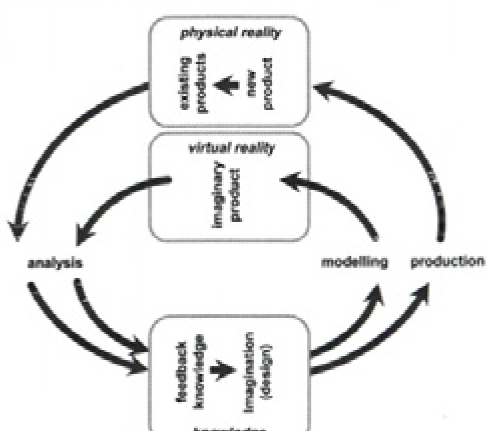

Fig. 4. *To improve speed and quality of a design, physical reality can be simulated through virtual reality as part of the cognitive product development cycle.*

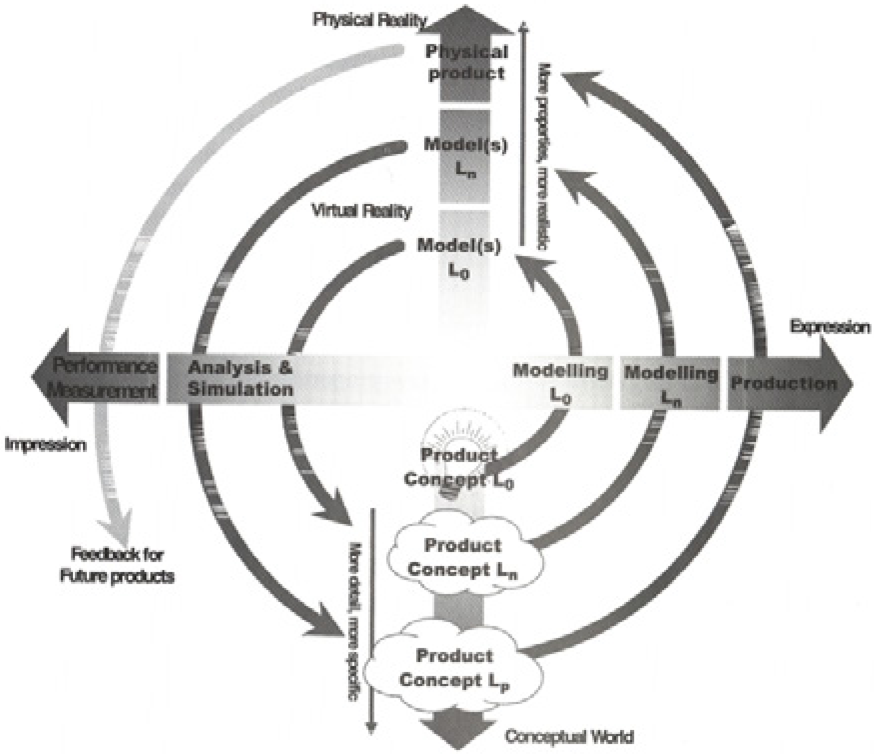

Fig. 5. *A top-down design process can be depicted in the Cognitive Cycle by a spiral*

is ready (Product Concept Lp), after which production can start. Production is the final stage of expression, resulting in the intended physical product.

The Figure 5 shows that the cognitive loop doesn't stop there. The physical product, once in use, can be considered as a prototype for a future product. Knowledge that is acquired from the product in actual use can be very helpful for the creation of new products, for example for analysis and simulation purposes.

A product concept is not limited to a static description of the product. It may also apply to processes, such as production, maintenance and operation processes.

The whole of models, analysis results, performance data and other information forms an interrelated structure of product and process knowledge that can be used as a basis for new designs. This structure will be briefly described in the next chapter.

4 THEORY OF SYSTEMS

Modern products can be seen as complex systems, consisting of objects, where each object interacts with one or more other objects to form a functional whole. Hence, because of their interaction, the whole is more than the sum of objects that form its parts. An object can be a system by itself, in which case it is called a sub-system. Complex systems may have multiple levels of sub- and sub-sub-systems. And as the performance of a product is determined by its behaviour in its environment, the product itself can also be considered as a sub-system.

