The nature of evolutionary artefact and design process knowledge coupling

by

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To my dear mum MA Xiu-rong

献给我亲爱的妈妈，马秀荣

ABSTRACT

Artefact and design process knowledge continually evolve during design development and are closely coupled. Considerable research has been conducted on the artefact, design process knowledge, and their inter-relationships. However, they have only focused on general or specific aspects of their coupling. To address this lack of knowledge, the research presented in this thesis has focused on modelling the nature of the coupling of evolutionary artefact and design process knowledge. A triangulation approach was adopted in the research, through which a coupling model was developed based on different methods including literature review, content analysis, and protocol analysis. The model was subsequently evaluated by questionnaire.

A basic set of artefact and design process knowledge elements involved in the coupling (22 in all) were identified through literature review and verified by content analysis of eight industrial design documents and protocol analysis of a supervised student design project. They include 11 fundamental and 4 contextual artefact and 5 fundamental and 2 contextual design process knowledge elements. Occurrence trends of these elements over task clarification, conceptual, and embodiment design were revealed through the protocol analysis, which shows that different types of knowledge elements exhibit different trend patterns, such as increasing, decreasing, or relatively stable. The coupling was found to be composed of 6 creation and 15 employment links through the content analysis. The protocol analysis of the coupling links resulted in 18 creation and 15 employment links. The evolved coupling model is derived through combining the results obtained from both the content and protocol analysis, which was found to be composed of 19 creation and 17 employment links between the artefact and design process knowledge elements.

The work reported in this thesis was evaluated through questionnaires answered in two workshops by eight practising designers. The evaluation revealed that all of the 22 knowledge elements were considered to occur during design development. Differences were found not only between the results obtained from the analysis and evaluation, but also among the designers. Specifically, it showed that, of the 22 evaluated elements, 2 were viewed as having the same trend as that obtained from the protocol analysis, while 7 were viewed as similar, and 13 were viewed as different. Moreover, the evaluation resulted in 48 creation and 42 employment links. Among them, 9 creation and 12 employment links were also identified from the content and protocol analysis. However, there were still 12 creation and 7 employment links identified from the analyses that were not identified from the evaluation. Possible reasons for these differences were discussed by comparing results from different designers.

Finally, strengths and weaknesses are discussed and potential future work to build on the research are identified.

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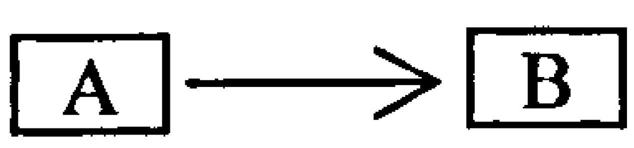
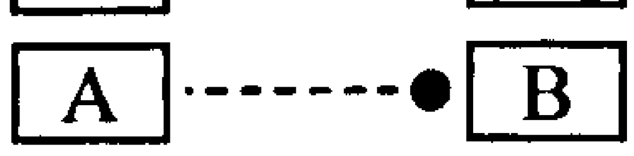
NOMENCLATURE

Unless stated explicitly, the following abbreviations and symbols are used in this thesis, with their meaning listed below.

Abbreviations	Meaning
A	Design activity
B_e	Expected behaviour
B_{it}	Interpreted behaviour
B_{is}	Instantiated behaviour
C	Design context
Ct	Constraints
CR	Causal relationships
D	Design description
DA	Design artefact
DK	Domain knowledge
DK_A	Domain artefact knowledge
$DK_{A/it}$	Interpreted domain artefact knowledge
DK_{A-Bit}	Interpreted domain artefact behavioural knowledge
DK_{A-Fit}	Interpreted domain artefact functional knowledge
DK_{A-G}	Domain artefact general knowledge
DK_{A-Sis}	Instantiated domain artefact structural knowledge
DP	Design process
F_e	Expected function
F_{it}	Interpreted function
G	Design goal
I	Design issues
In	Design input
M	Motivations
Out	Design output
R	Resource
Rq	Requirements
S_e	Expected structure
S_{is}	Instantiated structure
WK	Current working knowledge
WK_A	Current working artefact knowledge

$WK_{A/C}$	Contextual current working artefact knowledge
$WK_{A/E}$	Expected current working artefact knowledge
$WK_{A/F}$	Fundamental current working artefact knowledge
$WK_{A/It}$	Interpreted current working artefact knowledge
$WK_{A/Is}$	Instantiated current working artefact knowledge
WK_{A-B}	Current working artefact behavioural knowledge
WK_{A-Be}	Expected current working artefact behavioural knowledge
WK_{A-Bit}	Interpreted current working artefact behavioural knowledge
WK_{A-Bis}	Instantiated current working artefact behavioural knowledge
WK_{A-CR}	Current working artefact causal relationships knowledge
WK_{A-Ct}	Current working artefact constraints knowledge
WK_{A-F}	Current working artefact functional knowledge
WK_{A-Fe}	Expected current working artefact functional knowledge
WK_{A-Fit}	Interpreted current working artefact functional knowledge
WK_{A-M}	Current working artefact motivations knowledge
WK_{A-Rq}	Current working artefact requirements knowledge
WK_{A-S}	Current working artefact structural knowledge
WK_{A-Se}	Expected current working artefact structural knowledge
WK_{A-Sis}	Instantiated current working artefact structural knowledge
WK_{P}	Current working design process knowledge
$WK_{P/F}$	Fundamental current working design process knowledge
$WK_{P/C}$	Contextual current working design process knowledge
WK_{P-A}	Current working design process activity knowledge
WK_{P-C}	Current working design process context knowledge
WK_{P-G}	Current working design process goal knowledge
WK_{P-I}	Current working design process issues knowledge
WK_{P-In}	Current working design process input knowledge
WK_{P-Out}	Current working design process output knowledge
WK_{P-R}	Current working design process resource knowledge

Symbols	Meaning
	: Causal relationships
	: Causal relationships serial number
	: Comparison
	: Artefact knowledge space
	: Design knowledge element
A  B	: Cause-effect link of creation
A  B	: Link of employment
A  B	: Link of referral
A  B	: Link of containment
A  B	: Link of usage
	: Link of creation represented in the coupling model
	: Link of employment represented in the coupling model

Chapter 1 INTRODUCTION

Designing[1] is considered as a significant intelligent human activity due to its complexity (Gero and McNeill 1998). Engineering design, as one type of design, generally begins with ambiguous requirements or an idea for an artefact. The design then evolves as it progresses from an initial concept to a more detailed design that satisfies such requirements. While the former produces concepts for the whole or different parts of an artefact, the latter gives a detailed description of the artefact (Pahl and Beitz 1996). Such a process is mediated by scientific, engineering, and technological knowledge, which is generated, used, or maintained by designers (Reddy et al. 1997; Smithers 1998).

The term knowledge has been used in Artificial Intelligence (AI) and design research for decades (Manna and Waldinger 1975; Gregory and Commander 1979). Despite its prevalence in such phrases as knowledge engineering and knowledge based design, the definition of knowledge has been an on-going debate both in epistemology, as well as other fields, e.g., AI. Such debate has resulted in a diversity of definitions of knowledge ranging from its nature: "justified true belief" (Plato and Cornford 2003), its location in a computer system: "medium of a systems level that resides immediately above the symbol level" (Newell 1982), its function: "being a potential for generating action" (Newell 1982), its status: "awareness or familiarity gained by experience" (Fowler 1990), to its cognitive ways of acquisition: "psychological result of perception and learning and reasoning" (TheFreeDictionary). In the research presented in this thesis, the concept of knowledge has been adopted based on Newell's definition of the knowledge level, i.e., "the medium of a systems level that resides immediately above the symbol level" and "the principle of rationality as the law of behaviour" (Newell 1982).

Design knowledge, in the engineering field, means the knowledge "about" and "for" design (Horvath 2004). It could be categorised as different types of knowledge from different points of view (Wang and Duffy 2007). Based on its content, it could be classified to design artefact, process, management, and supplementary knowledge (Wang and Duffy 2007). Artefact knowledge is the knowledge that concerns the nature of the artefact, for example, what the design is used for, how the design works and how the design is constructed (Zhang 1999). Process knowledge is the realisation knowledge of an artefact (Aken 2005). Management knowledge concerns the characteristics and properties of a design process, which is used to reason and manage the design process (O'Donnell and Duffy 2005). Design supplementary knowledge is the knowledge that affects the current design, but does not belong to the previous three types, such as company strategy or environmental policies.

As two main types of design knowledge, artefact and design process knowledge evolves throughout design development (Reddy et al. 1997; Huang and Gu 2006a). In this process, different types of artefact and design process knowledge, such as requirements, function, behaviour, structure, activity, goal, resource, just to name a few, emerge, are modified or deleted. Different from evolution in biology, which represents species of animals, plants, or insects' gradual development, permanent adaptation, and continuous optimisation towards an aim over a period of time (Darwin 1952), knowledge evolution, in the context of this thesis, refers to any addition, modification, or deletion of knowledge, which affects the status of the

[1] Design is a representation of an entity, which can be interpreted as an artefact or design process of the artefact. As an artefact, it is an object that was conceived and realised in some way. As a process, it is the sequence of events from conception to realisation of the design artefact. In this thesis, design is used to represent the design artefact and design process is used to represent the process of executing design activities.

knowledge of the current design (Zhang 1999). Such evolution applies to both the artefact and design process knowledge.

Artefact and design process knowledge are closely inter-related to each other. As Zhang (1999) discussed, the design process starts with initial knowledge of the required artefact, which is utilised to progress the design process. As the design process progresses, artefact knowledge evolves. Meanwhile, artefact knowledge can be utilised to determine either to terminate the design process, if a satisfactory and reliable solution has been generated, or otherwise to continue design activities to evolve the design. It could be observed that the evolution of the artefact and design process knowledge is not independent. Rather, the artefact knowledge evolution is triggered by the design process, and the enactment of the design process is triggered by the artefact knowledge. It is proposed, therefore in this thesis, that the artefact and design process knowledge are coupled throughout design development. That is, they are combined through a bi-directional relationship. The evolution of one can trigger the evolution of another through such inter-relationship, and vice versa.

Considerable work has already been carried out in investigating artefact and design process knowledge (Horvath 2004). It was found, through the literature review, research has been conducted with the focus being either on the artefact or design process. There has also been some research addressing the relationships between these two types of design knowledge. However, they are either too high level, or only addressed partial aspects of such coupling. That is, the nature of the coupling between the artefact and design process knowledge is still under-researched. Consequently, an insight of such coupling can contribute to knowledge in the design research domain.

1.1 Scope of the Work

The research reported in this thesis focuses on the nature of the coupling of evolutionary artefact and design process knowledge, i.e., from the identification of a lack of knowledge on this topic through to the description of the findings addressing this issue, which should include not only the knowledge involved in the coupling, but also the inter-relationship of the coupling.

The boundary of the research is defined as follows.

- Coupling of evolutionary artefact and design process knowledge

  Coupling and evolution is closed related. While this work is intended to investigate the coupling of evolutionary artefact and design process knowledge, the focus is on the coupling of the knowledge, rather than knowledge evolution. Knowledge evolution itself is a major topic involving considerable effort in its own right.

- Type of design

  Due to the author's main research focus being on engineering design and accessibility to data sources, the coupling is presented in the context of, though not constricted to, technical system design, such as mechanical design, that delivers effects to transfer operands from one state to another or in general (Hubka and Eder 1988), to fulfil some purpose. Design, such as industrial and chemical design, is not the concern of the research.

- Design phase

  Within the commonly recognised design phase model (Roozenburg and Eekels 1995; Pahl and Beitz 1996), it is generally considered that design problem is analysed and design specification is created in ***task clarification phase.*** Basic solution is identified in ***conceptual design*** and it is developed into a more concrete proposal in ***embodiment design.*** The definitive layout of the artefact is further refined in ***detail design.*** Because the fundamental changes of the artefact and design process mainly occur in the first three phases. Hence the affection between the artefact and design process is considered comparatively stable after embodiment design. Therefore, the coupling will be analysed based on task clarification, conceptual, and embodiment design, though the results might also apply to other phases of the design process, e.g., detail design.

- Types of knowledge

  Among the four types of design knowledge, artefact and design process build the core of the design, and is used/created directly by designers. Consequently, they have received considerable attention from researchers. As seen in Figure 1-1, the research focuses on the coupling of the artefact and design process knowledge. Design management and supplementary knowledge, therefore, is not the focus of the research.

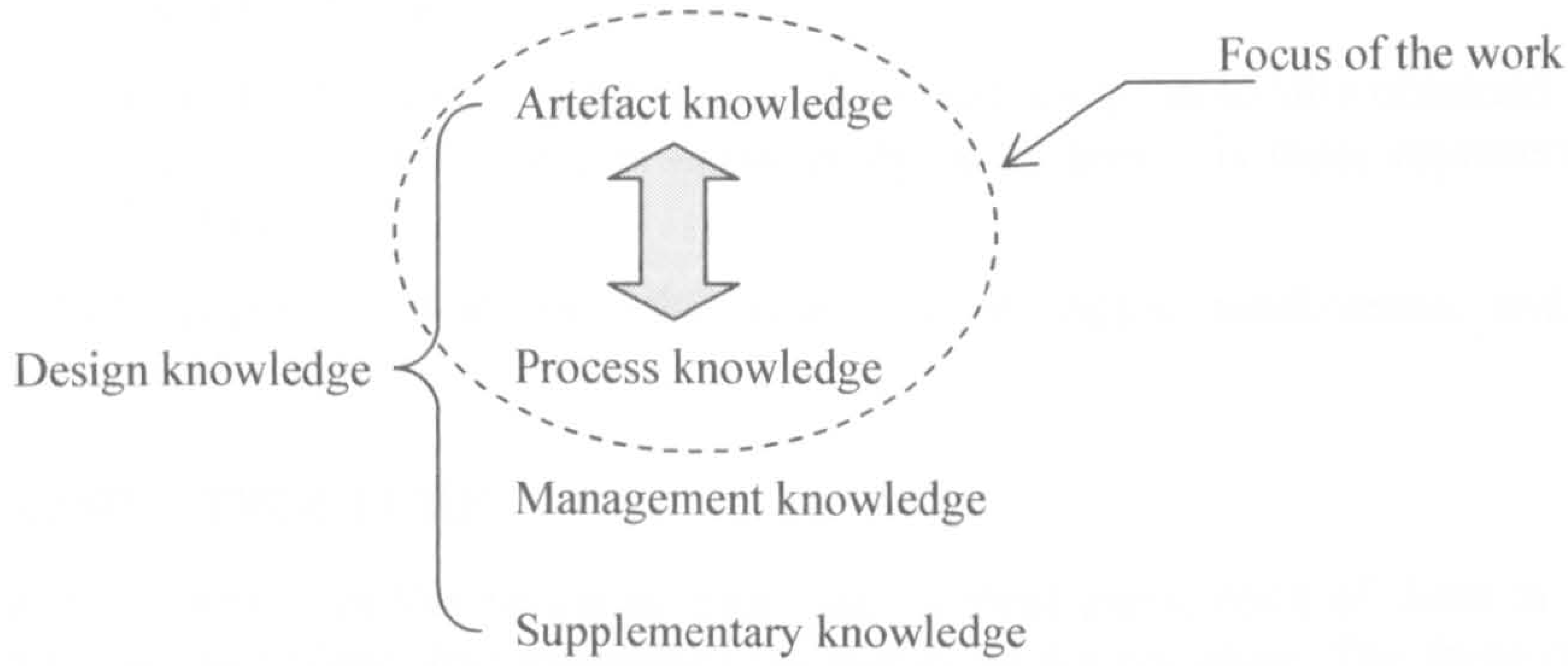


Figure 1-1: Research focus

To investigate the nature of the coupling, the research presented in this thesis has adopted the post-positivism philosophy and a triangulation research methodology, which triangulates the research from three aspects: data source, method, and theory. In essence, literature review and industrial practice are used to derive the research focus. The coupling is investigated through content analysis of eight company design documents and protocol analysis of a supervised student design project. The work is then evaluated through questionnaires answered by eight engineering designers in two workshops. A detailed description of the research methodology is explained in Chapter 2.

