General strategic knowledge models and their interaction with domain-specific knowledge in design

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Abstract

This research concentrates on the modelling of general process knowledge that is understood to be represented as a common strategic knowledge relevant to the various design domains, such as product and information design. Its objective is to illustrate the connections between general knowledge and strategies and how they interact with the domain–specific design knowledge.

The knowledge identification in this research is based on the study of designers' sketches generated during the early stage (conceptual stage) of the design process. The applications of general and goal–limited strategies are analysed and compared within the domain of product design and information design.The findings are used as the basis to infer the models of general design strategic knowledge and its interaction with relevant domain–specific knowledge.

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Introduction

This research is based on the premise that studies of human expertise show that detailed specific knowledge is necessary to solve problems successfully. To relate this to any area of design one has to understand the design activity itself and what constitutes its general strategic knowledge and its domain–specific knowledge. Design can be categorised mainly as an *adaptive expertise* (Popovic 2000) as designers adjust to the design tasks by utilising their knowledge which they adapt to the current tasks and apply during the design process (Suwa, Gero and Purcell 1999).

In his research on creativity in design, Christiaans (1992) identified that for a designer to derive any solution, knowledge of strategies, domain–specific knowledge, and general process knowledge are required (Christiaans 1992). The process of designing asks for generating ideas which lead to new understanding (Greeno 1978). This encompasses: (a) knowledge of implementation methods for generating possible solutions; (b) control knowledge for guiding the search for satisfactory design. It involves knowledge of monitoring and evaluation of one's own design process (Michell 1985). Simon (1984) identified that ill-structured tasks utilise domain–specific knowledge and knowledge for organising the overall solution process. This supports the claim that designers possess knowledge and strategies to execute the tasks and monitor the design process. Love (2002) defines designing as a "non–routine" human activity which he sees as being an essential aspect of processes that lead to a design of an artefact. This supports the notion of design being an "adaptive expertise" within the framework of the "non–routine activity" of designing. It might also help to explain the utilisation and interaction of knowledge between the domains, and within the domain, in order to look for communality between them.

Experience plays an important role in design and problem solving (Visser 1996; Kolodner and Simpson 1986); their research illustrates that experience contributes to problem solving activity and brings modifications to its associated reasoning processes. In cases of successful experience, already-known principles are reinforced and improper ones modified. In some cases "individual experience acts as exemplars upon which to base later decision" (Kolodner and Simpson 1986). Visser (1996) studied the use of "episodic" knowledge, which is "particular experience-linked sources" in design-related problem solving. It was found that a designer used personal and other people's experience during the problem solving activity and that previous experience could help in procedures to be followed or avoided. It could help to predict task outcomes and the steps to be taken in situations where immediate action is required, such as in an emergency. It may help in selecting and applying situational knowledge chunks to a particular task domain. In cases of error, it could suggest an explanation of failures (adapted from Kolodner and Simpson 1986).

Therefore, this research focus is on the strategic knowledge which refers to knowledge or processes and strategies that are utilised during the acquisition or utilisation of knowledge. This knowledge exists in varying degrees of generality or separation from specific domains. These are the procedures that are planned or intentionally included prior to, or during, or after the design task. Strategies can be associated within the domain or across domains.

Strategic and domain–specific knowledge

Knowledge is of major importance for understanding problem solving (Kotovsky and Simon 1990). This is identified by the assumption that human problem solving, in general terms, is described as an "interaction between the problem representation and cognitive action" (Reimann and Chi 1989). That is, problem representation is a mental representation that people have (Kieras and Polson 1985; Young 1981; Hammond at al. 1982; Rouse and Morris 1986).

Domain-specific knowledge is understood to be knowledge in the particular area of expertise. There are many studies done referring to domain-specific knowledge. They occur in well-structured or ill-structured problem domains such as physics and mathematics (Larkin, McDermont, Simon and Simon 1980; Chi, Feltovich and Glaser 1981), design (Akin 1979), and novice and expert user models (Popovic 1998). All these studies show that detailed, specific knowledge is necessary to solve problems successfully. However, a certain amount of domain knowledge is necessary to be able to use strategic knowledge on a domain task.

This research intends to identify general strategic knowledge and how this interacts with the domain– specific knowledge in design. To understand both knowledge categories that are utilised during the design process, relevant knowledge descriptions are presented. The knowledge associated with the design field (product or information design) is called "domain knowledge". It is the knowledge designers have within their particular area of expertise. It is a "segment of an individual's existing conceptual knowledge that is related to a 'specific' area" (Alexander 1992). Domains of expertise differ. Some are in the area of academic research or design while others are driven by principles or by task performance. Tasks can be well-defined or ill-defined. Alexander (1992) argued that this distinction between tasks and "dissimilarity among domain" plays an important part in the interaction of domain knowledge and strategic knowledge. For the purpose of this work, the definition of domain knowledge proposed by Alexander and Judy (1988) is used. The generally accepted classification of domain-specific knowledge consists of four main categories.

These categories are:

- *Declarative knowledge* refers to factual information — knowing what.
- *Procedural knowledge* refers to the compilation of declarative knowledge into functional units — chunks that incorporate domain-specific strategies; knowing how.
- *Conditional (situational)* knowledge refers to understanding where and when to access particular facts or employ particular procedures.
- *Strategic knowledge* refers to knowledge or processes and strategies that are used during acquisition or utilisation of knowledge

The knowledge structure is manifested through the output of the procedure that will generate the appropriate response. Benefits of procedural representation relevant to design are " the ability to encode heuristics and to readily incorporate both knowledge processing considerations within the same structure" (Rumelhart and Norman 1985).

Domain-specific strategies are assumed to be generated from the proceduralisation of declarative knowledge (Chi 1981). Without a body of content knowledge, the existence of domain-specific knowledge is unlikely. Smith and Good (1984) argued that a certain body of relevant knowledge is a prerequisite to completing a task. Effective problem solving depends very much on the content

and structure of knowledge about the particular domain (Greeno 1978; Bhaskar and Simon 1977; Chi, Feltovich and Glaser 1981). Strategies can be associated within the domain or across domains. There are "goal-limited" and "general" strategies. This classification was developed by Pressley et al. and reviewed by Alexander and Judy (1988). Goal-limited strategies include processes that are relevant for task accomplishment. General strategies are applied more on a broader level and they may interact with goal–limited strategies. Alexander and Judy (1988) overviewed some characteristics of the interaction of domain-specific and strategic knowledge from relevant literature. The following three hypotheses of their interaction are found relevant to this research:

1. A foundation of domain-specific knowledge seems requisite to the efficient and effective utilisation of strategic knowledge.
2. Strategic knowledge contributes to the utilisation and acquisition of domain-specific knowledge.
3. Perceiving the relatedness in domain and strategic knowledge across tasks and across domains seems to characterise competent performance.

Alexander and Judy (1988) also revealed differences between the knowledge structures and problem solving procedures of novices and experts. This is supported by the idea that a suitable, organised cognitive structure plays a significant role in retrieving and encoding knowledge relevant to problem solving. Chase and Simon (1973) argued that the main differences among novices, experts, and masters in different domains were related to their immediate access to relevant knowledge.

Problem solving theory and knowledge representation

Reimann and Chi (1989) pointed out that mental representations can be identified on the assumption that human problem solving in general terms can be described as an "interaction between the problem representation and cognitive action" (Reimann and Chi 1989). In other words, the problem representation is a mental representation that designers have of the artifacts they design.