Systems are often modelled and depicted graphically by means of an inverted tree structure. The top (or root) of this inverted tree depicts the whole; the branches depict the parts; see also Figure 6.

The terms 'whole', 'system', 'sub-system' and 'part' have no absolute meaning. Parts may be seen as 'wholes' or 'systems' in their own right. Any object of which a model is made, is part of a larger whole: buildings are part of cities, while cities are part of regions or nations, and so on. On the other side, even the smallest object that is modelled consists of things that are smaller. Hence, no absolute dividing line can be drawn between the model of a system and the context in which it is placed. For this reason, the presented theory does not use the terms 'system' or 'part'. These terms are only used for explanatory reasons,

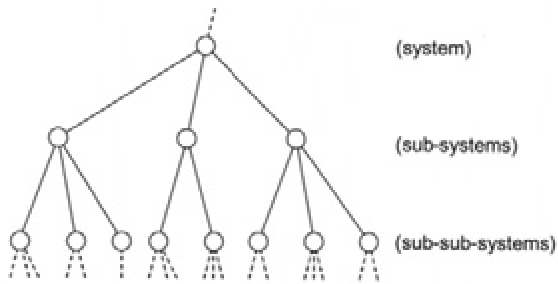

Fig. 6. *System composition can be modelled in the form of an upside-down tree*

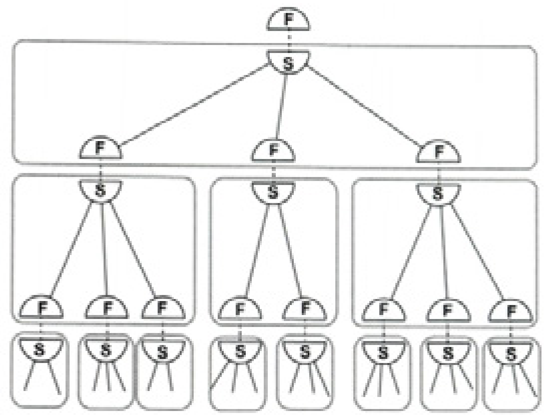

Fig. 7. *Modular system decomposition*

and are therefore placed between parentheses in Figure 6.

The present theory is about knowledge of systems, and considers therefore knowledge as a system by itself. The circles in Figure 6 refer to Units of Knowledge (UoK's). These Units may comprise any kind of knowledge about any subject. For reasons of comprehensibility, Units of Knowledge will also be referred to as 'knowledge objects', or simply 'objects'. A knowledge object may refer by itself to a physical object, a (physical) process, a feature of a physical object, or other phenomena that are subject of interest.

Modern enterprises operate today in collaborative networks. A vehicle, for example, is not designed and built by a single company, but by many companies that together form a supply chain. As a consequence, a part or subsystem within a vehicle may have two intellectual owners: the OEM and the supplier. The OEM defines requirements and boundary conditions for the part or subsystem, while the supplier proposes a solution for it. The supplier may, on his turn, have its own supply-chain.

This idea is depicted in Figure 7 by splitting each circle in two halves. The upper halve represents requirements and boundary conditions, the lower halve the proposed solution. This idea was first proposed as part of the General AEC Reference Model [3], where the upper halve was called 'Functional Unit' and the lower halve 'Technical Solution'.

The importance of this concept is that knowledge about objects in a system can now be modularized, where modules of higher aggregation subsume modules of lower aggregation.

The split between Functional Units and Technical Solutions does not have to be restricted to knowledge transactions between different companies. Also a single company can benefit from the modularization of a system model.

The Functional Units in a system model may form network relations with other Functional Units within the same module, or with other modules on the same level of aggregation.

Each module can be described at two distinctive levels: (1) generic, parametric description, and (2) specific description, where all parameter values are defined or where objects are described in explicit non-parametric form.

The specific description is split into three sub-levels: (2a) Lot (i.e. one or more identical objects), (2b) Individual (a single individual object) and (2c) Occurrence (a moment in the life of an individual).

The modules should not be made too large so that the number of interactions or dependencies inside a module remain limited. Complexity reduction makes it possible to describe all modules with parametric technology. The resulting hierarchy of modules is capable to represent any system, regardless its overall complexity, using parametric technology.