1.2 AIM AND OBJECTIVES

1.2.1 Aim

The primary aim of the research is to model the nature of the coupling of evolutionary artefact and design process knowledge, which includes both the knowledge elements involved in such coupling, and the inter-relationship, i.e., different types of links, between the artefact and design process knowledge, which compose such coupling.

1.2.2 Objectives

To achieve such aim, the objectives of the research were identified to be:

✓ (O1) Design the research approach so that the research is conducted in a systematic and controlled manner.

✓ (O2) Identify the research focus through literature review:

- (O2.1) Increase understanding of the field.

- (O2.2) Identify basic artefact and design process knowledge elements.
- (O2.3) Perceive the lack of knowledge in the field, so that to identify the research focus.

✓ (O3) Model the nature of the coupling of the artefact and design process knowledge through:

- (O3.1) Obtain an initial insight of the coupling through content analysis.
- (O3.2) Analyse coupling knowledge elements occurrence trends over the design process through protocol analysis of a design project.
- (O3.3) Identify the inter-relationship, i.e., the links between the basic artefact and design process knowledge elements that compose the coupling through the protocol analysis.
- (O3.4) Evolve the coupling model by combining the results obtained from both the content analysis and protocol analysis, so that it is more representative and reflective.

✓ (O4) Evaluate the work in order to identify strengths, weaknesses, and areas for future work.

1.3 THESIS STRUCTURE

The research presented in this thesis is organised in three parts, each of them is associated with identifying, modelling, and evaluating the nature of the coupling. The three parts of the thesis are listed below, with the addressed objectives listed following each chapter's description.

Part one: Research problem formalisation (Chapters 2, 3, and 4)

Chapter 2 presents the research methodology. Based on the nature of design, as well as the aim and objectives of the research, the research philosophy, methodology, and methods adopted in undertaking the presented research are discussed and outlined (O1).

Chapter 3 reports a review of research in the area of artefact and design process knowledge. Their basic elements are identified respectively. Coupling is considered to relate to the knowledge evolution. Requirements for investigating the nature of the coupling are established (O2.1, O2.2, and O2.3).

Chapter 4 reviews existing research pertinent to the coupling while summarising its weaknesses. The research focus to be addressed by the research work is defined (O2.1and O2.3).

Part two: Approach and findings (Chapters 5, 6, and 7)

Chapter 5 presents the initial findings of the knowledge elements involved in the coupling and presents a coupling model based on content analysis of eight company design related documents (O3.1).

Chapter 6 presents the knowledge elements involved in the coupling. Occurrence trends of the elements over task clarification, conceptual, and embodiment design were identified through protocol analysis of a supervised student design project (O3.2).

Chapter 7 presents a coupling model identified through the protocol analysis, which is composed of a number of links between the artefact and design process knowledge elements. The evolved coupling model is derived by combining the results obtained from both the content analysis and protocol analysis (O3.3 and O3.4).

Part three: Evaluation and discussion (Chapters 8, 9, and 10)

Chapter 8 describes the evaluation of the work presented in this thesis through questionnaires. The results obtained in Part two of the thesis are compared with those obtained from the questionnaires answered by practice designers in two evaluation workshops (O4).

Chapter 9 provides a discussion on the work presented in terms of its strengths and weaknesses. Areas for further research are presented (O4).

Chapter 10 concludes the thesis with a description of the main results of the research.

Part One: Research problem formalisation

Chapter 2 RESEARCH METHODOLOGY

Being 'scientific' comes not from what you study and what you do with it but the methodology (Thorpe 2004).

Research methodology adopted by researchers should illustrate that the research was conducted in a scientific way. Overall, research methodology functions in two ways. The methodology could convince readers that the researchers have planned and carried through the study as well as analysed and drawn conclusions in a way that other people can rely on (Karlsson 2002). In addition, a correct research methodology not only keeps the researchers on the correct research direction, not deviating from the right way towards the research aim, but also ensures that the data collection and analysis methods chosen at different phases of the research are appropriate to answer the original research questions. To this end, specifically, the work presented in this thesis is based on a post-positivism philosophy (Reich 1994; Trochim 2000; Crossan 2003) and triangulation approach (Denzin 1970; Jick 1979; Trochim 2000; Green et al. 2002). Both qualitative and quantitative research methods (e.g. content analysis (Holsti 1969), protocol analysis (Ericsson and Simon 1984), and questionnaire) are adopted to conduct data collection and analysis, to investigate the nature of the coupling of the artefact and process knowledge, followed with its evaluation.

This chapter is primarily concerned with the research methodology adopted in this work. It is organised as follows. Research methodology and philosophy are examined in Section 2.1 and Section 2.2. The approach of the research presented in this thesis is discussed in Section 2.3; and finally in Section 2.4, the overall research structure adopted for the work is built up and presented.

2.1 RESEARCH METHODOLOGIES

Research is a kind of systematic investigation and study in order to establish facts and reach new conclusions (Allen 1991). The word "research" is composed of two syllables: the first is 're' and the second is 'search'. 'Re' is a prefix meaning again, anew or afresh and 'search' meaning to look through or go over thoroughly, to examine or question closely and carefully, or to probe or penetrate into (Allen 1991). Together, they form a noun describing a structured inquiry or a careful, systematic, patient study and investigation in some fields of knowledge that utilise acceptable scientific methodology; aiming at solving problems and creating new knowledge that is generally applicable (Grinnell 1993; Kumar 1999).

According to Kumar (1999), the process of research work should abide by these three principles: first, it should be undertaken within a framework of a set of philosophies; second, it should use procedures, methods and techniques that have been tested for their validity and reliability; and finally, it should be designed to be unbiased and objective. Consequently, in order to conduct a controlled, rigorous, systematic, valid and verifiable research so as to establish reliable and valid knowledge, an appropriate research methodology, based on an appropriate philosophic paradigm, is critical.

Reich (1994, P.266) defines research methodology as "a collection of methods for doing research and their interpretations". More specifically, research in different disciplines requires different research methodologies. In chemistry and physics, for example, laboratory experiments would build the basis of the methodology. Here, researchers use experiments to verify a hypothesis or attempt to find some new theories. In social science, on the other hand, action research (Ottosson 2003) could be adopted to improve organisation management efficiency by the researchers' iterative, participatory diagnoses, taking action, and reflecting. Instead of using large samples followed with a rigid protocol, case-based research aims to examine a limited number of variables through a more in-depth analysis of a single instance or event: a case. It could assist the researchers to gain a sharpened understanding of why the instance happened as it did, and what might become important to look at more extensively in future research (Yin 2003). Furthermore, in the engineering design research domain, different methodologies may be required for different types of research such as pure, applied, and clinical research (Friedman 2005).

As the above discussion shows, the term 'methodology' is different from 'method'. That is, each type of methodology requires a specific set of research methods. Closely related with philosophy (Reich 1994; Easterby-Smith et al. 2001; Crossan 2003; Efinger et al. 2004), methodology is the science of methods or the "theory of methods" (Reich 1994, p264). By definition, a method is a particular way of doing something (Collins 1989). For example, a thread could be used to draw a circle when compasses are not available. Thorpe (2004) defines research method as a technique or instrument used to collect and analyse data. Others define a research method as a means of doing research work. For instance, questionnaires could be used to find out customers' requirements for a kettle to be put into market. Bititci (2003) talks about research methods for establishing the reliability and repeatability of the research process and justifying decisions and choices made during the research. Although research methods can be classified in various ways, one of the most common distinctions is between quantitative and qualitative research methods (Myers 1997; Kumar 1999; Easterby-Smith et al. 2001; Crossan 2003).

In some particular research areas, there are standard research methodologies to follow. For example, in industrial management, there are four main types of research methodology, namely concept-analytical, nomothetical, decision-methodological and action-analytical (Kekale 2001). In information systems research, there are action based research, ethnography, and grounded theory (Myers 1997). In operation management research, researchers may use case, interview, survey and action-based research (Coughlan 2002; Voss et al. 2002). A design research environment is a complex one, which is composed of artefacts, people, tools, processes, organisations and the environment. As Pahl and Beitz (1996), Bender et al. (2002), Friedman (2005) and Horvath (2005) have argued, different disciplines are involved in design research, such as engineering science, computer science, cognitive science, social sciences, humanities and liberal arts. Each discipline has its own appropriate research methods and underlying paradigms (Bender et al. 2002). In turn, design research is built upon a wide range of methods of these disciplines.

Beitz (1994) Blessing et al. (1995), Dixon (1987), Eekels and Roozenburg (1991), Green et al. (2002), Horvath (2005), Reich (1995) and Steinberg (1994), among others, have worked on research methodologies in Artificial Intelligence (AI) and Design. Despite some shortage of research in this field, there has been, however, a trend to apply social science methods to design research (Beitz 1994; Cross 1995; Reich 1995; Kennedy 1997; Bender et al. 2002; Green et al. 2002).

In line with research in other domains, design research should acquire and validate knowledge systematically. More specifically, the goals of design research are to formulate and validate models and theories about design, to acquire and validate knowledge, methods and tools and to improve the design process (Bender et al. 2002). Moreover, as Horvath (2005) mentioned, the methodological characteristics of design research are strongly influenced and determined by philosophical assumptions and other associated factors. Therefore, knowledge of research philosophy and how it directs the choice of research methodology is necessary to build a suitable research methodology. Therefore, the following sections present the current main streams of research philosophy, and the rationale of the choice of the research method' ›gy for the research.

2.2 RESEARCH PHILOSOPHIES

According to Love (2002, p.410), researchers have three perspectives, namely "ontological", "epistemological", and/or "methodological", towards the world or the research problem. The ontological perspective consists of the assumptions, beliefs and collection of human values that build a researcher's individual view of the nature of the world. The epistemological perspective defines the relationship between a researcher's ontological perspective to theory/knowledge for each analysis and theoretical proposal. Finally, the methodological perspective provides the interface between theory and methodologies. It is used to aid a researcher to choose appropriate research methodologies, which include research methods and required techniques as well as the connections between the methodology and the research theoretical details. Popper (1976) on the other hand, refers to subjective, theory, and external as the individual, theory and world mentioned by Love. In the interest of clarity, these three perspectives and their relations with other entities, i.e. individual, world, theory, and research methodology, are shown in Figure 2-1.

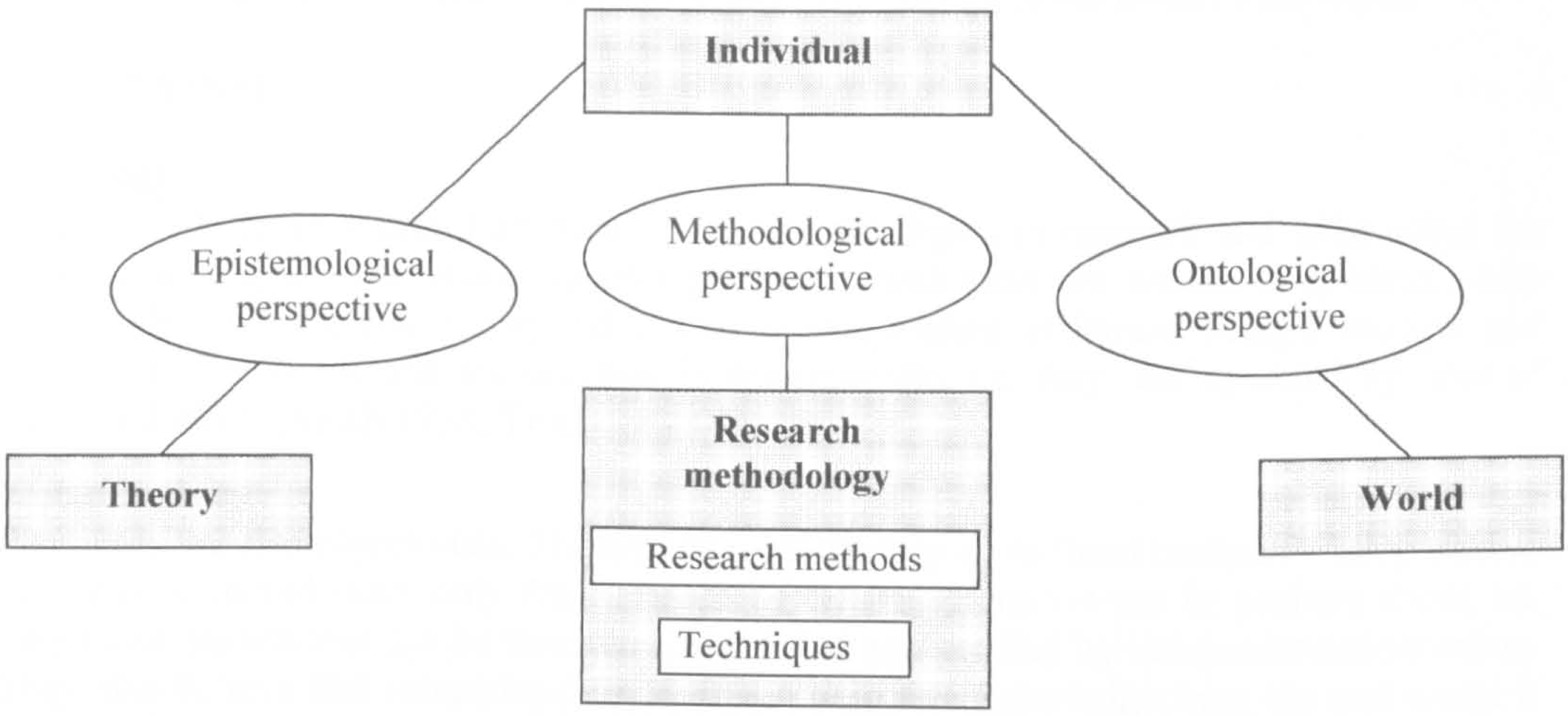


Figure 2-1: Multiple theoretical perspectives and their relation with the world

These three perspectives compose the worldview of researchers (Reich 1994). As Reich argues, research methodology is intimately connected with, and constrained by the worldview it serves. As a result, choices in each of the above perspectives[2] and research methodology are not completely independent of each other; instead, they must be epistemologically coherent.