The theory of problem solving has been developed in the context of information processing and cognition (Anderson 1983, 1993; Newell and Simon 1972). This framework gives opportunities to explore hypotheses of cognitive actions and their forms of representation (Greeno and Simon 1988) as they were manifested in the conceptual design stage.

Problem solving theory is based on problem space as a main organisational unit (Newell and Simon, 1972), around which different models and knowledge representational systems have been developed (Card, Moran and Newell 1983; Kieras and Polson 1985; Akin 1979, 1986). These are based on well-defined problem solving tasks where the whole problem space is simple when compared with interactive artifacts (Payne 1987; Carroll 1991).

Any human's task occurs in its context in which people construct its internal representation. Hypotheses about cognitive representations of problems are developed around the idea of problem space (Newell and Simon 1972; Greeno and Simon 1988; Maher at al. 1996; Dorst and Cross 2001).

There are two other characteristics present in problem solving which are semantically rich (Greeno and Simon 1988). These are (a) complexity of problem representation, characterised by complex domain-specific knowledge and (b) domain-specific procedural knowledge that allows designers to accomplish the task. Bhavnani and John (1997) reported Siegler and Jenkins definition of problem solving as any procedure that is “nonobligatory and goal directed". Specific procedures relate to

know-how and when to apply domain-specific knowledge during the problem solving activity such as a specific design task.

Various types of strategies are associated with problem solving. Strategies may be divided into those that apply weak methods and those that use strong methods (Anzai 1991). Weak methods include general methods independent of domain-specific knowledge such as trial-and-error processes and means-end analysis. A person evaluates and compares the current state of information with a goal of the problem (task) to be achieved. This is understood to be general problem solving heuristics used to explore ill-structured domains (Newell and Simon 1972) and they are utilised in many different domains. Successful use of means-ends analysis requires the designers to have some domain-specific knowledge (Alexander and Judy 1988) in order to be able to associate them with the design task procedures.

The key to any problem solving activity is building the representation (Larkin 1985; McDermont and Larkin 1978; Simon and Simon 1978). These authors found that experts spent more time on "qualitative analysis" before they started to solve a problem. Reimann and Chi (1989) summarised the research on the representation of ill-defined problems (social sciences). Experts with the expertise domain (and also non-domain experts) worked on qualitative analysis and formed representations before attempting a solution. They often had better problem representation and therefore better solution outcomes.

Strategic knowledge and design: exploratory study

Two design domains were selected for this exploratory study. They were product design and information design. In both fields, designers were to do the following: (a) produce novel solutions, (b) work with information that is not complete, (c) use drawings and other media as part of problem solving and (d) apply imagination to problem solving (Cross 1995). However, the concentration of this study is on the analysis of visuals that designers use, as a part of problem solving, during the early stage of the design process. Its aim is to identify how strategic knowledge is represented across the domains and within the domain. It is understood that the utilisation of visuals is a very powerful strategy that designers use. This analysis is based on six selected projects (information design and product design) from practice and education. The educational projects were done in a postgraduate program and the students whose work was analysed had three to ten years of practical experience. Overall, the designers' experience was between three to more than twenty years. The early stage of the design process was analysed only. The designers had already dated all visuals during the design process and archived them as project documentation. Each project was analysed from its beginning.

The studies of design emergence (Oxman 2002) demonstrated that a high level domain knowledge of visual form can be seen as cognitive content. In design, word, images and shapes in combination or independently are used to communicate the concepts and represent the understanding of the physical world of artifacts. They are the most common media that designers use to interpret and reformulate the design concepts. The visual language (Horn 1998; Bucciarelli 2002) might be the media "to represent classes and structure of domain knowledge" (Oxman 2002) shown in them. This supports the hypothesis that the images and other visuals used by the designers might convey the strategies and knowledge representation within and across design domains. Therefore the main objective was to identify the following for both domains:

- general strategies (GS)
- goal–limited strategies (GLS)
- domain–specific knowledge (DSK)
- knowledge interaction

The visuals were divided into segments. Each segment was numbered and associated by the date of its occurrence. The coding process of knowledge was repeated three times by the same person with one week's break between codings. The characteristic segments are used as representative examples (Figures 1 to 7).

Information design

Information design was analysed using the early stage of idea generation related to web and publication designs. Each project started with a brief or initiative from the client. However, the designer worked together with the client in order to develop the brief further. The general strategies that applied throughout the projects were strategic identifications of where and how to approach, and work with, a client in order to establish design constraints. The designer applied goal–directed procedures that were planned, intentional, or situational. Figure 1 illustrates her strategic identification of the design direction. The segment selected from the money action planner design (Figure 1) illustrates designer's initial strategy (GS) to understand the clients and their customers' needs utilising general strategy (GS) and goal–limited strategies (GLS) in order to acquire and interpret what they said.

Figure 1: Designer's identification strategies and knowledge representation

Figure 1 shows that goal-limited strategies (GLS) and experiential knowledge are utilised to interpret the needs. For example: in the first column, GLS was to look at what the "first user of a planner" might like to expect as (a) "basic/beginning"; the second column refers to a possible "linear approach" and the third column exhibits "references". Knowledge representations observed in this example are (a) general strategic knowledge (GSK) that interacts with (b) situational strategic knowledge (SSK) and (c) experiential knowledge (EK). General strategic knowledge controls the search for the satisfactory outcome of this segment.