A top-down oriented design process usually stops at a point where pre-existing solutions exist that fulfill the requirements of corresponding Functional Units.

More details about the theory of lifecycle modeling are given in [6] and [7].

5 PRODUCT CREATION AS A COGNITIVE PROCESS

The system model that is described in chapter 4 fits into the cognitive product development process such as described in chapter 3. While a top-down design process progresses, it uncovers several layers of detail, each layer corresponding with a level of the composition hierarchy of the system. This continues until pre-existing solutions are found that meet the requirements of corresponding Functional Units. These final (pre-existing) solutions are depicted by the halve circles marked F at the bottom of this figure.

The system modules that are depicted by rectangles with rounded ends in Figure 7 may also be based on pre-existing solutions. These solutions may be reused in parametric form, so that parameter values still have to be defined, or in explicit, non-parametric form. In either case it will be possible to replace older solutions that were chosen in previous designs by new solutions. This principle is shown in Figure 9.

It shows on the left the configuration hierarchy of the design of an initial product, and on the right of a revised design, possibly of a next version of this product. The solutions colored white are reused without modification. The solutions colored black are new. The solutions colored grey are reused but with some modification. The latter group may make use of the same generic (parametric) template, but with different parameter values.

This idea can be remotely compared with the configuration of a personal computer. At the top-level of a computer model, a computer has a processor, primary memory and secondary memory.

The architecture of a computer is such that for each functional unit different solutions can be installed: a computer may use different processors,

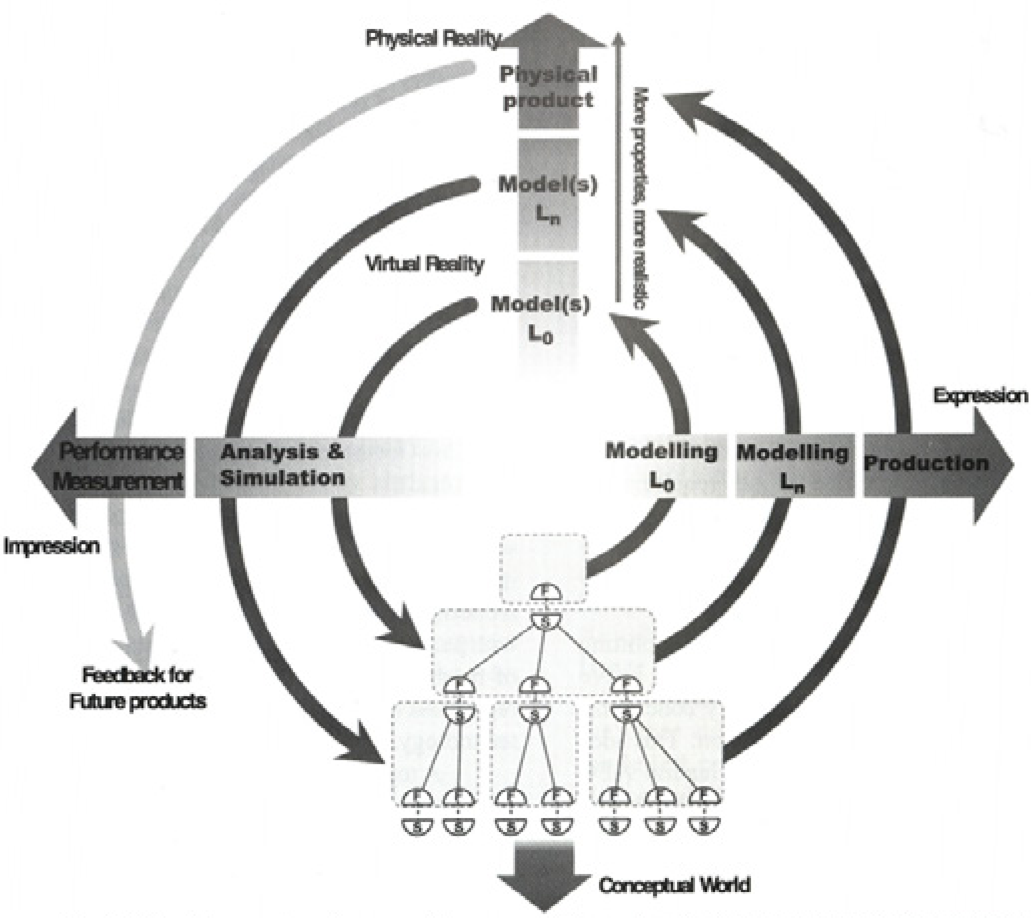

Fig. 8. *Modular system decomposition as an integral part of the cognitive design process*