For some researchers (e.g. Clark (1998) and Crossan (2003)), research methods can be described, considered and classified at different levels, the most basic of which is the philosophical level. In this respect, The Oxford Dictionary of Philosophy (Blackburn 1996) has pointed out that the philosophical level of a research method focuses on its assumptions relating to the most general features of the world, encompassing aspects such as the mind, matter, reason and proofs for knowledge. In other words, how people view knowledge, and how the knowledge could be obtained. In addition, different research methods, as Clark (1998, p.1242) maintains, "may share or greatly differ in their philosophical conceptualisation of truth". This is the position taken by Easterby-Smith et al. (2001) who identify three reasons why the exploration of philosophy is important concerning research methodology. First, it helps researchers to refine and specify the research methods. Second,

[2] In addition to these three perspectives, Horvath (2005) also mentioned another three, namely axiological, ethical, and historical. However, ontological, epistemological, and methodological perspectives are considered three basic ones and are the ones discussed in this thesis.

it enables and assists the researchers, specifically at the very early stage, to identify the limitations of particular approaches through evaluation of different methodologies and methods and therefore avoiding inappropriate use and unnecessary work. Finally, it could help the researchers to be creative in either selection or adaptation of methods that were previously outside their experience. According to Kumar (1999), the philosophical orientation may stem from one of the two paradigms in research, i.e. positivism and naturalism, and the academic domain in which researchers have been trained. More specifically, the paradigm that is rooted in physical sciences is called the systematic, scientific or positivism approach. In contrast, as Kumar noted, the opposite paradigm has come to be known as the qualitative, ethnographic, ecological or naturalistic approach. Having the same meaning as positivism and naturalism, some other terms are used in different literature, namely positivism and post-positivism (Clark 1998; Trochim 2000; Crossan 2003), positivism and constructionism (Dorst and Dijkhuis 1995; Lenart and Pasztor 2002), and scientism and practicism (Reich 1994). In this thesis, positivism and post-positivism are used to refer to these two branches of research philosophy and are discussed with more detail with respect to the researchers' three perspectives towards the world.

POSITIVISM

Ontology

Reich (1994) gives a useful account of various paradigms in research and talks about the basic reasoning of positivism. According to him, positivists are realists and, hence, they assume that an objective reality exists that is independent of human being's thought and behaviour. The world and the universe is deterministic, i.e. they are operated by laws of cause and effect (Reich 1994; Trochim 2000).

Epistemology

Positivists are also objectivists. The type of research they do is "hard research". They believe that science should study only those aspects of the world that we can be positive about, i.e. only those aspects that can be measured, quantified and verified by independent observation. They also believe that researchers could obtain objective knowledge from the real world if they apply the unique approach of scientific methods (Reich 1994). In a similar vein, Crossan (2003) notes that all knowledge should be obtained from human being's observation of objective reality. That is, Trochim (2000) argues, the goal of knowledge is to describe the world that people encounter, and the purpose of science is to get the truth, to know the world so as to be able to predict and control it. Furthermore, science is largely a mechanistic or mechanical affair. Thus, positivists seek causal explanation and universal laws to explain the world. In addition, they also believe that complex problems can be better understood if they are reduced into simpler component parts (Crossan 2003). In this sense, positivists are called reductionalists.

Methodology

In respect of the methodological approach, positivism research is quantitative (Crossan 2003). Because the source of facts is empirical, positivists study observable behaviour with operational concepts. Trochim (2000) takes this argument further and talks about both observation and measurement as the main positivistic research methods. Similarly, according to Reich (1994, p.267), the key approach of the positivistic method is experimental and manipulative and large samples are employed. This, in turn, attempts "to discern natural laws through direct manipulation and observation" (Trochim 2000). Here, deductive reasoning is used to postulate theories that can be tested.

However, the positivist approach has received several criticisms. As Crossan (2003, p.51) mentioned, one of the major criticisms of the positivist approach is that "it does not provide the means to examine human beings and their behaviours in an in-depth way". Put simply, "humans are not 'objects', and are subject to many influences on behaviour, feelings, perceptions, and attitudes that positivists would reject as irrelevant and belonging to the realms of metaphysics". Other critics of the positivist approach argue that it yields limited data that only provides a shallow view of the complex phenomenon it investigates. Therefore, post-positivism emerged to counteract to these criticisms.

POST-POSITIVISM

Ontology

Since its recognition in the 1950s (Popper 1959), post-positivism has provided an alternative to the traditions and foundations of positivism for conducting disciplined inquiry. The post-positivist researcher is relativist, hold the view that the reality exists only in their mind (Reich 1994). Crossan (2003, p.51) also argues that reality is a creation of those individual researchers involved in the research. As a result, there could be various constructions of reality depending on its different context. Therefore, as Crossan noted, most post-positivists are constructivists in a way that they believe that everyone constructs their worldview based on the awareness of it. Similarly, Trochim (2000) gives a useful account of this approach by talking about critical realism as one of the most common forms of post-positivism. Here, a critical realist believes that there exists a real world independent of human mind driven by natural causes and this is a world that science can study. Trochim also believes that positivists are realists either. However, he articulates that "the post-positivist critical realist recognizes that all observation is fallible and has error and that all theory is revisable". Human beings can not know the true reality with certainty. Thus, because perception and observation is fallible, their constructions are imperfect.

Epistemology

Despite their tendency to objectivity, post-positivists believe that knowledge and facts are subjective (Reich 1994). They also believe that problems can not be fully understood in isolation, but only as part of a complex pattern of links and relationships. While the positivist believes that the goal of science is to reveal the truth, the post-positivist critical realist believes that "the goal of science is to hold steadfastly to the goal of getting it right about reality, even though we can never achieve that goal" (Trochim 2000).

Methodology

The epistemology of the post-positivism implies that qualitative approaches are the main research methods adopted by post-positivists. For them, research is "soft" and generally, small samples are employed for more in-depth investigations. As a result, critics of post-positivist approaches relate their limitations to the nature of qualitative methods, which is "interactive and participatory" (Crossan 2003, p.53). Mays and Pope (1995), among others, summarise the main criticisms as being subject to the researchers' bias, a lack of reproducibility (i.e. no guarantee that a different researcher would come to the same conclusions) and a lack of generalisability.

The above discussion of post-positivism indicates that, since all measurements are not sufficiently accurate, multiple measures and observations (although each of them may possess different types of error) are needed in order to approach objectivity with the consequence of more valid results (Trochim 2000). Here one example is using a combination of qualitative and quantitative methods. According to Guba and Lincoln (1998), this is sometimes described as "critical multiplism" that refers to the notion that research can generally be approached from several perspectives. Others (e.g. Jick (1979), Shih (1998), Massey (1999), Trochim (2000), Kekale (2001) and Green et al. (2002)) talk about such combination of multiple methodologies as triangulation. It should be mentioned that, the word "triangulation" used here has originated from navigation and military strategy that use multiple reference points to locate an object's exact position. Given basic principles of geometry, multiple viewpoints allow for greater accuracy. Similarly, researchers can improve the accuracy of their judgements by collecting different sources of data bearing on the same phenomenon (Jick 1979). In more elaborate language, triangulation is "the combination of methodologies in the study of the same phenomenon" (Denzin 1970). According to Denzin (1970), the use of multiple measures may result in uncovering some unique variance which otherwise may have been neglected by a single method.

For the purpose of clarity, Table 2-1 summarises the main characteristics of the aforementioned two research philosophies (i.e. positivism and post-positivism) from four different aspects of general, ontology, epistemology and methodology.

Table 2-1: Positivism and post-positivism

	Positivism	**Post-Positivism**
	General	
Research type	-"Hard" research	-"Soft" research
Other names	-Scientism	-Practicism -Naturalism
Paradigm	-Systematic -Scientific	-Ethnographic -Ecological -Naturalistic -Cognitive, action or phenomenological
Researcher's role	-Positivist -Realist -Behaviourist -Reductionalist	-Post-positivist -Critical realist -Constructivist
	Ontology	
Ontology or World view	-Reality exists independent of human behaviour -The world is deterministic (laws of cause and effect)	-Reality is multiple, subjective, and mentally constructed by individuals -A creation of individuals involved in the research
	Epistemology	
Philosophical viewpoint Or Epistemology	-Believes that knowledge and facts are objective -All knowledge should be obtained by observation -Believes that complex problems can be best understood if they are reduced into a simpler component parts	-Believes that knowledge and facts are subjective -Believes that problems cannot be fully understood in isolation, but only as part of a complex pattern of links and relationships (Holist)
Explanation	-Seeks causal explanation and universal (fundamental) laws that govern behaviour	-Seeks individual's own understanding and interpretation of the world as a basis for behaviour
Goal of science	-To uncovers truth sticking to what we can observe and measure -To understand the world well enough so that we might predict and control it	-Hold steadfast to the goal of getting it right about reality, even though we can never achieve that goal
	Methodology	
Data	-Quantitative	-Qualitative (primary)
Study object	-Studies observable behaviour with	-Study meaningful action and the

	operational concepts	unobservable
Research method	-Empiricism (observation and measurement are the core of the scientific endeavour) -Experiment is the key approach -Large samples	-Observation is fallible and has error -Triangulation is needed to approach objectivity -Small samples investigated in depth

2.3 APPROACH

Having discussed the research philosophies as the background of research methodology, this section presents the rationale towards the methodology of this research project. The research design in this work was based on the "Critical Methodological Choices/Decisions" procedure (Bititci 2003), which includes the decision on types of research, research paradigm, research strategy, research questions, and finally research design.

The aim of the research presented in this thesis is to model the nature of the coupling of evolutionary artefact and design process knowledge during design development. To this end, it involves modelling the development of artefact and design process knowledge possessed by designers, with particular attention to the interactions between the artefact and process knowledge.

In respect of the type of research, much of the nature of design research is similar to cognitive psychology or sociology due to the involvement of people, society, and organisation (Dixon 1987). Accordingly, there has been a growing appreciation that designing is a social process (Horvath and Duhovnik 2005). For example, Beitz (1994), Bender et al. (2002), Cross and Cross (1995), Green et al. (2002), Horvath (2005), and Kennedy (1997), among other design researchers, have identified that the research methods used in social sciences should also be taken into account in design research. Similarly, from a cognitive point of view, research design aims to understand the human aspects of being involved in, and/or influenced by design through a statistical prediction of aggregate human behaviour (Horvath and Duhovnik 2005). In line with this argument, some research methods, such as content analysis, interview, protocol analysis, and questionnaire, adopted in this work originated from social sciences.

Through initial research, it was found that the decisions made by designers during the design process contribute significantly and play a key role for design knowledge evolution. However, it should be noted that the decisions made by designers are not only affected by the current artefact knowledge, such as function, behaviour, and structure, but also other factors such as designers' domain knowledge, project deadline, manufacturing cost, and other available resources do have their impact on the designers' decisions. These parameters are of qualitative character and could not be formulated in an accurate positivism way. This implies that it is therefore not suitable to do the research in a quantitative positivistic manner. In addition, all the design cases that were analysed in the course of research were unrepeatable simply due to the nature of design. Based on the above analysis and discussion, therefore, of the two main streams of research philosophies, positivism and post-positivism, the latter is adopted as the philosophy paradigm for the current research. Consequently, due to the nature of the characteristics of post-positivism that were discussed earlier (see Section 2.2), special attention was devoted to the use of the triangulation methodology. This, in turn, helped the author delivering a comparatively representative and reflective coupling model by using multiple data sources and multiple research methods.

Specifically, the research methodology used in the research presented in this thesis is in line with Denzin's (1970) argument that research could be triangulated in terms of multiple and different data sources, methods, investigators, and theories. Data triangulation refers to the need to retrieve data from a number of different sources to form one body of data. In addition, method triangulation is simply the use of multi-method, which is described as being either "within-methods" or "between-methods". A "within-methods" approach involves the same method being used on different occasions (e.g. repeating the same experiment at different times), and a "between-methods" approach uses different methods with the same object of study. Moreover, investigator triangulation involves the use of a number of investigators to observe the same problem, thus attempting to ensure objectivity and avoid bias. Finally, theory triangulation requires the testing of developed theories against the same body of objective data.

In light of the above discussion, three aspects of Denzin's argument were triangulated in this work: data source, between-methods, and theory. This means that data were collected from different sources and different methods were adopted in different phases of the research, including data collection and analysis, model development, and model evaluation. For the purpose of clarity, the rationale for the methodology is given below.

The choice of methods depends on many factors, in particular, the nature of the research being undertaken. In the research presented in this thesis, the nature of the coupling, which involves the elements involve in the coupling and links among the elements were required to be modelled. In order to develop this model, a number of issues must be addressed:

- What has been done by former researchers on this research topic?
- Does industry have any problems related with such topic?
- What kind of data is required to explore the coupling?
- How to develop the model so that it is based on both theoretical analysis and empirical study?
- How to develop the model so that it reflects the nature of the coupling more representative?
- How to evaluate the model after it has been developed?

Clearly, each of the above issues has a corresponding impact on the choice of the research methods. To justify the use of the methodology adopted in the research, the following paragraphs briefly answer the above-mentioned questions.

At first, in order to determine the previous work in the area, a review into the current state-of-the-art need to be conducted. Here, a literature review was carried out to help the author understand the domain as well as analyse the research problem. This review, then, was updated to take account of upcoming related issues by other researchers in the field.

To identify whether industry has any problem regarding the research problem, results from a workshop in Company A[3] that was intended to identify the opportunities, drivers, and problems of Product Lifecycle Management (PLM) were analysed. A follow-up visiting to the company in November 2005 identified further problems now encountered by industry, which are related to the artefact and design process knowledge.

Then, in order to collect related data from different sources for triangulation purpose, it was decided to collect data from company documents, student projects, and company designers. To this end, design related documents were collected, protocols from a supervised student design project were transcribed, and questionnaires were answered by designers.

Design is a type of empirical activity. In order to develop the model not only based on the literature study, design data based on empirical projects were collected. In the research, both

[3] The real name of the company was decided to be completely confidential and therefore the name has been changed to 'Company A' for the purpose of analysis and discussion. From July 2004 to April 2005, the author participated in the Product Lifecycle Management (PLM) project within the company, and was actively engaged to support, analyse, and develop their strategic PLM system.

design data from company and design projects from educational institutes were studied in order to explore the nature of the coupling. This, in turn, resulted in an evolved model that can benefit from both theory and empirical inputs. The company project was a hypothesised one based on a number of design artefact and process related documents, which were collected from Company A. The student projects were recorded in the Department of Design, Manufacture and Engineering Management (DMEM), University of Strathclyde, from September 2005 to May 2006.