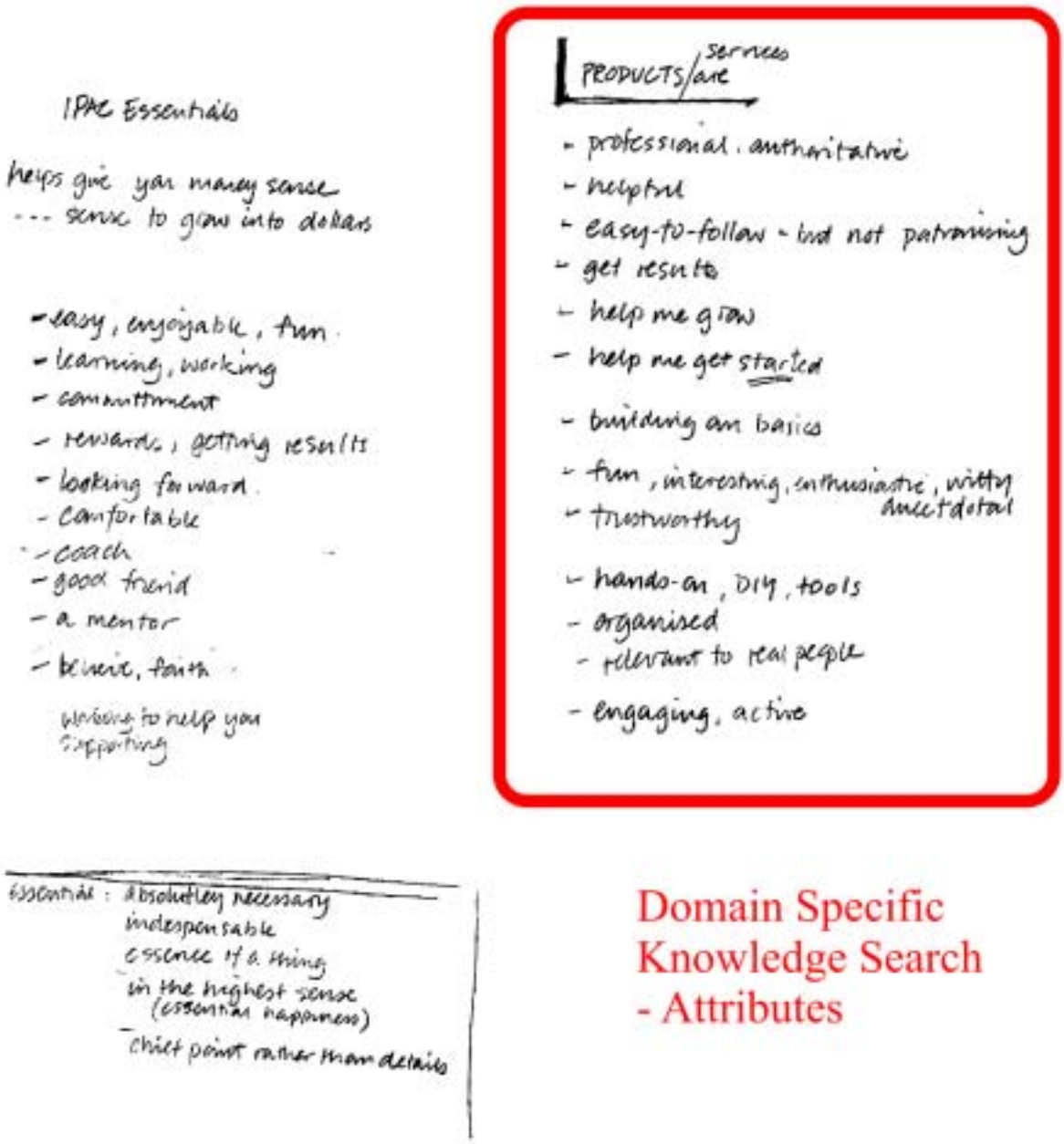

Figure 2: Designer's strategy of domain–specific knowledge acquisition

The illustration in Figure 2 represents the designer's strategy of how to acquire domain–specific knowledge about the client and the users in order to apply these attributes to the design. Further within the project, the designer was searching for domain–specific knowledge of the attributes that might identify human experiences related to particular services and tasks. General strategic knowledge is represented through the process of guiding a search to generate domain–specific knowledge relevant to the task. This supports the view of design as adaptive expertise (Popovic 2000) as the designer generated the knowledge as she responded to the situation within a non–routine activity (Love 2002). Interpretation occurred at the end of the early stage of the design process where all attributes were incorporated into the search for the "best fit". This is demonstrated in the sketches presented in figure 3 where the designer used drawing to generate a solution. Here she interpreted the attributes of the product and services by applying the semantics of – "a helpful hand", "a guiding hand" or "building blocks". The knowledge is represented as general strategic knowledge, situational knowledge, and domain–specific knowledge. The designer's manipulation of images and their transformation (Figure 3) might be controlled by general strategic knowledge that

guides the search for satisfactory design that is supported by domain–specific knowledge (Alexander and Judy 1988; Oxman 2002).

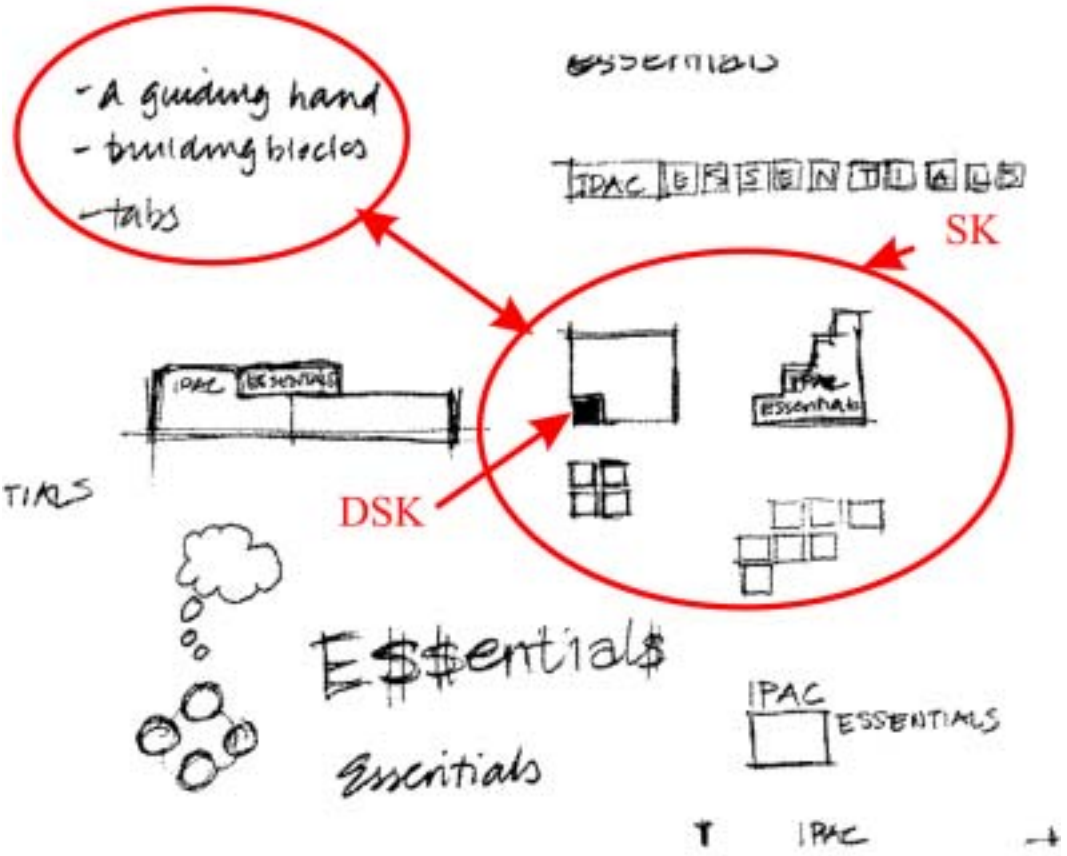

Figure 3: Manipulation of images and their transformation

Segment in figure 4 illustrates sketches for the web pages for a petrol company. Each web page design is driven by the goal-limited strategies (GLS) in reference to the information they have to display, for example: "welcome" or "set up your order". Lines (textual information) or shapes (web "window") and the division of the web page into activity/interact zone and execution area illustrate evidence of domain-specific knowledge (DSK). The left side of each page has the company name and relevant information. Strategic knowledge representation was evident from the consistency in design of each individual web page.