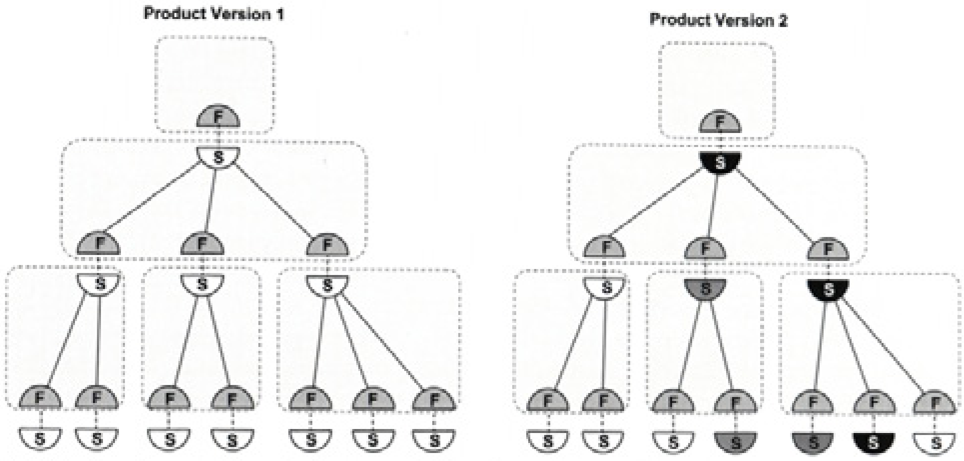

Fig. 9. *Solutions (or specifications) are marked with an S. Reused solutions that are not changed are coloured white, the ones that are changed but based on the same generic template are coloured grey, and fully new solutions are coloured black*

different primary memories and different secondary memories. To replace one by another is often as simple as pulling out one card or device and plugging in another. Although two primary memory cards may have different capacity and be produced by different vendors, the chips or other electronic components may be obtained from the same sub-supplier. Hence, re-use of solutions may occur on any level.

Using this principle, design becomes basically a process of configuring solutions.

If each module – i.e. each solution – is traced from design to subsequent lifecycle phases, lifecycle performance knowledge becomes