Towards developing a model that is more representative, the aforementioned data were collected from different environments, which covered different categories of design, such as by individual (student design projects) and group (company design projects), design from both academia (student design projects) and industry (company design projects), as well as design by both experienced designers (company design projects) and novices (student design projects).

Finally, the work requires evaluation to verify its validity. To this end, designers' views of the nature of the coupling were collected through questionnaire during workshops in order to evaluate the developed coupling model. Two workshops were organised in two companies: (i) BAE Systems Surface Fleet Solutions Limited (SFS) and (ii) Company A on the 2nd and 7th of March respectively.

In short, as the above discussion shows, the design data used in the research cover different categories of design, namely: commercial and non-commercial, group and individual, distributed and single site, formal and informal, and small and large-sized design projects (by experienced or novice designers), in different design phases. In the interest of clarity, the characteristics of each data source are summarised in Table 2-2.

Table 2-2: Data sources of the research

	Company A design documents	**Undergraduate students design projects**	**Company workshops**
Commercial	Hypothesised to be yes	No	Yes
Group work	Hypothesised to be yes	No	Yes
Design scale	Hypothesised to be large	Small	Large
Distributed	Hypothesised to be yes	No	Yes
Formal	Hypothesised to be yes	No	Yes
Designers	N/A	Novice	Experienced
Gender	Hypothesised to be male and female	Male and female	Male and female
Covered design phases	Product life cycle	Task clarification Conceptual Embodiment Detail	Task clarification Conceptual Embodiment
Research methods	Content analysis	Protocol analysis	Questionnaire
Environment	Industry	Academe	Industry
Roles of Researcher	Analyser	Participant-as-observer	Analyser

In the research, the coupling model was developed based on the analysis of both design documents of company and undergraduate individual design projects. This, in turn, was evaluated against designers' views that were collected through two workshops.

Taken together, Figure 2-2 summarises three aspects of triangulation used in the research presented in this thesis.

- Data triangulation
  - Literature (Papers, Books)
  - Views of designers (Company A)
  - Design related documents from industry (Company A)
  - Design cases from academe and industry (University of Strathclyde, SFS, and Company A)
- Method triangulation
  - Literature review
  - Content analysis (Company A)
  - Protocol analysis (University of Strathclyde)
  - Workshop and questionnaire (Company A and SFS)
- Theory triangulation
  - Model development (Content analysis, Protocol analysis)
  - Model evaluation (Questionnaire)

Figure 2-2: Triangulation in the research

Having decided on the choice of philosophy and research methods, the next section attempts to address the issue of research structure in further detail.

2.4 RESEARCH DESIGN

In the light of the research philosophy and multiple methods chosen for the study, the research structure as shown in Figure 2-3 was designed. It should be noted that this framework was based on and derived from the research methodology developed by Duffy and O'Donnell (1998), which was successfully applied in the CAD centre, University of Strathclyde (Zhang 1999; O'Donnell 2000; Wu 2004).

Here, the overall approach is characterised as triangulation and the final decision on research has been addressed with the use of two related means of research: first, protocol analysis of student project work, and second the design practice of skilled designers from a company. These two means are used in both model development and evaluation. In all, the approach of the research presented in this thesis is explained in Figure 2-3, the research structure.

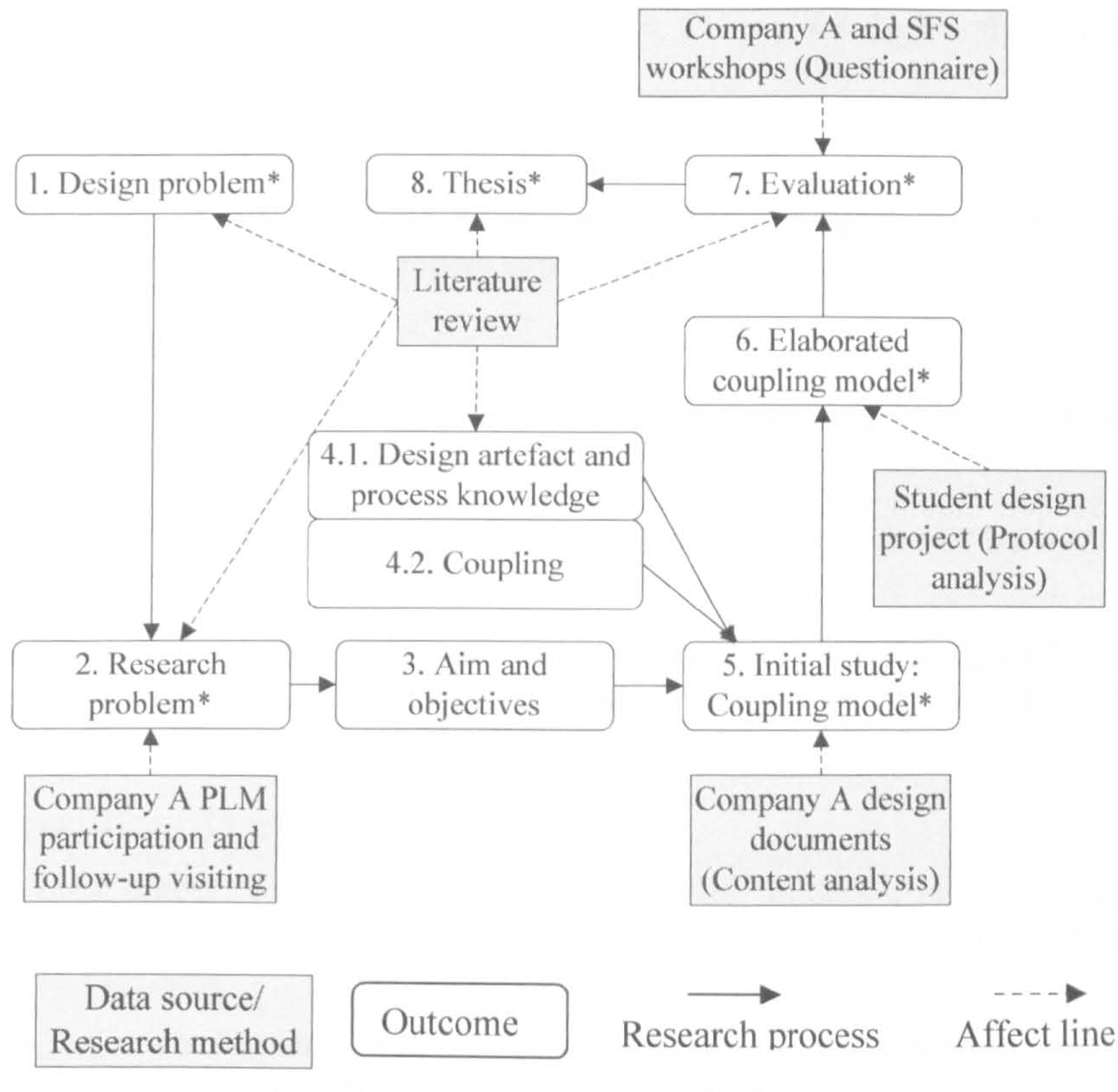


Figure 2-3: Research structure

As Figure 2-3 indicates, the research structure can be split into eight stages with their related outcomes. A brief explanation of the outcomes after each stage is given below.

1. Design problem:

Through initial literature review of the research conducted in design knowledge, a lack of sufficient formalised body of knowledge between artefact knowledge and design process knowledge was identified (see Chapter 3 and Chapter 4).

2. Research problem

Through further literature review and the author's participation of PLM project in Company A from 2004 to 2005, and a follow-up visiting in 2005, the research focus was identified as: "to investigate the coupling of evolutionary artefact and design process knowledge" (See Chapter 4).

3. Aim and objectives

Having identified the research problem, the aim and objectives of the research were then adjudged (See Section 1.2).

4. Review on design artefact and process knowledge and the coupling

Through a critical literature review, a state of the art research on design knowledge was reviewed with the focus on design artefact, design process knowledge (in Chapter 3), and the coupling of them (in Chapter 4). Then the requirement towards better understanding of design knowledge coupling is analysed in Chapter 4. Chapter 4.4 depicts the formalisation of research problem.

5. Initial solution

A content analysis of design related documents from Company A was carried out, which resulted in an initial coupling. The model is presented in Chapter 5.

6. Evolved solution

The coupling of artefact and design process knowledge was further identified and evolved through protocol analysis of a supervised student design project. Chapter 6 and Chapter 7 present the coupling knowledge elements and the evolved coupling model respectively.

7. Evaluation

The model was then evaluated by comparing it with industrial designers' view of the coupling, which was collected through questionnaires answered by designers during two workshops in SFS and Company A. The evaluation is presented in Chapter 8.

8. Documentation—Thesis

This is the main output of this research project. In writing the thesis, particular attention was given to Perry's (1998) five-chapter model of thesis writing, which built the standard basis for producing the thesis.

In order to make sure that the research work has been done appropriately and in a sound methodological manner, a regular check and verification of the work was conducted. To this end, questions such as "whether what the researchers have done is in line with their research aims and questions?"; "is the methodology adopted appropriate?" were asked and reviewed to ensure the validity and reliability of the whole research process. In short, such monitoring processes have also been identified in the above framework, which are shown with "*" mark.

Chapter 3 DESIGN ARTEFACT AND PROCESS KNOWLEDGE

Designing is considered as one of the significant intelligent human activities due to its complexity (Gero and McNeill 1998). Engineering design generally begins with incomplete knowledge, which can be regarded as an ambiguous requirement or idea for an artefact. The design then evolves as it progresses from the initial conceptual design stage to a more detailed design, while the former produces concepts for the whole or different parts of an artefact; the latter gives a precise and detailed description of the artefact (Pahl and Beitz 1996). Throughout this process, considerable knowledge is involved, either used or generated by designers. For example, in aerospace design, approximately 40,000 documents are produced for a design of a single aero engine (Ahmed and Wallace 2006). The knowledge involved in design is complex and heterogeneous, covering different disciplines such as geometry, logics, mathematics, mechanics, physics, psychology, and thermodynamics (Pahl and Beitz 1996). Moreover, some particular types of knowledge interact with and evolve together during design development (Klein 2000).

Despite its complexity and the plethora of research on this topic, design knowledge has not yet received enough attention with a particular focus on the fundamental aspects of evolutionary artefact and process knowledge, especially the coupling between these two types of knowledge. This chapter aims to present a review of artefact and design process knowledge through first, presenting a design knowledge pyramid (Wang and Duffy 2007) in Section 3.1, which is a framework describing how knowledge-based design research is structured; second, providing an overview of design knowledge classification in Section 3.2 based on its content; third and fourth, the basic knowledge elements of both the artefact and design process are discussed respectively from a knowledge level (Newell 1982; Smithers 1998) in Section 3.3 and 3.4. Section 3.5 summarises this chapter.

3.1 A KNOWLEDGE PYRAMID IN DESIGN SUPPORT

Engineering design research aims to explore, describe, rationalise, and utilise design knowledge. Designers obtain design knowledge from various sources, either theoretically or empirically. According to Horvath and Duhovnik (2005), there are four sources of design knowledge: (1) natural phenomenon of design, (2) scientific knowledge, (3) professional (including craft and art) knowledge, and (4) human common sense knowledge. When all these sources are intertwined and combined, the outcome can be termed "design knowledge".

To support knowledge based design development, considerable research has been conducted from various perspectives and levels. For example, the research on knowledge-based design support systems (KBDSSs) (Coyne 1990), generic design artefact or process modelling (Roozenburg and Eekels 1995), and the inherent quality of design knowledge itself (Alberts 1994; Sim and Duffy 2003; Aken 2005) represent some of the previous work, which has aimed at enhancing and developing knowledge-based design.

Despite the appearance of disparate research on knowledge-based design support, there seems to be an underlying research pattern in this area that can be regarded as a foundation for KBDSSs research. This pattern is presented as the design research pyramid in this section, of which a three layer research framework lays underneath the various research. In this three-layer framework, design knowledge builds the ontological basis, providing support for the development of knowledge models. At the top of this pyramid, the application layer, KBDSSs provide support for design development based on the middle layer, design knowledge models.

3.1.1 Knowledge-based design support systems

To support design development (O'Donnell and Duffy 2002), a number of KBDSSs and knowledge representation techniques (Iwasaki et al. 1995; Sasajima et al. 1996; Al-salka et al. 1998; Vranes and Stanojevic 1999; Ursu 2000; Hatzilygeroudis and Prentzas 2004) have been developed. In this thesis, a knowledge-based design support system, as one kind of computer aided design system, refers to a system that a knowledge base is associated with storing knowledge intended to support design development more efficiently and effectively through numerous applications. In this respect, C^3 (Nomaguchi and Tomiyama 2004), CONGEN (Gorti and Sriram 1996), CODSAS (Al-salka et al. 1998), DGLs (Filippi and Cristofolini 2007), Dominic (Howe et al. 1986), KIEF (Yoshioka et al. 1998), *n*-dim (n-dim Group 2001), NIST (Szykman et al. 2000), NoDes (Kavakli 2001), REV-ENGE (Kim and Bekey 1994), SWPK (Ociepka and Swider 2004), and among others, are examples of KBDSSs.

There are two categories of design support system that reflect different extremes of the philosophy concerning their role in design (MacCallum 1990), i.e., automated design systems and design assistant systems. While the former considers a design support system to be a designers' substitute and could conduct designing independently after it is input of the design requirements, the latter considers it to be a designers' subordinate, meaning the system could not completely substitute for a designer, but rather supports designers with fast reliable computing and large storage capacity.

A closer look at the aforementioned systems shows that they were developed to support one type of design or one, as opposed to all, of the design phases (Pahl and Beitz 1996), thereby solving one type of design or one specific design problem. For example, CONGEN, SWPK, and CODSAS were specifically developed for conceptual design, a phase of the design process that identifies basic solutions; Chawla and Sangal (1992) described a system for configuration design, a phase of the design process that generates artefact descriptions; and REV-ENGE was developed for synthesis of Design-for-Assembly redesign. As a result, different knowledge models are required for different types of systems and applications.

3.1.2 Design knowledge modelling

Within the AI domain, Newell (1982) proposed knowledge level, an abstraction level above the program/symbol level in the computer system levels. In this level, knowledge acts as medium that processed by "agent". Smithers argued the need for knowledge level theories of design process (Smithers 1996, 1998). To support design from a knowledge level, KBDSSs are normally based on design knowledge models (Al-salka et al. 1998; Leeuwen and Wagter 1998). Therefore, in order to develop and implement these design support systems, design knowledge models are generally required to provide an appropriate knowledge framework for them. Design knowledge is then structured in the defined framework. As mentioned earlier, most knowledge-based design support systems provide support for just one specific type of design or design problem, or for one specific design phase. Accordingly, design research has resulted in a number of design knowledge models representing the design artefact or process for various design situations to meet different purposes (e.g. Gero 1990; Takeda, Veerkamp et al. 1990; Alberts et al. 1992; Brazier et al. 1994; Zha and Lu 2002).