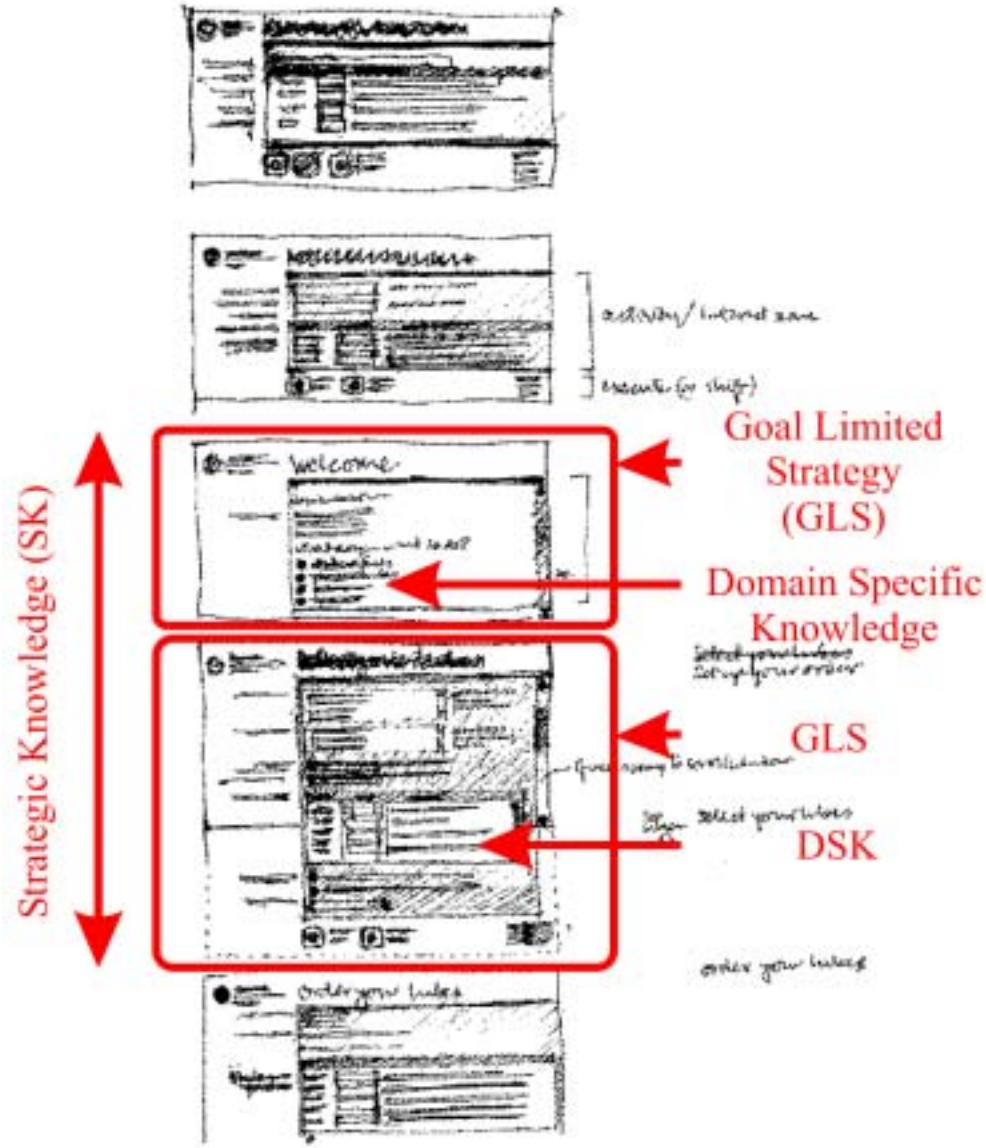

Figure 4: Web page design – goal-limited strategies and domain-specific knowledge

In summary, all projects from information design had very strong strategic goals that were evident at the beginning of each project. The overall design strategy affected the choice for more specific strategies (Brazier, van Langen and Treur, 2002). General strategic knowledge (GSK) was represented through each segment and it was guiding the goal-limited strategies and utilisation or acquisition of knowledge. Interaction with domain knowledge and strategic knowledge is within the Goal-limited Strategies (GLS).

Product design

Product design visual information was analysed at the idea generation stage (beginning of the project) and related to a hand tool, a workstation, and medical device designs. Each project started with a client brief or written proposal that directed the designs. They had design constraints specified that directed the designers where to search for domain specific knowledge and what strategies to apply.

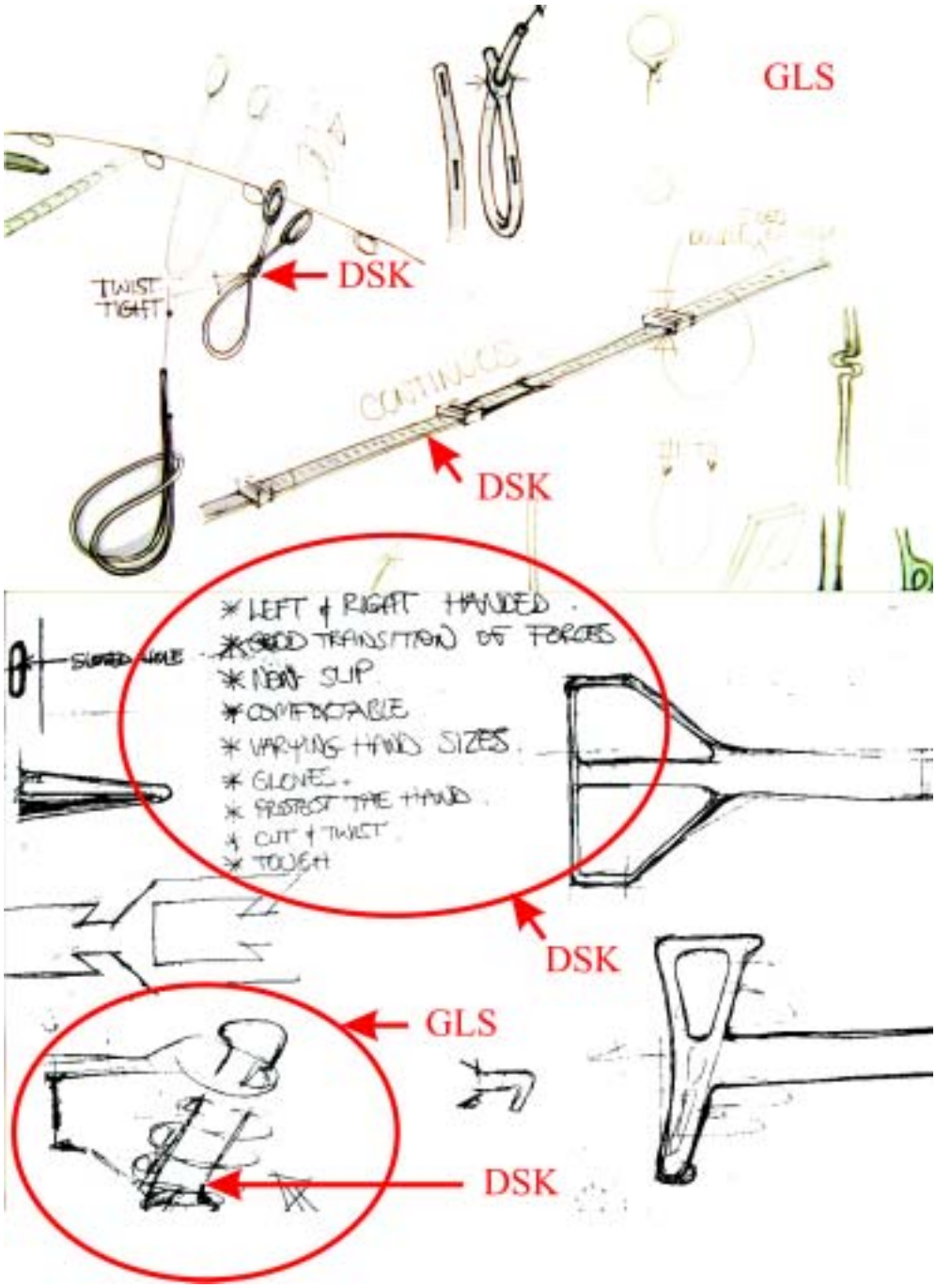

Figure 5: Hand tool segments – goal-limited strategies and domain-specific knowledge

Figure 5 illustrates two segments from the hand tool design (fastening of concrete reinforcement). The first segment shows that the designer was looking for different possibilities of fastening techniques and that domain-specific knowledge was utilised to accomplish the task. For example: continuous or tight twist. This segment is coded as a goal-limited strategy (GLS) as it is related to the task accomplishment. The second segment illustrates visual thinking regarding the various kinds of handle design. The constraints were annotated and are interpreted as domain–specific knowledge utilised to accomplish the relevant task. For example: left and right handed, comfortable, good transition of forces. This is coded as a goal-limited strategy. Characteristics for this project's conceptual stage was that it incorporated 93 segments of goal–limited strategies (GLS).
The integration of different design tasks occurred at the end of the conceptual phase when general strategies were applied as goal directed procedures and represented as general strategic knowledge.