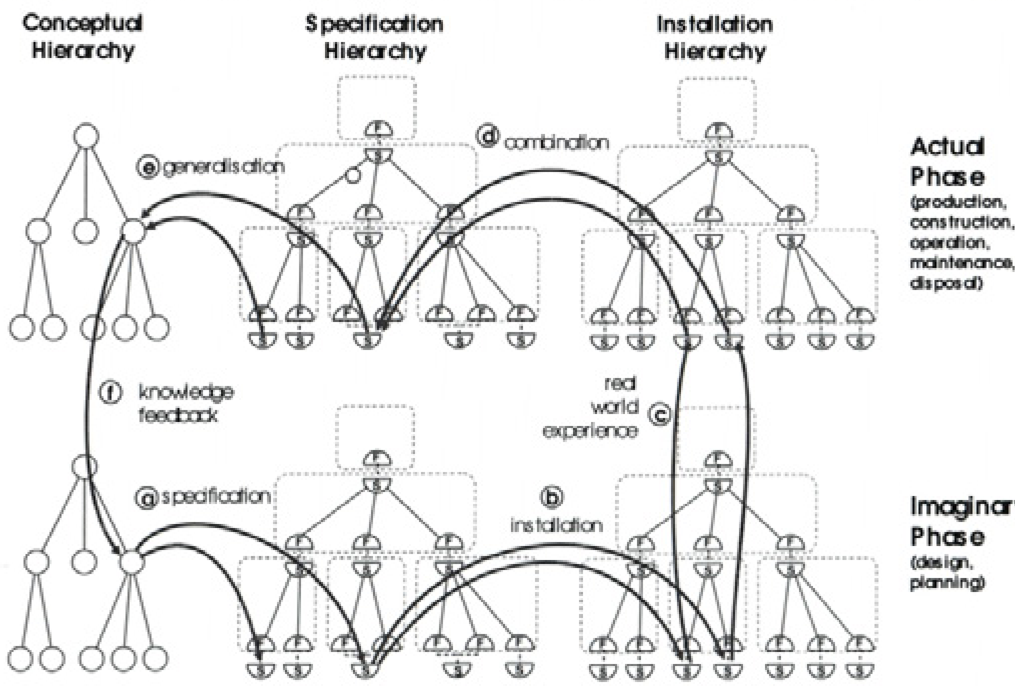

Fig. 10. *The three types of hierarchy, filled with imaginary or actual data, form the basis for cognitive product development. It starts at the lower left corner (a) with the specification of a product using the generic design objects. During and after the realization of the product, real world data are collected, analyzed, combined and generalized, and made available for use and re-use in future projects.*

available for each object. This knowledge will be acquired for individuals at different occurrences, but can be generalized and, after statistical processing, be made available to generic (parametric) descriptions. This means that for all objects marked white or grey in Figure 9 product lifecycle knowledge is available for design. This knowledge can be used for gradual improvement of a design.

The result is that the generic parametric design objects in design systems provide access to a huge amount of lifecycle data associated with previous applications and implementations. The more this system is used, the more experiences become available for design. Design then becomes a cognitive process, where generic, parametric templates built on top of the knowledge acquired by other experts in the product lifecycle play the role of cognitive schemes.

Figure 10 shows horizontally the three types of hierarchy (i.e. the conceptual hierarchy of implicit parametric objects, the specification hierarchy of explicit objects, and the installation hierarchy of individual objects) and vertically actual versus imaginary data.

The cognitive cycle starts with the specification of a new product (10a, lower left corner). This specification can be either in explicit or implicit form. In the latter case, use is made of a generic parametric model. The result is an Imaginary Specification Hierarchy. The individual components are derived from the specification, resulting in an Imaginary Installation Hierarchy (b). After realization of the product, real world experiences are collected first on an individual level (c) and then combined via statistical analysis (d). This knowledge can then be generalized and added to a generic (parametric) product model. From then on it will be available at the start-up of new design projects.

After several traversals the solution base becomes richer and offers increasing levels of historic life-cycle knowledge to the designer.

6 APPLICATIONS

6.1 Early Applications Based on Parametric Technology

Most principles described in this paper have been applied, implemented and improved in projects of different kind and for different industrial sectors, such as mechanical products, ship-building, electronics, automotive and construction.

The first detailed software implementation was for a manufacturer of interior walls in 1982, and is described in some detail in [7].

A second case was the implementation of a feature based, fully integrated CAD/CAM solution for a manufacturer of ship propellers. It is described in [4].

Both cases led to significant efficiency gains in the overall production process. But they lacked knowledge feedback to support the cognitive process such as described in this paper.

6.2 Application in a Large Project for the Oil and Gas Sector

The case that will be described in more detail here did address the latter subject. For practical reasons it was not based on parametric technology but on a data warehouse supported by a PDM system. This case concerns the realization of 29 almost identical plants in a serial construction process.

Below the surface of Groningen, a province in the northern part of the Netherlands, lies one of the largest reservoirs of natural gas in the world. This reservoir is exploited since 1958 and is now more than half empty. As the natural gas-pressure has dropped there was recently a need to install compression units. Also, as the installations were nearing the end of their lifetime and had high operational costs, there was a need to renovate the installations. The company that exploits this gas-reservoir - NAM, a joint venture of Shell and Exxon - decided to contract this huge effort as an integrated Design-Build-Maintain project. The project started in 1996 and has a duration of at least 25 years.

The natural gas is exploited via hundreds of pipelines that reach the surface of the Earth on 29 locations, called clusters, distributed over a large area of land (Fig. 11). Each cluster is equipped with a small plant for the drying and cleaning of the gas, and for the separation and processing of pollutants. An aerial photo of one of these clusters is shown in Figure 12.