Generally, there are two main categories of design knowledge models: one reflects the design artefact and the other design process (Takeda, Veerkamp et al. 1990). This division is based on the knowledge content classification that will be discussed in the next section. Of these two categories, the former describes different aspects of the artefact, such as functional, behavioural or structural model. For example, the FBS model proposed by Gero (1990) introduced function, behaviour, and structure as the basic types of artefact knowledge. In order to support evolving design knowledge, SHOOD (Nguyen and Rieu 1992), an artefact knowledge model then, provided a flexible mechanism to support applications in which knowledge may evolve. Similarly, Deneux and Wang (2000) proposed a knowledge model in which artefact concepts and relations were represented as nodes and edges in a knowledge network.

The latter category represents knowledge models of the design process that includes, for instance, descriptive, prescriptive, and/or computational (Finger and Dixon 1989). Descriptive models can be further divided into two sub-categories. One is protocol studies, which consider how designers design and perform in the design process. The other is cognitive models, which address the description, simulation, or emulation of the mental processes used by designers during the process of creating a design (Finger and Dixon 1989). Typical work following this category can be found in Adelson (1989), Darlington et al. (1998), Kruger and Cross (2001), Maher and Tang (2003), Pons and Raine (2005), and Reymen et al. (2006). Prescriptive models show how the design process should be organised and executed. They integrate many different aspects involved in the design process in such a way that the whole design process becomes logical and comprehensible (Pahl and Beitz 1996). Prescriptive design process models also offer systematic procedures of the design process that makes it more transparent and effective (Finger and Dixon 1989). Examples of design process models in this category can be found in Hubka (1982), Pahl and Beitz (1996), Ullman (1997), and Reymen et al. (2006). The last category, computational models express methods, which are formalisation of, for example, the tasks, information, and procedures involved in the design process. Based on computational models, along with available computer techniques, computer systems can be developed to accomplish design tasks automatically or interactively. In this respect, Smithers (1990), Takeda et al. (1992), Tomiyama (1994), Gero (1996), Sushkov et al. (1995), and Braha and Reich (2003), for example, have focused on specific aspects of the design process and developed various computational design process models.

In addition to the aforementioned artefact and design process knowledge models, there are some others that are combinations. For example, the Common Product Data Model (CPDM), developed by Cambridge University's Engineering Design Centre (Ball et al. 1998), supports both artefact and process description. At the same time, Gorti et al. (1998) put forward the SHARED object model, which could model design knowledge including both artefact and process. Moreover, Brazier et al. (1994) developed a generic task model of design in which artefact and design process knowledge were combined by relating design artefact and process to subtasks of this model.

To construct a design knowledge model, design knowledge can be described or explained in terms of ontologies, which clarify the nature of design knowledge by defining different types of design knowledge, their relationships, and basic operations to knowledge chunks (Alberts 1994; Chandrasekaran et al. 1998; Sim and Duffy 2003; Aurisicchio et al. 2006).

3.1.3 Design knowledge ontologies

Ontology is a branch of philosophy that deals with the nature of existence by clarifying the nature and structure of the world (Sim and Duffy 2003). In artificial intelligence, ontology means a formal system for representing domain concepts and their related linguistic realisations by using basic elements (Chandrasekaran et al. 1998). Uschold and Grundinger (1996) advocated ontology in order to have a shared understanding as a unifying framework for different viewpoints. This section explores the complexity and heterogeneity of knowledge involved in design by presenting a description of design knowledge ontology – which is a depiction of different design knowledge classifications from different points of view. A review of related literature reveals that there has been a variety of classifications of design knowledge. With regard to different researchers' views of the classifications, there appear to be some inconsistencies among them, which seems to stem from the researchers' different research objectives, approaches, and adopted principles and standards. To this end, this section gives an account of some of the most commonly used classifications in engineering design while attempting to accommodate such differences. The following nine classifications are examples of the types of design knowledge. The list is not meant to be exhaustive but more indicative of the engineering design domain.

- Current working and domain (Zhang 1999);
- Declarative and procedural (Achten et al. 1998);
- Descriptive and prescriptive (Roozenburg and Eekels 1995; Aken 2005);
- Documented and undocumented (Ishino and Jin 2002);
- Formal and informal (Conklin 1996);
- Qualitative and quantitative (Gero 1990);
- Tacit and explicit (Nonaka and Takeuchi 1995);
- Textual and graphical (Al-salka et al. 1998); and
- Design artefact, process, management, and supplementary (Takeda, Veerkamp et al. 1990; Ishino and Jin 2002).

Of these classifications, the first eight could be applied to general knowledge. That is, they are suitable to classifications of knowledge not only in engineering design but also in other disciplines. However, the last one, design artefact, process, management, and supplementary knowledge, is dedicated to knowledge classification in the engineering design domain. Table 3-1 summarises the nine design knowledge ontologies, of which a more detailed explanation can be found in Appendix A.

Table 3-1: Classifications of engineering design knowledge

Classification viewpoints	Knowledge types	Examples
Source	Current working knowledge	Functions of the current working design
	Domain knowledge	Functions of a past design case
Cognition	Declarative knowledge	Artefact functions
	Procedural knowledge	Artefact behaviour and consequent functional results
Function	Descriptive knowledge	Components of a finished design
	Prescriptive knowledge	Description of what components should a design has
Availability	Documented knowledge	Company procedures
	Undocumented knowledge	Designers' intuition of a design
Style	Formal knowledge	Company procedures
	Informal knowledge	Design concept sketches
Accountability	Quantitative knowledge	Dimension of the structure components
	Qualitative knowledge	Rationale used in decision making
Accessibility	Tacit knowledge	Design experience
	Explicit knowledge	Physical laws
Representation	Textual Knowledge	Paragraphs describing design specification
	Graphical knowledge	3D drawing of a design
Content	Design artefact knowledge	Functions, behaviours, structures, causal relationships, constraints
	Design process knowledge	Design goals, activities, resources, inputs, outputs, contexts, issues

Classification viewpoints	Knowledge types	Examples
	Design management knowledge	Process planning knowledge
	Design supplementary knowledge	Enterprise cultures, national policy strategies.

It should be noted that, with different views, a chunk of knowledge could belong to different knowledge types within different classifications at the same time. That is to say, it could be both declarative and prescriptive knowledge, it could also be documented, explicit, symbolic, and domain knowledge at the same time.

3.1.4 Design knowledge pyramid

From the above discussion, a design knowledge pyramid was derived, as shown in Figure 3-1. In this pyramid, research on the ontologies of design knowledge builds the base layer. As Chandrasekaran et al. (1998) pointed out, ontologies are situated in the heart of any knowledge representation system. Therefore, ontology research provides support for the development of design knowledge models. Research in this layer could, for example, define different categories of knowledge and reveal the relationships among them.

Above the ontology layer, lays the model layer, in which research is conducted to represent processes or objects with knowledge models based on the basic research conduced in the ontology layer. Depending on the objective of the research, different types of models may be built, such as descriptive and/or prescriptive. Therefore, to develop such models, researchers normally need to identify the knowledge elements needed to be considered in the models, as well as their relationships in order to build the models that could reveal the processes/objects in the real world.

Based on the model layer, the application layer is located at the top of the pyramid, where research on KBDSSs is conducted, providing direct support for various aspects of design development (for example, configuration design or design decision support). That is, design knowledge models, located in the middle of the pyramid, play the role of connecting the basic research on design knowledge with that of design support applications.

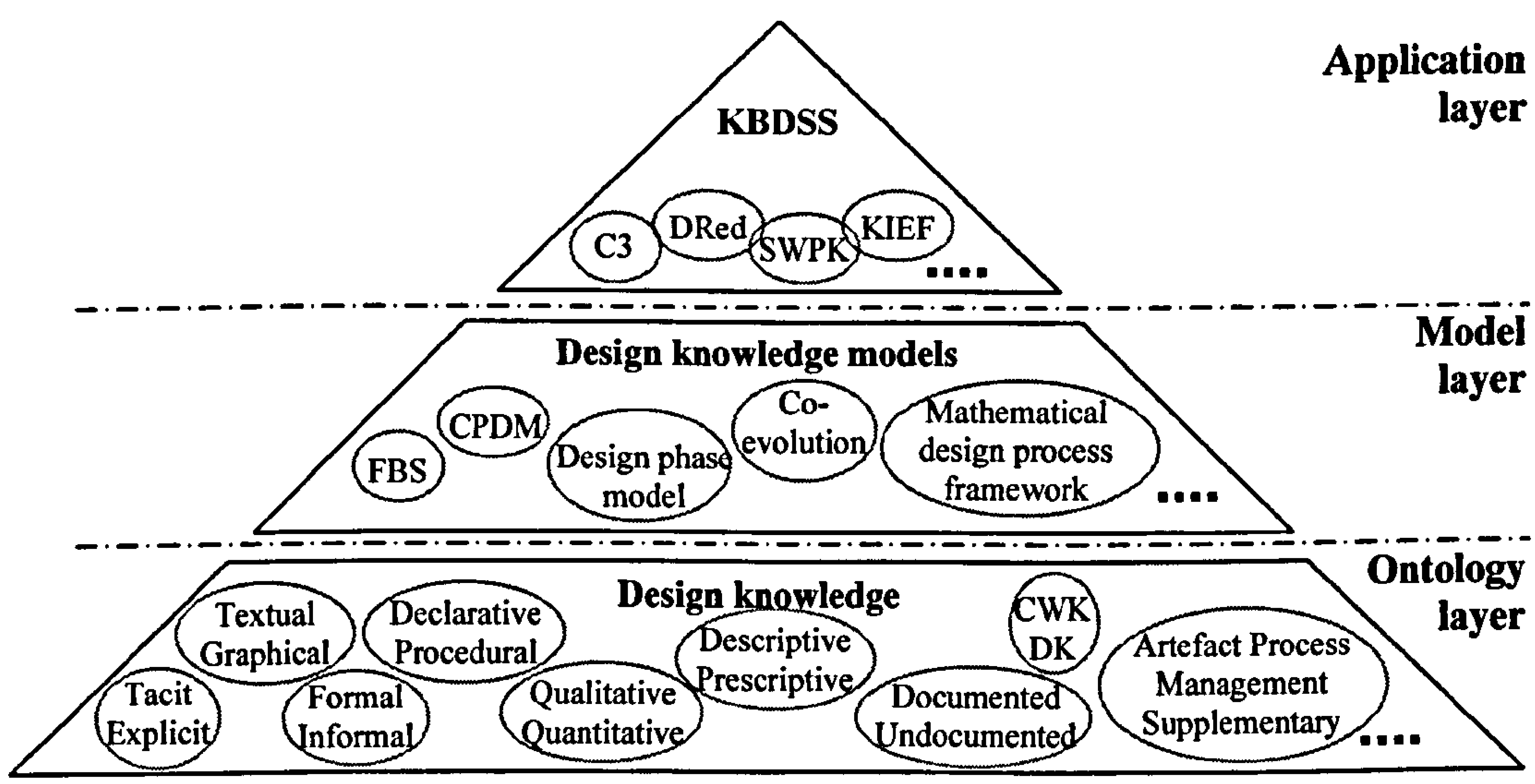


Figure 3-1: Design knowledge pyramid in supporting designing (Wang and Duffy 2007)

A pyramid is used here to indicate that the research in the upper layer is more domain focused than the one in the lower layer, or the research is more domain dedicated, which is called domain zooming-in character of the pyramid. For example, a design process model in the middle layer could be a domain-independent model such as (Reymen et al. 2006), or an engineering design process model such as (Pahl and Beitz 1996). However, a KBDSS in the top layer normally is dedicated to a specific design problem, design phase or artefact, such as design synthesis, conceptual design or aircraft design.

A typical illustration of this pyramid could be found in (Zhang 1999) (see Figure 3-2), in which the DeNote system was developed to support modelling and management for CWK evolution. The system is based on a Multi-Viewpoint Evolutionary Current Working Knowledge and Domain Knowledge Models, with a management mechanism and utilisation schema. Within the knowledge model, design artefact knowledge is represented by CWK and DK, which include function, working principle, solution, behaviour, etc.

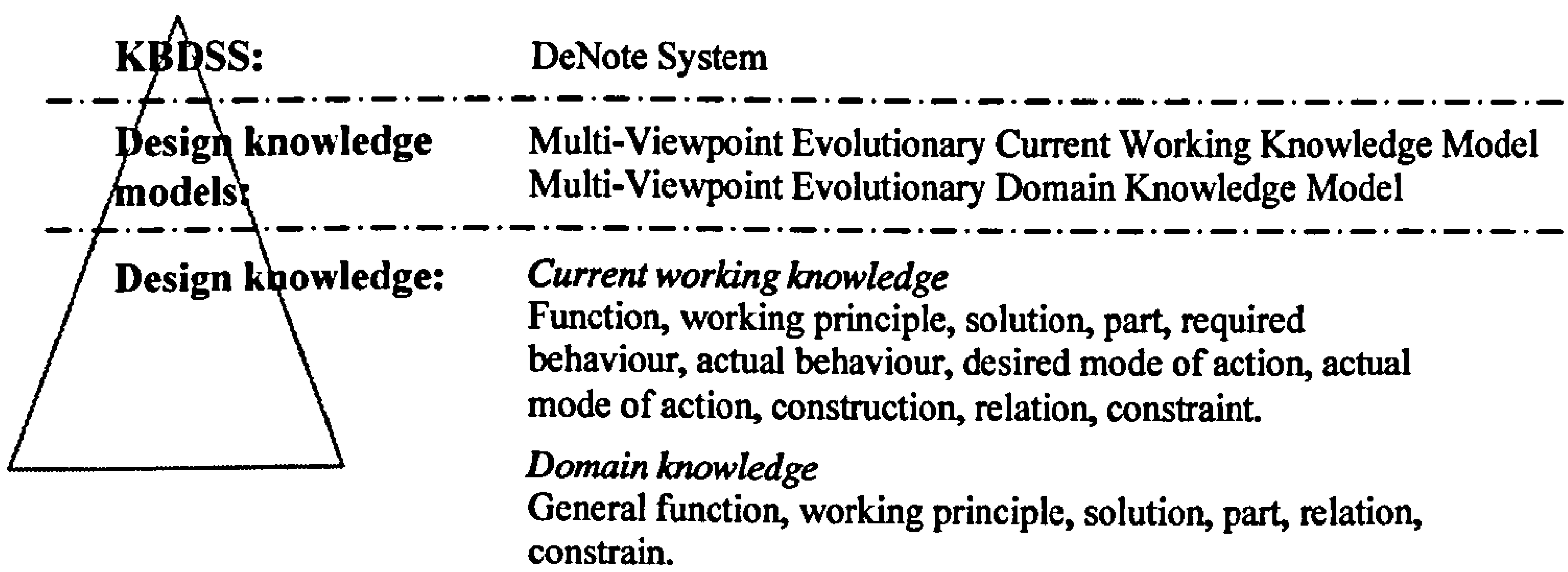


Figure 3-2: An example of the research pyramid

Presenting a formalism of engineering design research, Horvath (2004) presented a comprehensive framework of design research, which organised research into category, domain, and trajectory. In addition, Duffy and O'Donnell (1998) presented a research framework (see Figure 3-3) for conducting design research, which showed a holistic view, as well as the evolution of the framework through the research affecting reality.