The decision steps were not ordered. They occurred on the basis of information available – information about fastening techniques.

The conceptual stage of the disabled children's workstation had 232 segments coded as goal–limited strategies. Each GLS is associated with the utilisation of relevant domain–specific knowledge. From the documentation available it was evident that the designer at the beginning of the design process was searching for domain-specific knowledge about the station users and their needs. Figure 6 illustrates this search which was guided by strategic knowledge relevant for task accomplishment. For example: accommodation for children of different sizes or seat movement expressed by annotated sketches.

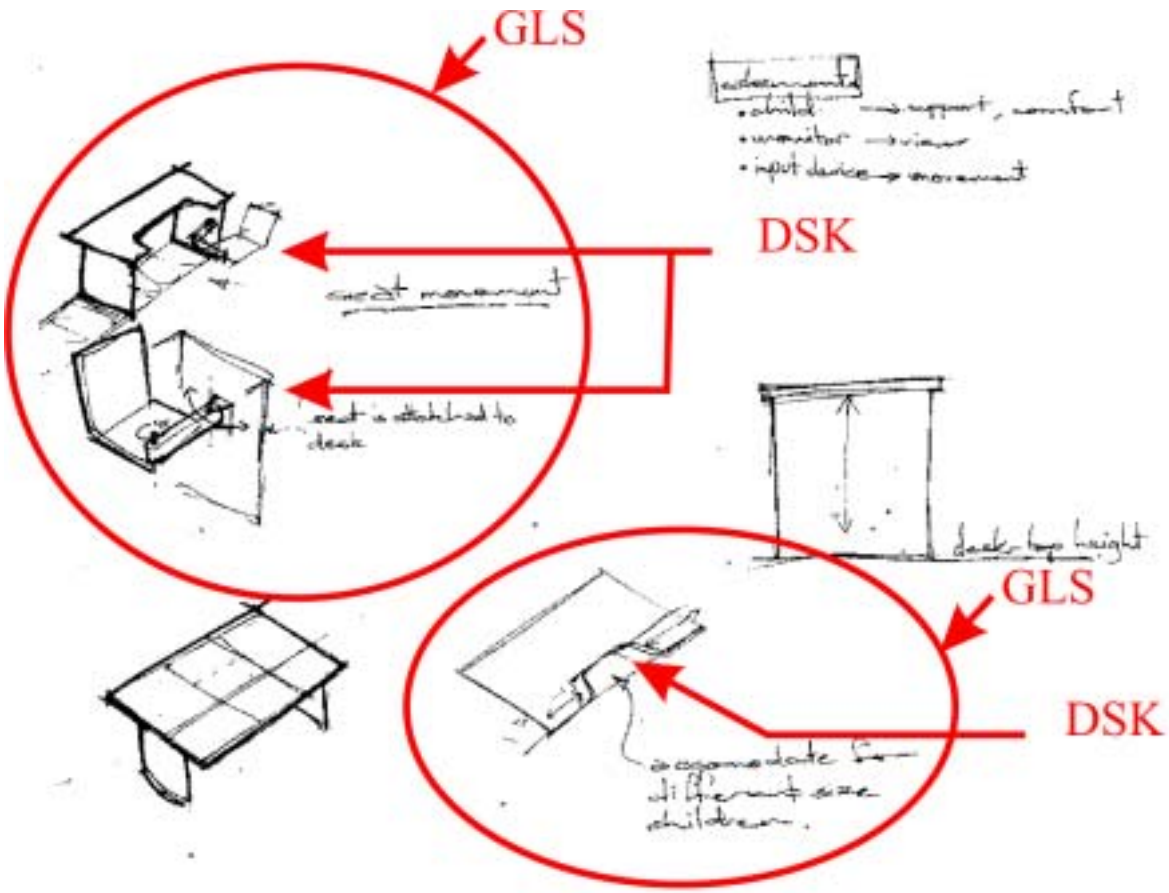

Figure 6: Workstation design - goal-limited strategies and domain-specific knowledge

Figure 7 illustrates an integration of processes that were relevant for different task accomplishments. The designer made the decision for the " table shape" that includes some goal-limited strategies and domain knowledge illustrated in Figure 6 eg. table shape.