The 29 plants cannot be constructed all at once. In the most favorable scheme between 2 and 3 plants per year would be constructed. Consequently, construction of the last plant would

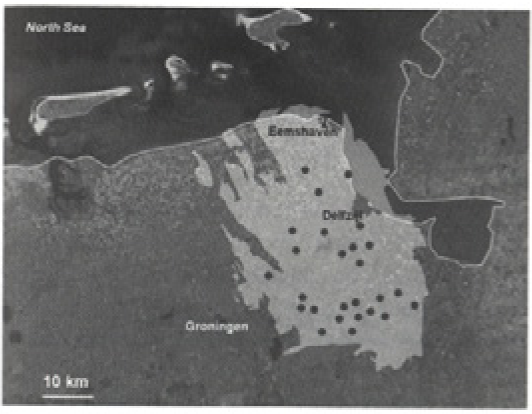

Fig. 11. *Northern part of The Netherlands with the towns Groningen and Delfzijl. The light grey area is the Groningen gas-field. Locations of gas production units (socalled clusters) are marked with dots.*

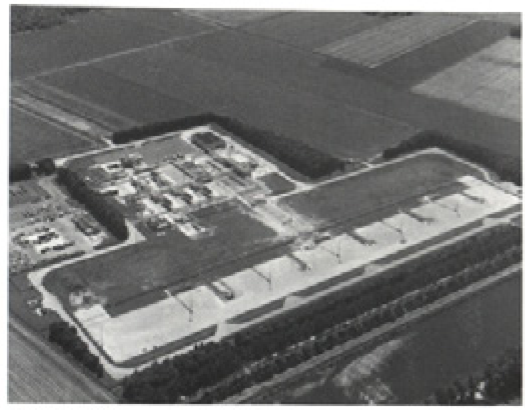

Fig. 12. *Aerial photo of one gas production cluster near a canal. The wells surface at the light-grey rectangular area. The gas is treated in a plant before it is supplied to the international gas distribution network.*

start 12 to 15 years after the first one. In these years, construction-, operation- and maintenance personnel gain a lot of experience that can be used to improve the quality of the design, the quality of processes, and the reduction of overall lifecycle costs.

Furthermore, technology and science will continue to develop. Equipment such as pumps and valves, measuring devices and control systems will be improved. It makes therefore sense to incorporate the potential of new knowledge into a design. But, on the other hand, it may be a disadvantage for operation and maintenance if all plants become different. Hence, it was decided to strive for an optimum between functional uniformity and technical differentiation.

This problem was solved by organizing the design as a modular system, in line with the principles described in this paper. Wherever possible, the same solutions would be chosen for each plant, resulting in uniformity. This made it also possible to track lifecycle experiences, enabling building and maintenance processes to be further optimized. The goal was to build the last plant for 70% of the costs of the first. New knowledge that could improve the design would be incorporated in new modules that replace older modules. Application of modularization principles was essential here: it had to be avoided that a simple design change would propagate too far in other places of a design.

An important tool for the realization of this concept was the development of the knowledge feedback system, see Figure 14. Knowledge created in each process would be used by that process for continuous improvement. But this knowledge also had to be made available to the design and planning disciplines, so that design and planning could be further optimized. The latter is also called front loading.

Three types of data and knowledge sources are identified; see also Figure 13. The first is automated data collection from sensors and other equipment in the plant. The second is non-automated data collection such as from inspection reports. Inspection reports are directly entered as data in a computer, such as lap-top or a hand-held device. These two sources of data are still raw and need to be processed before they become useful.

Figure 13 shows that this is a two stage process. Raw data may be analyzed and diagnosed for operational usage. Not all of that data is useful for other purposes. The filtered data are stored for long term data analysis, such as for tactical purposes (maintenance planning and scheduling) and strategic purposes (continuous improvement).

Tactical analysis can be supported by a knowledge system, using rule based inference, while tactical analysis can be supported by data mining technology.

The third source is explicit knowledge recording, such as in the form of idea's and suggestions for improvement.