To some extent, the research pyramid is similar to Duffy and O'Donnell's research framework in that both contain three aspects of design research, i.e., knowledge (which was termed phenomena in (Duffy and O'Donnell 1998)), model, and system (which was termed computer model in (Duffy and O'Donnell 1998)). However, compared with their work, the three layered framework focuses on knowledge-based design support research and presents a pattern towards directly supporting design by application systems. In addition, the pyramid reveals the domain zooming-in characteristic of different levels of research. Therefore, it provides novice researchers a framework for positioning their research.

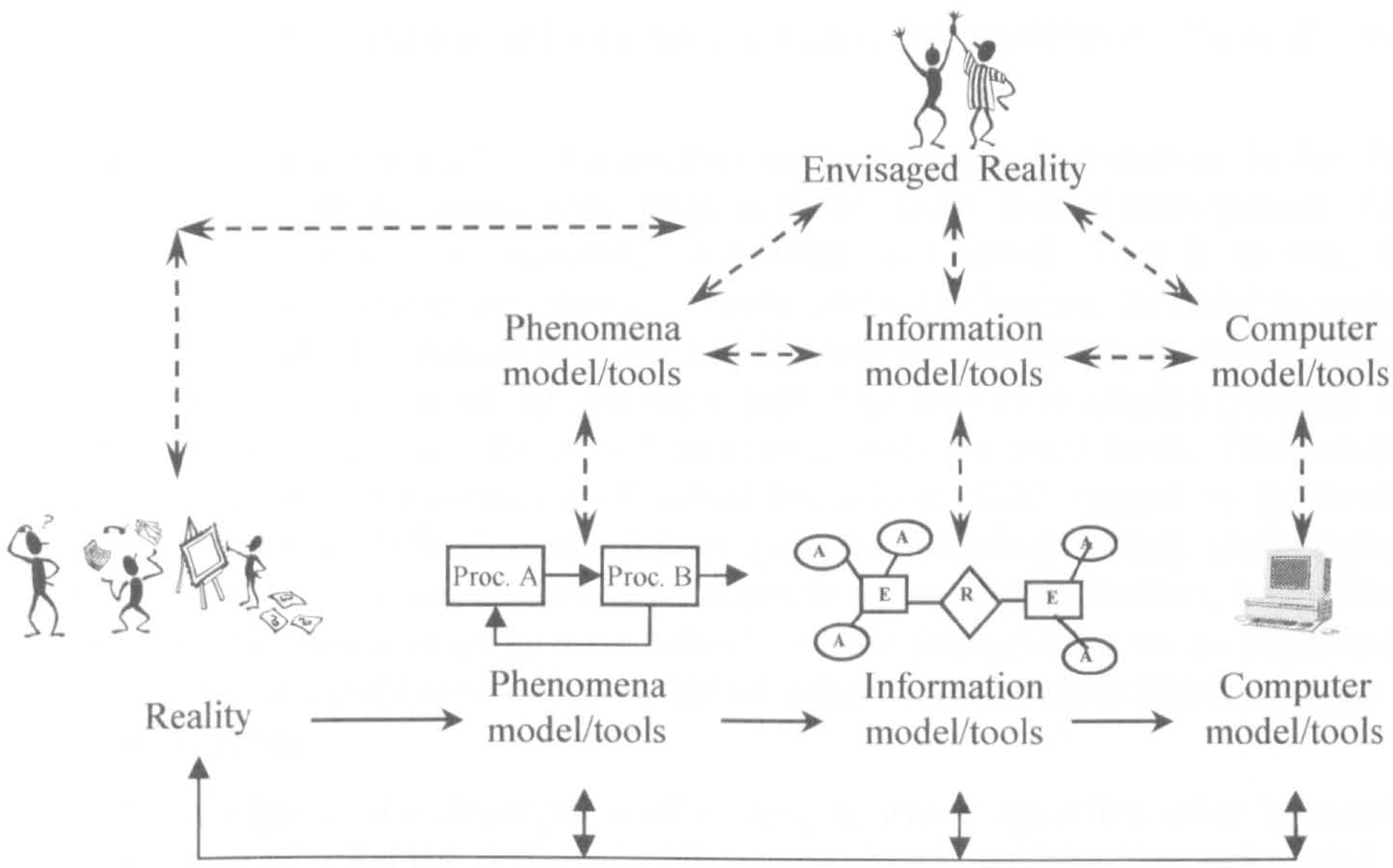


Figure 3-3: Research framework by Duffy and O'Donnell (1998)

As mentioned in Section 3.1.3, of the nine design knowledge classifications, the last one – design artefact, process, management, and supplementary knowledge, is dedicated to the engineering design domain. The next section discusses this classification in more detail.

3.2 DESIGN KNOWLEDGE CONTENT ONTOLOGY

A frequently used classification of design knowledge is associated with its content. In this respect, a number of researchers (e.g. Tomiyama and ten Hagen 1987; Takeda, Veerkamp et al. 1990; Treur and Veerkamp 1992; Yoshioka 1993; Gorti et al. 1998; Brissaud et al. 2003) have generally recognised that design knowledge is composed of knowledge about the design artefact and design process. Moreover, there is design management knowledge that is used to manage the design process (O'Donnell and Duffy 2005), and design supplementary knowledge, which does not belong to the former three types of design knowledge, though used and considered in the design process.

3.2.1 Design artefact knowledge

The design artefact refers to the object being designed to meet some requirements. As a result of designing, design solutions are represented with various combinations of functional and structural descriptions (Chakrabarti 1993). Accordingly, design artefact knowledge is the knowledge that concerns the nature of the artefact, for example, what the design is used for, how the design works and how the design is constructed (Zhang 1999). Bunge (1966) regards artefact knowledge as "substantive knowledge", which fundamentally includes function, behaviour, and structure of the design artefact (Gero 1990; Umeda et al. 1990; Takeda et al. 1996; Gorti et al. 1998). In addition to these three fundamental elements, design artefact knowledge also contains design motivation (Smithers 1998), requirements (Chakrabarti et al. 2004), constraints of these three elements (Zhang 1999; Chen and Lin 2002), and any associated relationships (Gorti et al. 1998; Gero and Kannengiesser 2004).

Functional knowledge describes the purpose of the artefact structure (Qian and Gero 1996). It expresses the state or a series of states that the device is required to achieve or avoid under specific conditions (Chandrasekaran 1990). According to where it is derived, function could be divided into expected and/or actual function (Rosenman and Gero 1998). The former is derived from the design purpose, which is the description of the artefact intention. However, the latter is derived from the artefact structure, which is the description of how the artefact could be used.

Behavioural knowledge reveals how the artefact works to realise its function. In the situated function-behaviour-structure framework proposed by Gero and Kannengiesser (2004), behaviour was categorised to expected, interpreted, and actual. That is to say, during designing, people have some expectations towards artefact behaviour in order to realise its function, which are called expected behaviour of the artefact. However, the actual behaviour of a designed artefact will depend only on the actual structure of the artefact (Bobrow 1984), and that can be derived from the actual structure, with physical laws. The interpreted behaviour is designers' interpretation of actual behaviour. With regard to its functional character, Qian and Gero (1996) talk about three types of behaviour namely spatial, temporal, and aesthetic. Moreover, whether a behaviour depends on any external effect, it could belong to either structure behaviour or exogenous behaviour. The former refers to the behaviour that is derived from the structure without any external effect, and the latter needs a trigger from outside of the structure.

Structural knowledge is the description of a design, which specifies what elements the design is composed of, what the attributes of the elements are and how they are related. Thus, structural knowledge contains components, attributes of the components, and relationships[4] among components (Qian and Gero 1996).

In addition to the aforementioned three fundamental types (i.e. functional, behavioural, and structural), design artefact knowledge also includes design motivations, design requirements, causal relationships, and constraints. The ***design motivations*** are the customers' needs or desires or the designers' will for changing the world (Smithers 1998). The ***design requirements*** formalise the motivation in the design space, which are characteristics expected to be fulfilled by designers through the design solution (Chakrabarti et al. 2004). The ***causal relationships*** here do not refer to the physical relationships mentioned in structural knowledge, but the causal relationships among function, behaviour, and structure, and are thus logical relationships. For example, the relationship that used for deriving expected behaviour from expected function. Design ***constraints*** reflect the requirements that need to be satisfied by design parameters (Nomaguchi and Tomiyama 2004). During designing, design constraints limit the freedom of choices of these parameters. Different from the three fundamental artefact knowledge types, the design motivation, requirements, causal relationship, and constraints are not knowledge of the artefact. Rather, they are contextual knowledge that is referred by designers that are closely related with the knowledge of the artefact.

3.2.2 Design process knowledge

A design process is composed of a continuous set of design activities or operations, which are executed to determine the structure of the designed artefact that can fulfil some demands (Hubka and Eder 1996). As Aken (2005) has argued, it is the knowledge that realises the artefact. For Yoshioka (1993), design process knowledge is operational knowledge that manipulates design artefact knowledge. In a similar vein, Bunge (1966) uses "operative knowledge" to describe design process knowledge. Thus, design process knowledge can be thought of as typically meta-level or action-level knowledge and controls object level reasoning activities (Nomaguchi and Tomiyama 2002).

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[4] a. This relationship refers to the physical and spatial relationshi, among structural components.
b. Qian and Gero also mentioned operations and processes as part of structure, which specially used in software engineering and chemical control systems. However the operations and processes can be regarded as components of the structural knowledge.

From a knowledge level perspective of the cognitive problem solving process presented in the literature, with regard to the knowledge elements of a design process, it includes ***design activity*** (Duffy 2002; Sim and Duffy 2003; O'Donnell and Duffy 2005), which is a rational action carried out by a design agent to achieve a knowledge change of the design and/or its associated process in order to achieve some design goal (Sim and Duffy 2003). Accordingly, process knowledge also includes ***design goal*** (Duffy 2002; Sim and Duffy 2004) that directs and constrains the activity, ***input knowledge*** (Sim and Duffy 2004) that is manipulated by the activity and ***output knowledge*** (Sim and Duffy 2004) as the result of carrying out the activity. In addition, ***resources*** (O'Donnell and Duffy 2005) are utilised within the design activity, which constitutes another knowledge element of the process.

In addition to the above five fundamental knowledge elements of the design process, there are design context and design issue that belong to the scope of the design process. However, rather than fundamental to the design process, they constitute the contextual knowledge of the process, that is, ***design context*** is the circumstances within which the design activities are carried out. It contains the factors influencing the current design. ***Design issue*** is referred to have as the subject that arises from the design context that should be solved by designers.

3.2.3 Design management knowledge

In addition to artefact and design process knowledge, there is design management knowledge used by designers during design development, that concerns the characteristics and properties of a design process and is used to reason and manage the process (2005)[5]. Design management knowledge is used to plan and enact the design process and could be applied to improve design effectiveness and efficiency from the process level (Baldwin et al. 1997; O'Donnell and Duffy 2005). A number of factors are considered in doing so, such as allocation of resources, goal orientation, and technology and tools (Duffy 1997a). Knowledge from project management and organisational design literature are examples of this type of knowledge. Also, within the "Design Activity Management Model" presented by O'Donnell an Duffy (2005), the knowledge that concerned with the decisions that direct the design activities, i.e. manage design activities and enact the design process, is an example of this type of knowledge.

3.2.4 Design supplementary knowledge

As previously mentioned, knowledge involved in designing is complex. One of the reasons is that different types of knowledge are considered and used by designers during design development. With the focus being on the artefact and process knowledge, this thesis, therefore, terms another category of knowledge that does not belong to the earlier mentioned three main categories of design knowledge (i.e. design artefact, process, and management knowledge) as design supplementary knowledge. However, design supplementary knowledge is indispensable during design. Generally, this type of knowledge involves the environment, organisational culture, and designers' preferences. One example of design supplementary knowledge is cited in the metaprocess model proposed by Nomaguchi (2002), in which the author talks about a type of design information called "information referred in the design". Furthermore, Lu's (2000) reference to background knowledge to intention, preference, and cognition of designers is an indication of such knowledge. Design for X knowledge and team collaboration knowledge are some other examples of supplementary knowledge, considering the research focus in this thesis is the artefact and design process knowledge.

[5] The author used process knowledge to refer to management knowledge and "realization knowledge" was used to reflect what is referred to in this thesis as process knowledge.

3.2.5 Design knowledge topologies

From the above discussion on classifications of design knowledge based on its content, two topology relationships can be derived: one is the ***teleology topology***, and the other is the ***evolutionary topology***. They reveal the supportive and evolutionary relationships among design artefact, process, management, and supplementary knowledge, which is a classification based on design knowledge content.

Figure 3-4 illustrates the teleology topology of design knowledge, in which "supportive relationships" among the four types of knowledge are represented as uni-directional solid arrows. Dashed arrows in the model reflect "representation relationships" between these object entities in the material and ideology worlds. To illustrate these supportive relationships, for example, in the material world, the purpose of a design process is to deliver an artefact that meets some specific requirements, and the purpose of management activities is to manage the design process so that the design could be carried out in an effective and efficient way (O'Donnell and Duffy 2005). Since artefact, design process, and design management knowledge are representations of these object entities in an ideology world, they possess the same supportive relationship. That is to say, design management knowledge supports the development of design process knowledge, which provides support for design artefact knowledge evolution. Moreover, design supplementary knowledge, which provides background knowledge for designing, is used to support the development of the other three types of knowledge.