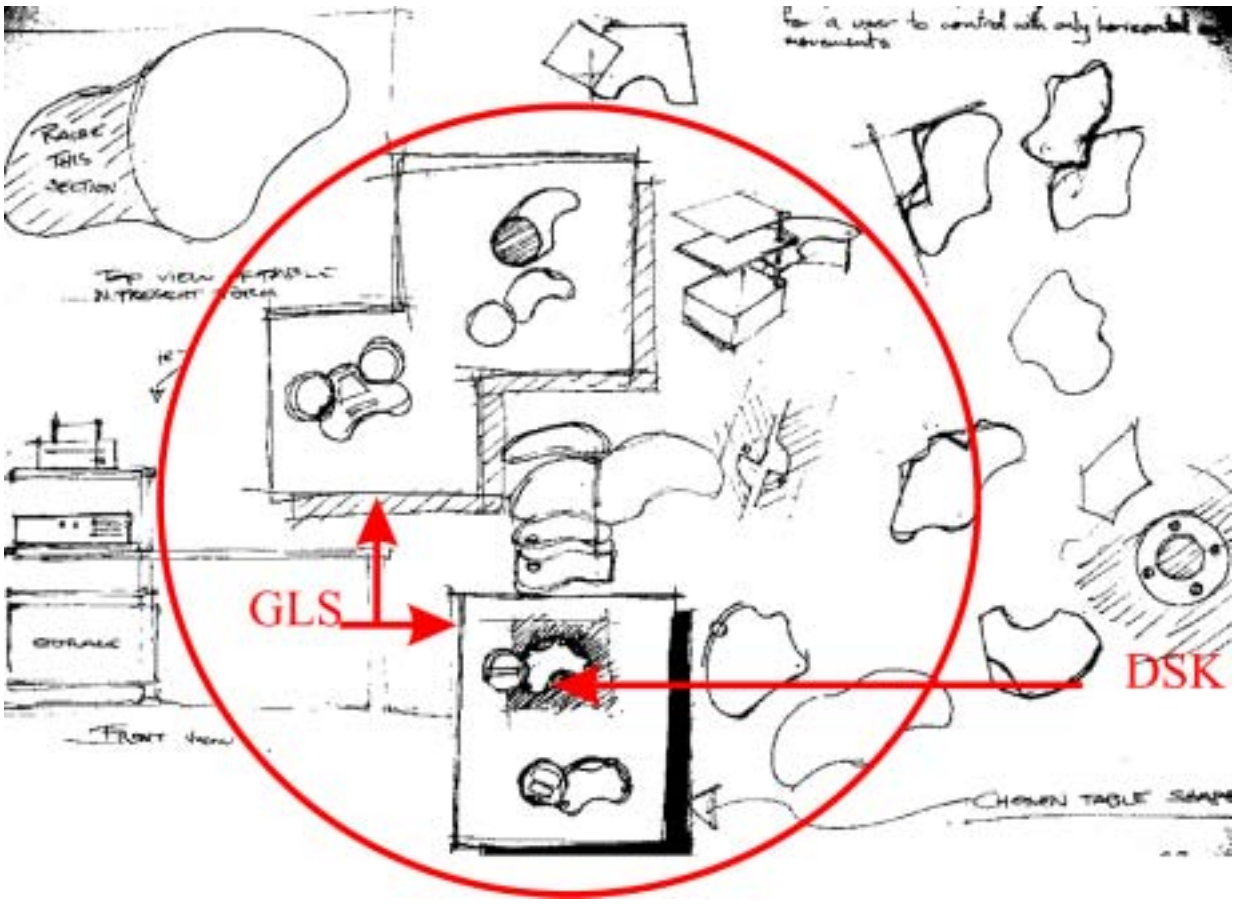

Figure 7: Workstation design – decision for the table shape

In summary, all product design projects were guided by the constraints. Goal-limited strategies were a significant part of each project. The designers responded to the constraints that at the same time formed goal-limited strategies for domain knowledge acquisition or utilisation. Their goal directed procedures were evident at the end of the process. The goal-limited strategies and decision steps were not ordered. They were based on the problem structure and what information happened to be available.

Knowledge connections models

The design activity provides rich material to study design formulation and related activities. This work is based on process formulation that is part of the design activity and makes an attempt to model general strategic knowledge and its interaction with the relevant domain–specific knowledge within the design expertise. Models are used here to gain an insight into the design process. The models developed are centered on two paradigms – design and planning (decisions making) (Vinze at al. 1993). The model construction is seen as design activity based on the study of the process of designing in two different domains – product design and information design. The repetition of knowledge representation and strategies was evident in both domains.

These models are based on the comparison of two design domains. The models are constructed using the comparison of differences and similarities (Figures 8 and 9). There are structural variations within the models but the distinction of domain-specific knowledge was evident. The analysis demonstrated that design is a procedurally rich domain. Within the acceptance that domains differ, then the difference exists in the interaction of domain and strategy knowledge. It is

understood that with well-defined tasks domain-specific strategies play a more important role than general strategies (Alexander 1992).

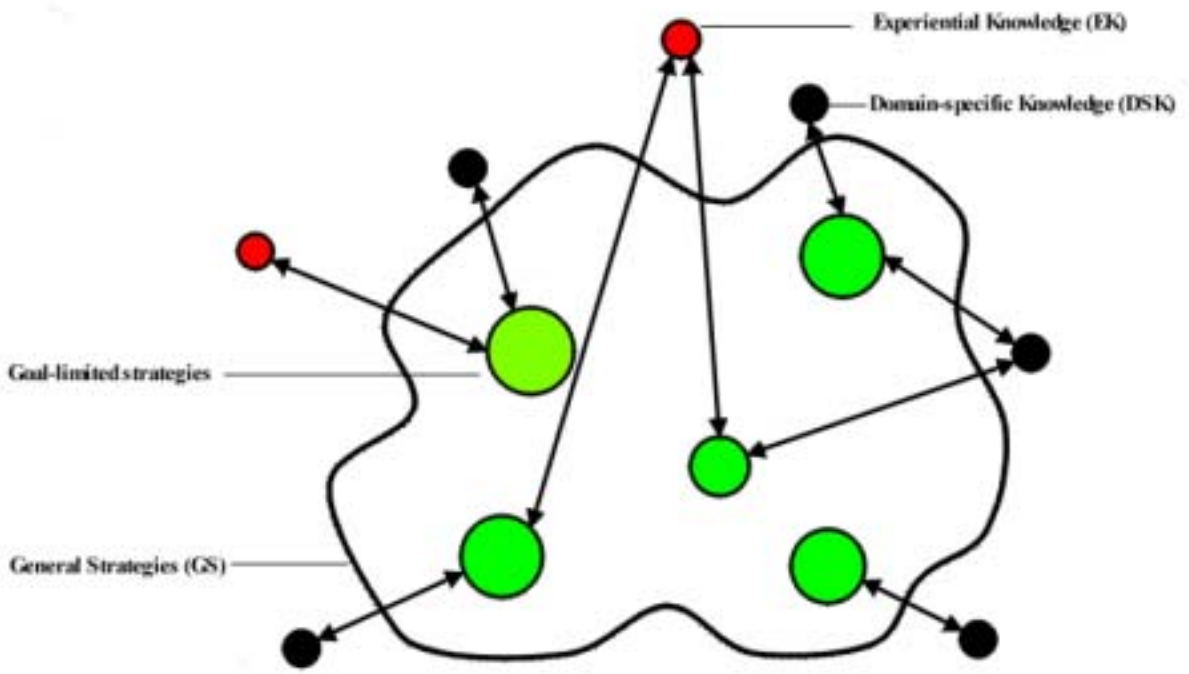

Figure 8: Information design knowledge connection model

Figure 8 illustrates the information design knowledge connection model that is guided by goal directed procedures. The knowledge connections occurred between goal-limited strategies (GLS) and domain-specific knowledge (DSK). General strategic knowledge was monitoring the designers' search for domain-specific knowledge (DSK) and its utilisation in design tasks.