The various kinds of data and knowledge associated with design modules are stored in a

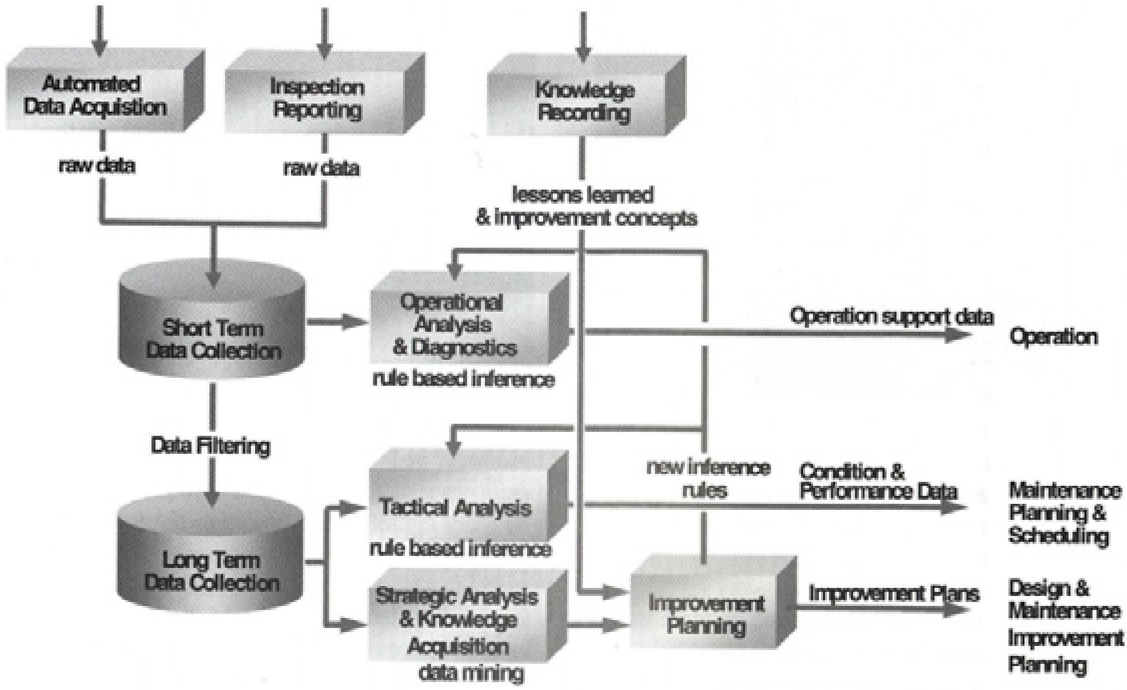

Fig. 13. *The GLT project uses three principal sources of data collection (top) that are analyzed and processed for operational, tactical and strategic usage*

common data warehouse and managed with support of a PDM system.

Apart from the PDM system, a large number of other computer applications are used in this project, ranging from a variety of CA-applications, ERP, maintenance management and operations management systems. The logical knowledge structure as described in this paper affects most – if not all – applications in use.

Practical limitations made it however unviable to change all applications according to the principles outlined in this paper. The reason was that software changes had to be done in a fully operational environment, which would disrupt the ongoing work too much. Therefore the principles were applied as a working practice within the organization, supported by the PDM/WFM software.

Despite this restriction, the principles appear to be highly beneficial for the structuring and organization of knowledge and supported continuous improvement of the design, construction and servicing processes. Benefits result from cost reductions and higher end-user value. Lifecycle costs are estimated to be reduced between 25 and 30%, while the system also contributes to other performance factors such as higher availability, better reliability and increased safety [6].

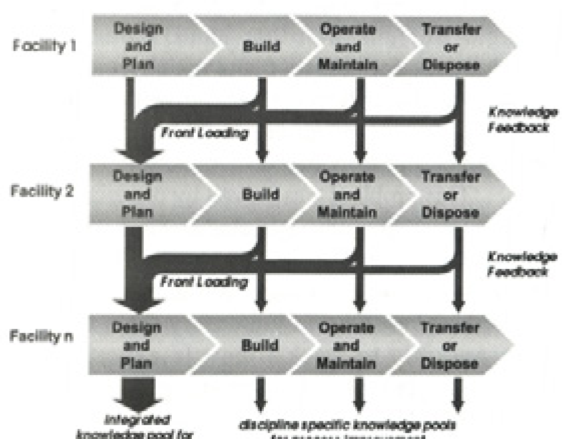

Fig. 14. *The creation of a learning and innovative organization by attaching knowledge created in all phases of the product lifecycle to design objects. This results in discipline specific knowledge pools and an integrated knowledge pool that is available for designers in new projects.*