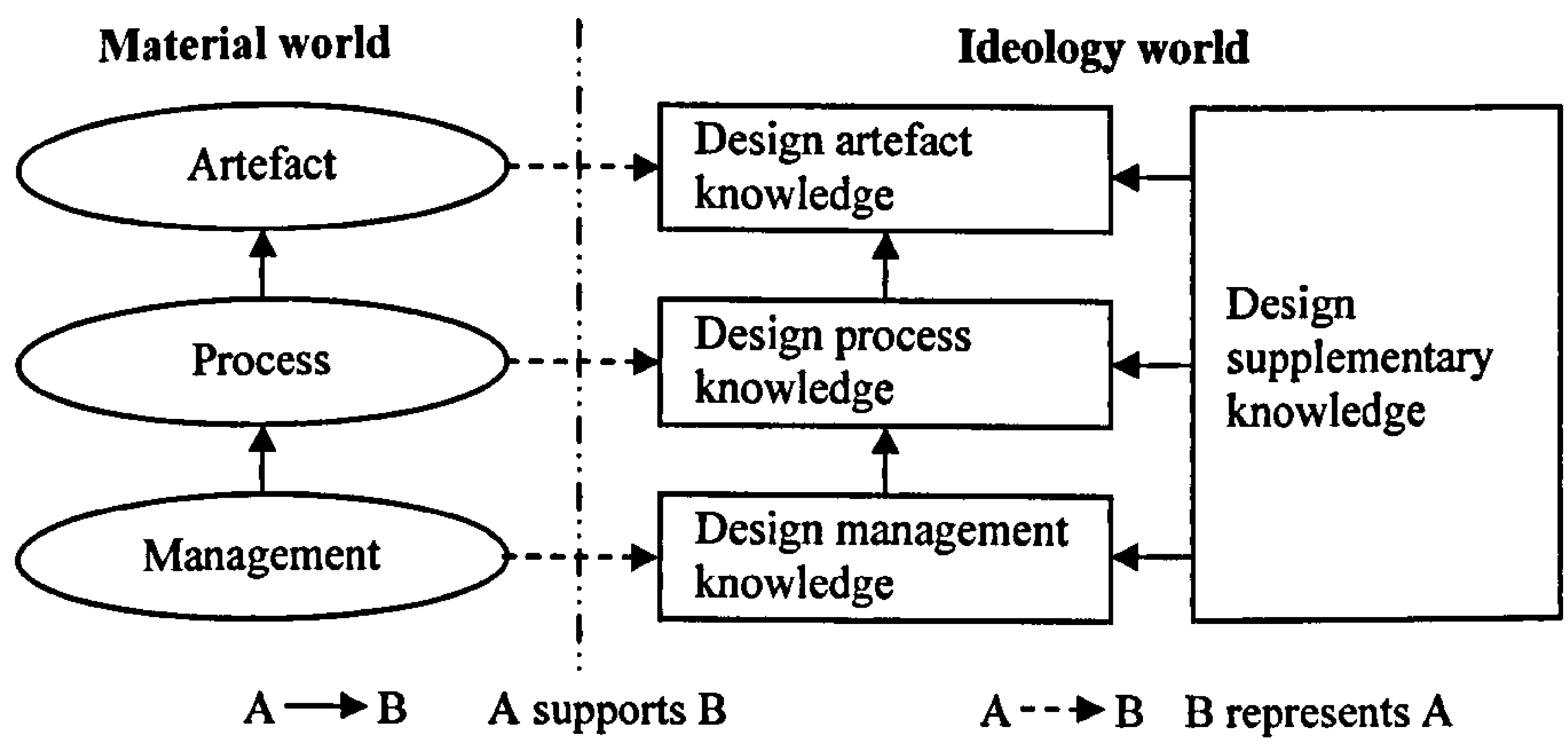


Figure 3-4: Teleology topology model of design knowledge

Design knowledge evolves throughout designing (Zhang 1999; Maher and Tang 2003) and the four aforementioned categories of design knowledge evolve each other from the outset. Accordingly, in addition to the teleology relationships among these four types of knowledge, there also exist "knowledge evolutionary relationships", depicted in Figure 3-5. As the figure indicates, there exist direct evolutionary relationships between artefact and design process knowledge, design process and design management knowledge, and design supplementary knowledge and the other three types of design knowledge. In addition, an indirect evolutionary relationship also exists between artefact and design management knowledge, which is represented with a dashed double arrow connector. Different from the supportive relationships in the teleology topology model, these evolutionary relationships are bi-directional. That is to say, for example, it is not only design process knowledge that evolves design artefact knowledge, the latter affects the former at the same time.

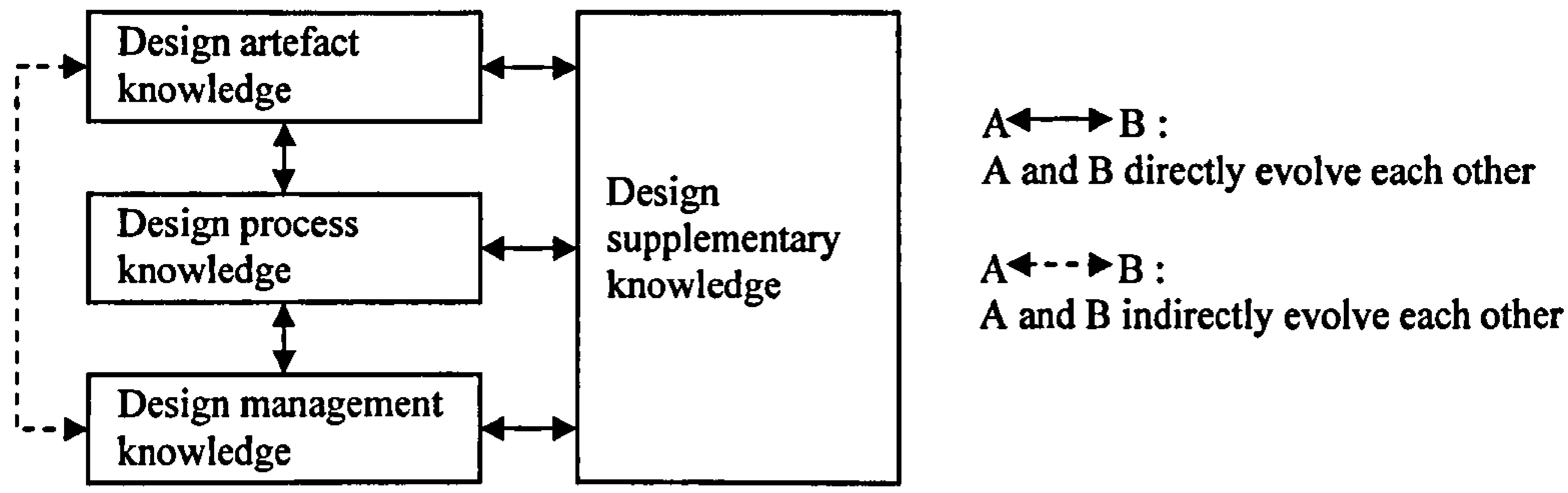


Figure 3-5: Knowledge evolutionary topology model of design knowledge

From the two topology models presented above, it can be observed that there is a close relationship and interaction between the artefact and design process knowledge. Before examining the relationships between them, the next two sections present a review of design knowledge with a particular focus on the artefact and design process.

3.3 DESIGN ARTEFACT KNOWLEDGE

As mentioned earlier, artefact knowledge is the knowledge that concerns the nature of the artefact. In particular, there are two main research issues associated with artefact knowledge modelling: one is specialised artefact knowledge modelling and the other is general artefact knowledge modelling. The former is applied to a particular domain such as knowledge modelling for aircraft or ships, and the latter to general design such as the research on artefact functions, behaviours, structures, constraints, and relationships that apply to different design domains, for example, architectural design, industrial design, graphical design, mechanical design, and software design. Rather than focusing on one particular design domain, this research will study design knowledge in general. Thus, this part of the review aims to explain the features and elements of general artefact knowledge. The evolution of the artefact knowledge is discussed at the end of this section. In addition, a post-positivism view of function behaviour structure is presented in this section resulting from the literature review and protocol study of a design project.

3.3.1 Features

As one primary type of design knowledge, design artefact knowledge possesses some main features. Of these, 'complexity' appears to be of high significance (Jonas 2005). It exists not only in the artefact itself with different elements such as structural, behavioural, and functional knowledge (and even within each kind there are multiple layers) (Thornton 1996; Gero and Kannengiesser 2003), but also embodied in its multi-disciplinary nature, with multi-representation with different users (Hubka and Eder 1990; Rosenman and Gero 1998; Zhang 1999). In addition, artefact knowledge of a current design does not keep static throughout the design process (Vajna et al. 2005). Thus, artefact knowledge can be considered to be complex and dynamic.

Complex

A review of previous work (See below) indicated that there exist several features of artefact knowledge that contribute to its complexity. Some examples of these features are as follows:

Hierarchical data: Design artefacts are usually composed of many design entities, which are either composite or primitive (which is the basic unit of structure and cannot be further decomposed) and have a hierarchical structure (Shen and Barthes 1994; Takeda et al. 1996; Pavlic et al. 2006; Pahl et al. 2007).

Semantic relationships: Various relationships exist among design entities with semantic meaning (e.g. dependency relationships among objects). As a result, they should be represented explicitly by semantic constructs. In fact, when determining the behaviours and functions of the artefacts, these relationships are as important as entities (Nguyen and Rieu 1992; Shen and Barthes 1994; Gorti and Sriram 1996; Gero and Kannengiesser 2004).

Multi-type or multimedia: Various data types and knowledge formalisms are used to describe the artefacts. For example, textual and graphical data are different data types. Declarative and procedural knowledge are examples of the knowledge formalisms that designers use to represent, manipulate, and reason about the artefact cognitively (Shen and Barthes 1994; Darlington et al. 1998; Klein 2000).

Integration of graphics: Design artefact knowledge is often integrated with graphics. By this integration, the concept of the design artefact can be presented by various sketches and the design result by detailed geometric model (Shen and Barthes 1994).

Incomplete and inconsistent requirements: Design can be initiated by requirements. However, not all the requirements are easy to be checked for fulfilment and some could be incomplete, inconsistent, and/or even impossible (Smithers 1998; Pahl et al. 2007).

Dynamic

The following characteristics highlight the dynamic nature of design artefact knowledge.

Dynamic evolution: Design artefact knowledge evolves throughout designing. The evolution of an artefact happens not only with their attributes and structure of the solution, but also their problem specification and function (Nguyen and Rieu 1992; Ullman et al. 1997; Zhang 1999; Maher and Tang 2003; Vajna et al. 2005).

Ambiguous input and design result: Design artefact knowledge begins with an ambiguous problem specification, design variables, and design goals (Smithers 1998; Pahl et al. 2007). As a result of designing, the design description provides an explicit and detailed characterisation of the designed artefact (Maher and Tang 2003).

Having discussed some basic features of design artefact knowledge, the next section explores elements of design artefact knowledge.

3.3.2 Elements

As mentioned in Section 3.2.1, there are seven types of artefact knowledge elements, which include fundamental functional, behavioural, and structural knowledge of the artefact, and contextual design motivations, requirements, causal relationships, and constraints. A review of these knowledge elements reveals that they are distributed among three knowledge spaces (Gero and Kannengiesser 2003) as presented in the following section.

3.3.2.1 Artefact knowledge spaces

From designers' viewpoint, as Gero and Kannengiesser (2004) have proposed, there exist three artefact knowledge spaces in design, namely expected, external (what we call here instantiated), and interpreted artefact knowledge spaces[6]. The expected design artefact knowledge space (ES) composes of designers' expectations towards a designed artefact, such as what components it will contain, how it will function and behave. The instantiated design

[6] Gero and Kannengiesser used 'world' instead of 'space' in describing the environment within which different types of knowledge exist.

artefact knowledge space (IsS) contains the design artefact knowledge that has been specified by designers and could be realised in a future implementation. Lastly, the interpreted design artefact knowledge space (ItS) exists in designers' mind, which is built up from their interpretation of the artefact being designed. These three design spaces contain design artefact knowledge in different states.

3.3.2.2 Function

The function of an artefact is its intention, purpose (Hybs and Gero 1992; Qian and Gero 1996; Deng et al. 1999), or as Hubka (1982) called it, duty of the artefact. It expresses the state or a series of states that the device is required to achieve or avoid under specific conditions (Chandrasekaran 1990). Put simply, the primary reason of designing an artefact is to meet some desired functions (Chandrasekaran and Josephson 2000; Ullman 2002). Similarly, Zeng and Cheng (1991) argue that the ultimate goal of designing is to create a form that displays the prescribed functions in its environment. Clearly, then, it is the prominent concept in determining an artefact's features (Umeda and Tomiyama 1997). In the early design phase, most of the design decisions are made with concern of the artefact functions (Roy et al. 2001). Much more specifically, function plays three roles during designing (Takeda et al. 1996). First, designers can use it as a modelling language to construct and develop design requirements. Second, it can link requirements and artefacts. Finally and third, it could be used to evaluate whether the artefacts meet their requirements in the later phase of design, i.e. when structural parameters are elaborated. Thus, functional knowledge is important in predicting, observing, describing, and verifying device behaviour (Iwasaki et al. 1995).

From a post-positivism viewpoint (See sections 2.2 and 2.3 about the research philosophy and the methodology adopted in the research presented in this thesis), artefact function is a subjective and situated concept (Gorti et al. 1998) and its existence depends on individual human being's expectation and interpretation of the artefact. Accordingly, function does not exist in IsS due to its subjective character. This is partly because, although a function could be recognised by designers in the IsS, it is still interpreted by human beings. Therefore, depending on whether it is derived from designers' intentional expectation towards the artefact to be designed, or their interpretation of the designed artefact, the artefact function can be categorised into two types: expected function (F_e) in the ES and interpreted function (F_{it}) in the ItS (Wang et al. 2007). The former stems from design requirements, which describes constraints, specifications of the artefact, regardless of whether these requirements are from customers, or from designers. Therefore, expected functions are the expectation or desire towards the function of the artefact. In contrast, the latter is derived from the artefact's instantiated structure and interpreted behaviour knowledge (see Section 3.3.2.3). As Hybs and Gero (1992) have argued, it is a representation of designers' perception of structure. Similarly, others (e.g. Sasajima et al. 1996; Takeda et al. 1996) explain interpreted function as an explanation of observed artefact behaviour when it works in a desired environment. Therefore, interpreted function becomes a combination of interpreted behaviours and these behaviours are observed based on a set of possible behaviours of the artefact (Sasajima et al. 1996).

This classification of function as being expected function and interpreted is similar with Chandrasekaran and Josephson's (2000) "function as effect" and "function as what a device does". However, their representation is based on whether the function description is environment-centric or device-centric. Though, artefact and its working environment are indivisible throughout designing. Although not designated to be one of these two types, i.e., expected and/or interpreted functions, the concepts of function mentioned by some other researchers only refer to either expected or interpreted and not both. For example, Gero and Kannengiesser's (2003) definition of function as the teleology of a design object refers to the former. On the other hand, Zeng and Cheng's (1991 p.138) definition of function as the artefact's "response to the environmental actions according to some natural laws, rules and principles" and Sasajima et al.'s (1996) discussion of the function as the interpretation of behaviour under a desirable state can be considered as the latter, i.e. interpreted function.

A review of research on artefact function models shows there are two typical models representing artefact function: systems model, and activity and operands model.