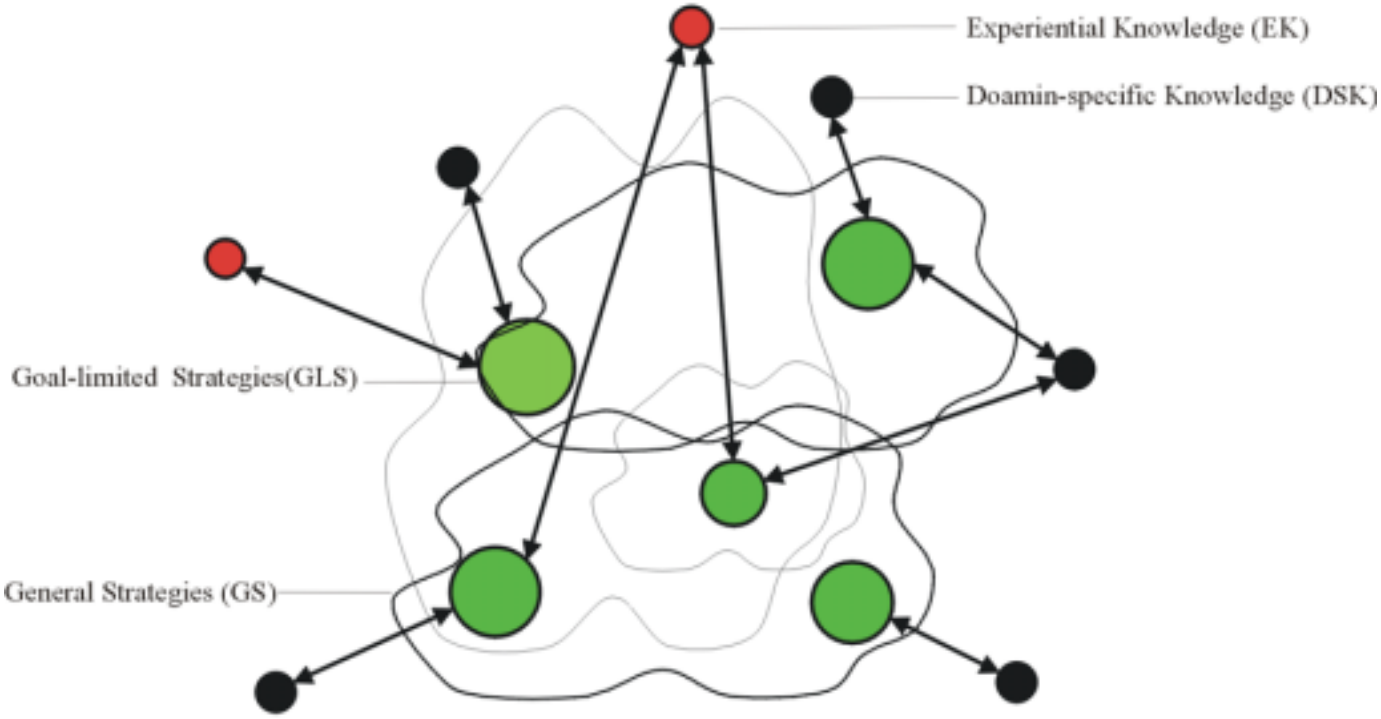

Figure 9: Product Design Knowledge Connection Model

Product design knowledge connections are illustrated in Figure 9. The strategies were determined by project constraints. They are expanding as more constraints are taken into consideration. Goal-limited strategies were determined by the project constraints. When all project constraints were explored they were integrated by utilising relevant strategies to control the integration of the accomplished tasks. Domain-specific knowledge interacts with both goal-limited strategies and general strategies.

Within this framework, it is expected to have both goal-limited strategies and general strategy knowledge (Goodchild et al as reported in Alexander and Judy 1988) that play an important part during the early stage of the design process. Goal–limited strategies include processes relevant for the task that are accomplished in different domains. General strategies can be applied more broadly and include the ability to relate to the current situation. The designer might be engaged here in strategic processing of a more general nature - general problem solving procedures. When working on a specific problem and details, the designer is utilising domain-specific knowledge that might interact with strategic knowledge.

The models are centred on the paradigm of design and decision making based on the analysis of the visual information. The decision steps were analysed and they are explained. It was found that the decision steps were not ordered. They were based on the problem structure and what information happened to be available. This is supported by the findings of Suva, Gero and Purcell (1999) who report that designers adjust to the design task by utilising their knowledge that they adapt to the current tasks and apply it to the design process.

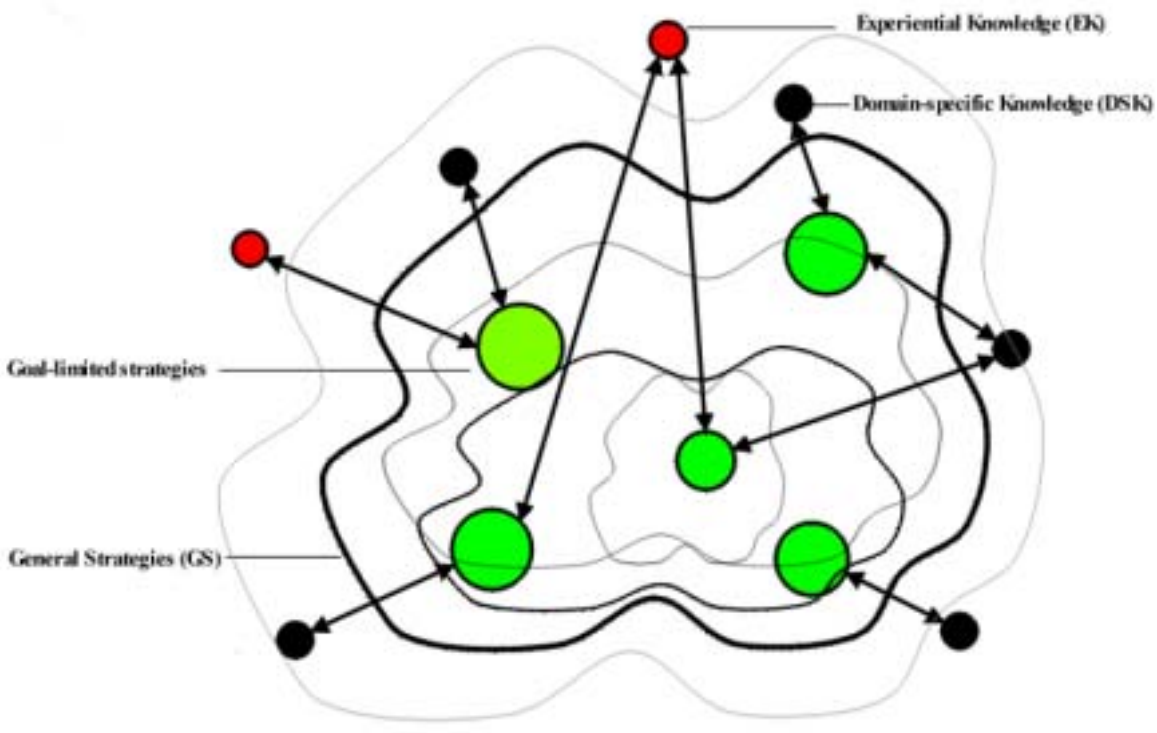

Figure 10: Integrated knowledge connection model

Figure 10 illustrates the integrated knowledge connection model in which general strategies (GS) are expanding to guide the search for satisfactory design. They are goal directed procedures that guide the design projects. Their expansion depends on the accomplishments of goal-limited strategies and their interaction with domain-specific knowledge and experiential knowledge that are dependent on the domain (product or information design). The model is adaptable and dependent on the complexity of design project.

Conclusion

Within the framework of expertise, developed knowledge becomes more structured and better integrated with the past experience. It is noted that the level of expertise plays an important role in problem representation. However, the study of representation of knowledge from visual data is very rarely studied, with some exceptions (Goel 1995; Casakin and Goldschmith1999; Oxman, 2002). The visual language designers use can be seen as elements that contribute to distinguish their expertise, knowledge and skills. It is the language of design (Bucciarelli 2002) that illustrates the thoughts and knowledge or new thought generation and stimulates creative and analytical thinking. The integrated knowledge connection model (Figure 10) presented here is adaptable and supports the notion of design being an " adaptive expertise" by attempting to find answers to cross-disciplinary utilisation of strategic knowledge and clarification of the utilisation of domain–specific knowledge within the early stage of the design process. It might also support the hypothesis done by Alexander and Judy (1988) about the interaction of general strategies, goal-limited strategies and domain-specific knowledge. It is hoped that these models would contribute to the better

understanding of design as an adaptive expertise whose characteristics are cross-disciplinary general strategies and goal-limited strategies that interact with domain-specific knowledge and experiential knowledge.

References

Akin, Omer. 1979. *Models of architectural knowledge*. PhD thesis. Pittsburgh: Carnegie-Mellon University.

Akin, Omer. 1986. *Psychology of architectural design*. London: Pion Limited.

Alexander, Patricia A. 1992. "Domain knowledge: Evolving themes and emerging concerns". *Educational Psychologist*, 27 (1): 33-51.

Alexander, Patricia A. and Judith E. Judy. 1988. "The interaction of domain-specific knowledge". In *Academic Performance. Review of Educational Research*, 4: 375-404.

Anderson, John. 1983. *The architecture of cognition*. Cambridge: Harvard University Press.

Anderson, John. 1993. *Rules of the mind*. Hillsdale: Lawrence Erlbaum Associates.

Anzai, Yuichiro. 1991. "Learning and use of representation for physics expertise". In *Toward a General Theory of Expertise*, edited by K. A. Ericsson and J. Smith. New York: Cambridge University Press: 64-92.

Bhaskar, R. and Herbert R. Simon. 1977. "Problem solving in semantically rich domains: An example from engineering thermodynamics". *Cognitive Science*, 1:193-215.