7 CONCLUSIONS AND RECOMMENDATIONS

The theory and methodology that is described here aims at the reuse and improvement of design and engineering solutions. It supports Continuous Improvement (CI) as a task that is fully integrated with regular business processes. Generic design objects that are available in the design and planning systems give designers and engineers access to actual performance data of these objects in earlier projects. This enables them to learn from the past, even if the designers were not personally involved in these projects.

The improvement process does not only rely on the creation of idea's by people involved in each business process, but makes also use of the analysis of data that are collected automatically via sensors or via inspection reports, or of knowledge records.

Early implementations were based on parametric technology and led to substantial efficiency gains in business processes. Parametric technology offers the possibility to re-use design knowledge even in the context of entirely new specifications. More details about these applications can be found in [7], [4] and [6].

A more recent application based on a PDM based data warehouse closed the cognitive cycle and supports a process of continuous improvement in a large construction project for the oil and gas sector.

Parts of the theory have been published and/ or used for standards for the exchange and sharing of product data, but are in these contexts not presented as a solution for cognitive processes. It could be of interest for users and application vendors to explore this aspect of the presented theory further.

Generic software that supports theory and methodology via parametric technology did exist in the past but was not maintained. Future applications would benefit from redevelopment of this software.

8 REFERENCES

[1] AIAG. *Engineering change management - business case*. AIAG Collaborative Engineering Steering Committee, 2005.

[2] Bessant, J., Caffyn, S. High-involvement innovation through continuous improvement, *Int. J. Technology Management*, vol. 14 (1997), no. 1, p. 7-28.

[3] Gielingh, W.F. *General AEC reference model* (version 4); Document N329 of ISO TC184/ SC4/WG1, Oct. 1988. Published as TNO Report BI-88-150.

[4] Gielingh, W., Suhm, A. IMPPACT reference model for integrated product and process modelling. Springer-Verlag, ISBN 3-540-56150-1 / 0-387-56150-1, 1993.

[5] Gielingh, W., Los, R., Luijten, B., Putten, J.van, Velten, V. The PISA project, a survey on STEP. Aachen: Shaker Verlag, ISBN 3-8265-1118-2, 1996.

[6] Gielingh, W.F. *Improving the performance of construction by the acquisition, organization and use of knowledge*. Delft, p. 372, ISBN 90-810001-1-X, 2005.

[7] Gielingh, W.F. A theory and methodology for the modelling of complex systems. Submitted for publication in the *Journal for IT in Construction*, 2008.

[8] Lindberg, P., Berger, A. Continuous improvement: design, organization and management. *Int. J. Technology Management*, vol. 14 (1997), no. 1, p. 86-101.

[9] Morris, P.W.G., Hough, G.H. *The anatomy of major projects*. John Wiley & Sons, ISBN 0-471-91551-3, 1987.

[10] Neisser, U. Cognition and reality - principles and implications of cognitive psychology, New York, ISBN 0-7167-0477-3, 1976.

[11] Nonaka, I., Byosiere, P., Borucki, C.C., Konno, N. Organizational knowledge creation theory. *International Business Review*, 3 (1994).

[12] Nonaka, I., Toyama, R., Konno, N. SECI, Ba and leadership: a unified model of dynamic knowledge creation. *Long Range Planning*, vol. 33 (2000), no. 1.

[13] Rocha, L. M. Complex systems modeling: using metaphors from nature in simulation and scientific models. *BITS: Computer and Communications News*, Los Alamos National Laboratory, November 1999.

[14] Shimizu, H. Ba principle: new logic for the real-time emergence of information. *Holonics*, 5(1), 1995

[15] Smith, E.E. *Concepts and thought. The psychology of human thought*. Cambridge: Cambridge University press, ISBN 0-521-32229-4, 1988.

[16] Womack, J., Jones, D., Roos, D. *The machine that changed the world*, New York, 1991.