Bhavnani, Suresh K. and Bonne E. John. 1997. "From sufficient and efficient usage: An analysis of strategic knowledge". *CHI97 Proceedings*. Atlanta: CHI: 91-98.

Braziler, Frances M. T., Pieter H. G. van Langen, and Jan Treur. 2002."Strategic knowledge in design: Compositional approach". *(Web document).* http://www.cs.vu.nl/~{frances, langen, treur}. Accessed: 30 March 2002.

Bucciarelli, Louis. 2002. "Between thought and object in engineering design". *Design Studies*, 3 (23): 219-231.

Card, Stuart K., Thomas P. Moran and Allen Newell. 1983. *The psychology of Human-Computer Interaction*. Hillsdale: Lawrence Erlbaum.

Carroll, John. 1991. Introduction: "The Kittle house manifesto". In *Designing interaction*, edited by John Carroll. Cambridge: Cambridge University Press.

Casakin, Hernan and Gabriela Goldschmith. 1999. "Expertise and the use of visual analogy: Implications for design education". *Design Studies*, 2 (20):153-175.

Chase, William G. and Herbert A. Simon. 1973. "Perception in chess", *Cognitive Psychology*, 4:55-81.

Chi, Michelene T. H. 1981. "Knowledge development and memory performance". In *Intelligence and learning*, edited by M. P. Friedman, J. P. Das and N. O'Connor. New York: Plenum: 221-229.

Chi, Michelene T. H., Paul J. Feltovich and Robert Glaser. 1981. "Categorisation and representation of physics problems by experts and novices". *Cognitive Science*, 5: 121-152.

Christiaans, Henri. 1992. *Creativity in design*. Utreht: LEMMA Publishers.

Cross, Nigel. 1995. "Discovering design activity". In *Discovering design* edited by R. Buchanan and V. Margolin. Chicago: The University of Chicago Press: 105-120.

Dorst, Kees and Nigel. Cross. 2001. "Creativity in the design process: co-evolution of problem-solution". *Design Studies*, 5 (22): 425-437.

Goel, Vinod. 1995. *Sketches of thought*. Cambridge: MIT Press.

Greeno, James G. 1978. "Nature of problem soving abilities". In *Handbook of learning and cognitive processes*. vol.5. Human Information Processing. Hillsdale: Lawrence Erlbaum: 239-269.

Greeno, James G. and Herbert A. Simon. 1988. "Problem solving and reasoning". In *Stevens' handbook of experimental psychology, volume 2*, edited by R.C. Atkinson, R. J. Herrnstein, G. Lindzey and R. D. Luce. New York: John Wiley and Sons: 589-671.

Hammond, N., J. Morton, A. MacLean, P. Barnard and J. Long. 1982. "Knowledge fragments and users' models of system". *Hursley Human Factors Laboratory Report, HF071*.

Horn, Robert E. 1998. *Visual language*. Bainbridge Island, Washington: MacroVu, Inc.

Kieras, David E. and Peter G. Polson. 1985. "An approach to the formal analysis of user complexity". *Int. J. Man-Machine Studies*, 22: 365-394.

Kolodner, Janet L. and Robert L. Simpson. 1986. "Problem solving and dynamic memory". In *Experience memory and reasoning*, edited by J. L. Kolodner and C. K. Riesbeck. Hillsdale: Lawrence Erlbaum.

Kotovsky, Kenneth and Herbert A. Simon. 1990. "What makes some problems really hard: Explorations in the problem space of difficulty". *Cognitive Psychology*, 22:143-183.

Larkin, Jill H. 1985. "Understanding problem representation and skills in physics". In *Thinking and Learning Skills (Vol 2): Research and Open Questions*, edited by S. F. Chipman, J. W. Segal and R. Glaser. Hillsdale: Lawrence Erlbaum: 141-160.

Larkin, Jill, John McDermont, Dorothea P. Simon. and Herbert A. Simon. 1980. "Expert and novice performance in solving physical problems". *Science*, 208:1335-1342.

Love, Terence. 2002. "Constructing a coherent cross–disciplinary body of theory about designing and designs: some philosphical issues". *Design Studies*, 3 (23): 345-361.

Maher, Mary Lou, J. Poon and S. Boulanger. 1996. "Formalising design explorations as co-evolution: a combined gene approach". In *Advances in formal methods for CAD*, edited by J. S. Gero and F. Sudweeks. London: Chapman and Hall.

Michell, T.M. at al. 1985. "A Knowledge-based approach to design". In *IEEE Transactions on Pattern Analysis and Machine Intelligence*. vol. PAMI-7: 502-510.

McDermott, John and Jill H. Larkin. 1978. "Re-representing physics textbook problems". In *The Canadian Society for Computational Studies of Intelligence, Proceedings of the 2nd National Conference*, University of Toronto Press, Toronto: 156-164.

Newell, Allen and Herbert Simon. 1972. *Human problem solving*. Englewood Cliffs: Prentince-Hall.

Oxman, Rivka. 2002. "The thinking eye: visual re–cognition in design emergence" *Design Studies*, 2 (23): 135-164.

Payne, Stephen J. 1987. "Complex problem spaces modelling the knowledge needed to use interactive devices". In *Human-Computer Interaction-INTERACT '87*, edited by H. J. Bullinger and B. Shackel. Amsterdam: North-Holland : 203-208.

Popovic, Vesna. 1998. *Novice and expert users models*. PhD Thesis. Sydney: University of Sydney.

Popovic, Vesna. 2000. "Product design research and knowledge utilisation". In *Proceedings of Design (plus) Research conference*, edited by S. Pizzocaro, A. Arruda and D De Moraes. Milan: Milan Polytechnic: 96-101.

Reimann, P. and Michelene T. H. Chi. 1989. "Human expertise". In *Human and machine problem solving*, edited by K. J. Gilhooly. New York: Plenum Press: 161-191.

Rouse, William B. and Nancy M. Morris. 1986. "On looking into the black box prospects and limits in the search for mental models". *Psychological Bulletin*, 100: 349-363.

Rumelhart, David E. and Donald A. Norman. 1985. "Representation of knowledge". In *Issues in cognitive modeling*, edited by A. M. Aitkenhead, J. M. Slack. Hillsdale: Lawrence Erlbaum: 14-62.

Simon, Herbert A. 1984. *The science of the artificial*. Cambridge: MIT Press.

Simon, Dorothea P. and Herbert A. Simon. 1978. "Individual differences in solving physics problems". In *Children's thinking: What develops*?, edited by R. S. Seigler, Hillside: Lawrence Erlbaum: 325-384.

Smith, M. U. and R. Good. 1984. "Problem solving and classical genetics - successful versus unsuccessful performance". *Journal in research in science teaching*, 21: 895-912.

Suwa, Masaki, John Gero, and Terry Purcell. 1999. "Unexpected discoveries and S–invention of design requirements". In *Computational models of creative design IV* edited by J. S. Gero and M.L. Maher. Sydney: Key Center of Design Computing and Cognition, University of Sydney: 297-320.

Visser, Willemien. 1996. "Use of episodic knowledge and information in design problem solving". In *Analysing design activity*, edited by N. Cross, H. Christiaans and K. Dorst, Chichester: John Wiley and Sons: 271-289.

Vinze, Ajay S., Arun Sen and Shue Feng T.Liou. 1993. "Operationalizing the opportunistic behaviour in model formulation". In *Int. Journal of Man – Machine Studies*, 39: 509-540.

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