Systems model of function

Pahl and Beitz (2007) describe function in a systems way as the intended input/output relationship of a technical system whose purpose is to perform a task, where inputs and outputs can be material, energy or information. In addition, in order to derive the desired output state, external controls and means may be adopted. Put in another way, function is the input and output relationship of an artefact with the effects of control and means (Hubka 1982; Ullman 1993). According to Deng et al. (1999), an artefact can only function in a certain (intended) working environment. Viewed in this way, a systems model of function can be represented in terms of its input state, output state, controls, means by which function is performed, and the working environment within which the function is performed (see Figure 3-6).

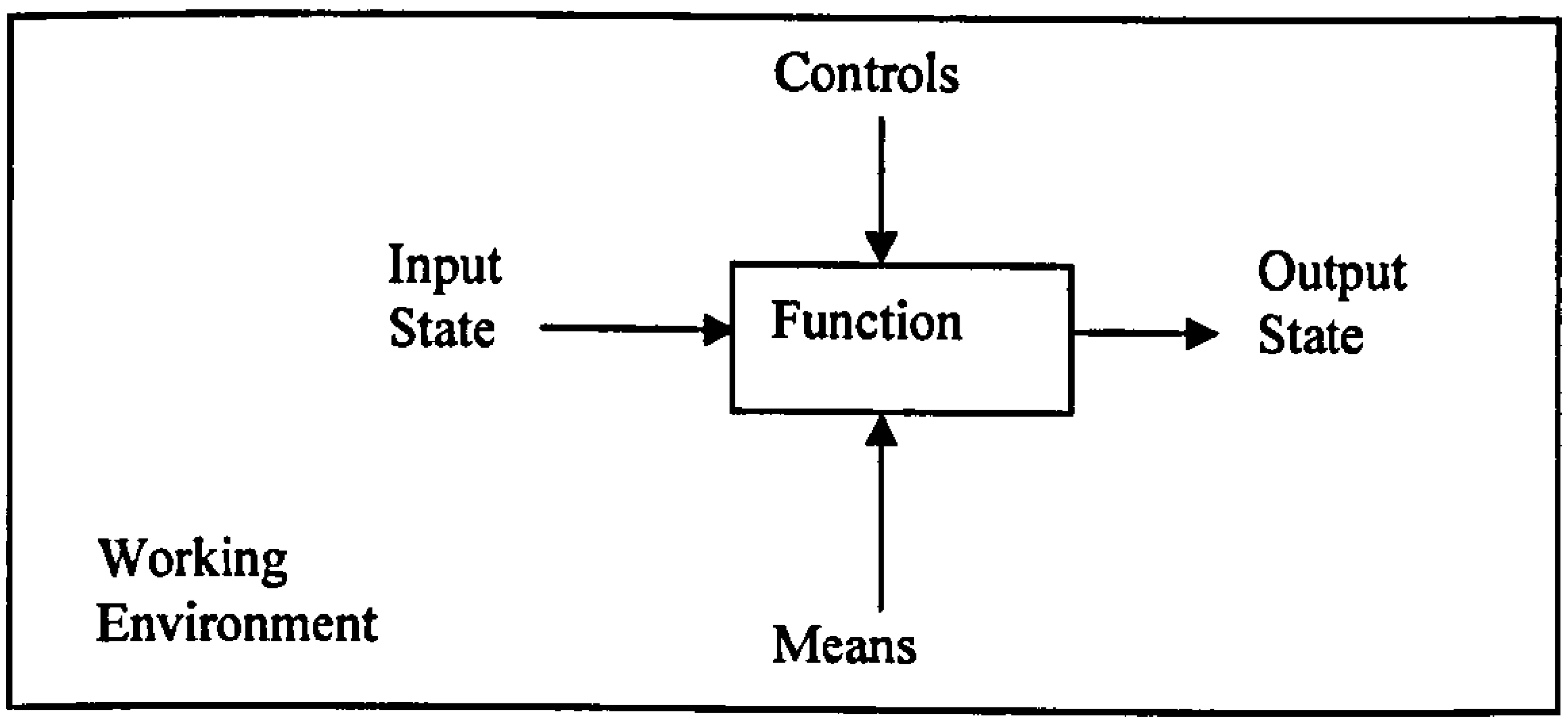


Figure 3-6: Systems model of function (Adapted from Ullman (1993, p.22))

A model with activities and operands

For Matousek (1963), function can be considered as the "action required" by the design problem. In his view, function could also be represented by an activity plus its operands (see Figure 3-7). Koller (1985 cited Ullman 1993, p.22) argues that there are thirteen elementary functions or action verbs as follows: change, change back, enlarge, reduce, change in direction, conduct, insulate, connect, separate, join, divide, store, and destore. These actions, as Pahl and Beitz (1996) argued, act on its operands, which could be material, energy or information.

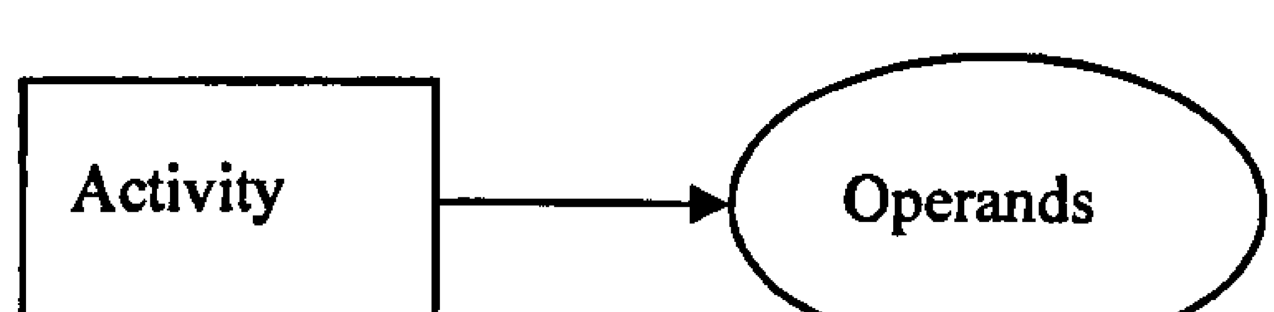


Figure 3-7: Function model with activity and operands

According to Kitamura et al. (2004), functional knowledge in the conceptual design phase is especially hard to capture. In order to facilitate the process of capturing functional knowledge, Pahl and Beitz (1996), and Kitamura et al. (2004), among others, presented a number of methods, namely: QFD (Quality Function Development), FMEA (Failure Mode and Effect Analysis) sheet, and fault trees in FTA (Fault Tree Analysis).

3.3.2.3 Behaviour

Simulating how the artefact works (Sasajima et al. 1996), behaviour describes what the artefact does, and how it achieves its functions (Gorti et al. 1998). Moreover, it is physical laws that control how an artefact demonstrates its behaviour through a series of status changes (Takeda et al. 1996; Deng et al. 1999). Generally, artefacts function in particular environments (Deng et al. 1999) and therefore, behaviour is affected by an artefact's interaction with its environment (Hybs and Gero 1992). For Qian and Gero (1996), a behaviour could be exhibited through two modes: it can either be derived from the structure without any external effect, or a trigger is needed from outside of the structure so that the behaviour could be conveyed. As a result, they are called either structure behaviour or exogenous behaviour. In addition, depending on its functional character, a behaviour could be classified into three types namely spatial, temporal, and aesthetic (Qian and Gero 1996). Spatial behaviour depicts how the objects behave in 2D or 3D space; temporal behaviour occurs according to specific time constraints; and aesthetic behaviour is the one that convey the visual or aural function of an artefact such as the satisfactory and pleasant feeling.

In comparison with function, behaviour could be derived entirely by objective qualitative physics or subject observation with a post-positivism viewpoint. Viewed in this regard, three types of behaviour can be employed in defining an artefact according to its origination, distributed among ES, IsS, and ItS respectively. The first is called expected behaviour (B_e), which are the attributes expected from the artefact's structure and derived from its expected function (see 3.3.2.2). The second is instantiated behaviour (B_{is}), which is also called behaviour of structure (Gero 1990). This type of behaviour is derived directly from the instantiated structure of the artefact that the designers are working on. Moreover, it is the instantiated behaviour that the artefact can exhibit with the designed structure. The last one, interpreted behaviour (B_{it}), refers to behaviour observed by designers and could be exhibited by an artefact in a particular environment, which is an explanation or the analysis of an artefact according to the designers' interpretation. According to Sasajima et al. (1996), interpreted behaviours are those selected by designers based on a set of possible working artefact behaviours. Accordingly, interpreted behaviour can then be used to evaluate the design (Malak and Paredis 2007).

Furthermore, during the course of designing, behaviour can be used for problem formulation, synthesis, analysis, evaluation, and reformulation (Qian and Gero 1996). These activities are realised by applying different types of the aforementioned behaviour. For example, whether interpreted behaviours are the same as expected behaviours is one criterion for evaluation of the designed artefact.

Systems model of behaviour

Similar to the systems model of function, the systems model of behaviour regards the artefact or components of the artefact as the centre, with the input, output object, and relationships between them (Sasajima et al. 1996). The input and output could be material, information, and energy. In consequence, the systems model of behaviour could be represented in terms of its input, output objects, and the relationships between them (see Figure 3-8).

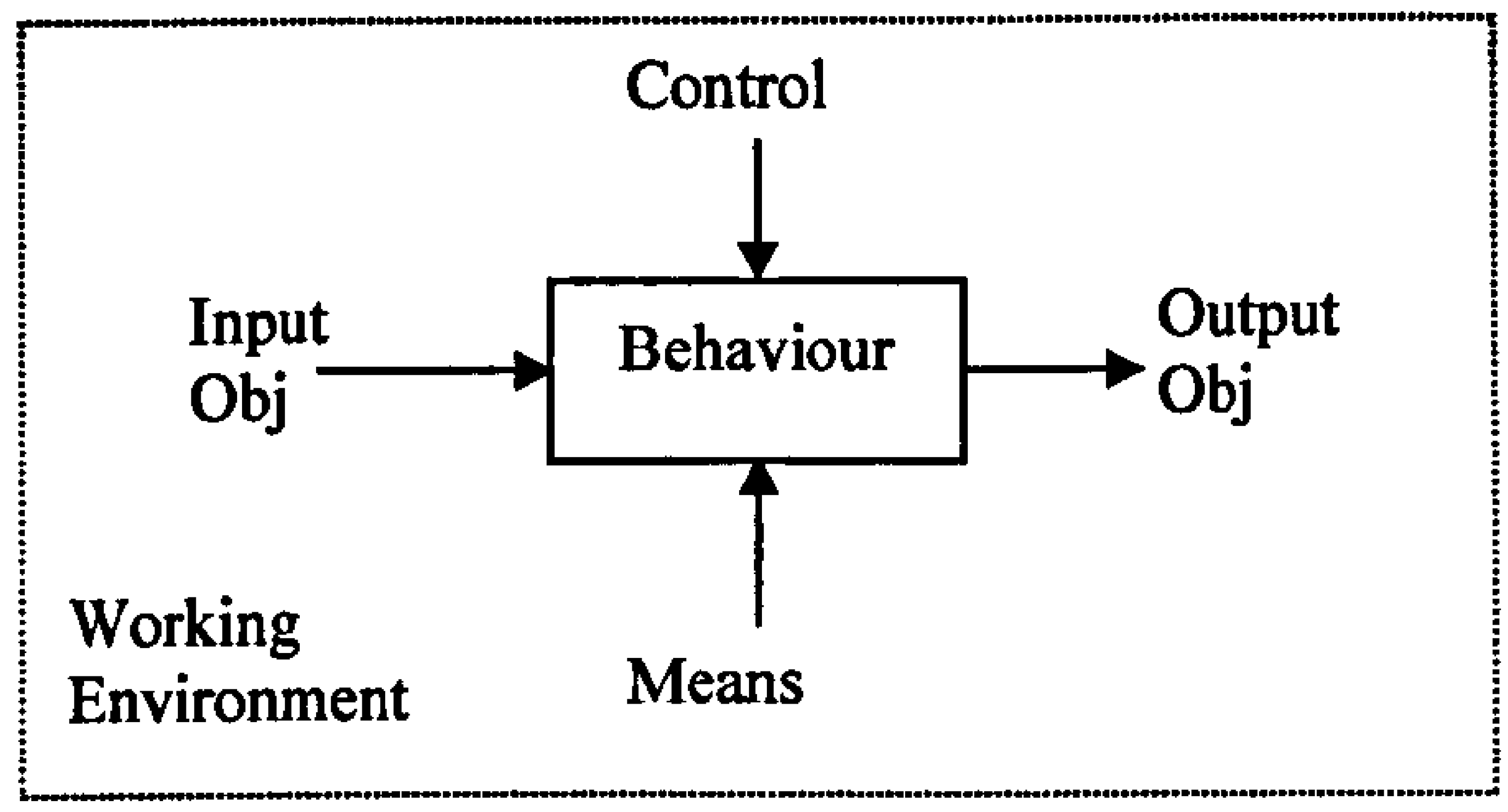


Figure 3-8: Systems model of behaviour

Function and behaviour

Having described function and behaviour, it is necessary to mention their relationship, not least because function and behaviour of an artefact have been often debated (Sasajima et al. 1996; Takeda et al. 1996; Umeda and Tomiyama 1997; Rosenman and Gero 1998). These two concepts are different; however, at the same time, they are cognate concepts and link with each other closely.

The most significant difference of function and behaviour is that while the former describes what an artefact is for, the latter illustrates what an artefact does (Umeda and Tomiyama 1997). In addition, to clarify the differences between these two concepts, Sasajima et al. (1996) talk about the intentional and structural descriptions of the artefact. Similarly, Gero and Kannengiesser (2004) employed expected, interpreted, and external world to describe the transformation of artefact knowledge. As mentioned earlier, function could be categorised as expected and interpreted. Behaviour, due to its subjective character, on the other hand, could be classified into three types: expected, instantiated, and interpreted. Of all these types, the expected function and behaviour belongs to the intentional description of the artefact knowledge in the ES, the instantiated behaviour belongs to the structural description in the IsS; and the interpreted function and behaviour belong to human being's subjective explanation of structural description of the artefact that belongs to the ItS. Thus, B_{is} does not depend on a human being's judgement; however, it can be derived entirely by qualitative physics (Bobrow 1984). That is to say, it could be derived directly from artefact structure and the environment in which it operates. Having said this, interpreted behaviour, on the other hand, represents the designers' view of the artefact behaviour based on their observation. However, in comparison with interpreted behaviour, Braha and Reich (2003) argue that the interpreted function of a product is a combination of interpreted behaviours selected from a particular situation. Moreover, the interpreted function of an artefact is subjective and context dependent (Gorti et al. 1998). It depends not only on the structure and the environment in which the artefact works, but also on how designers and users view the artefact. Furthermore, the relationship between behaviour and structure could also be observed from some other definitions of function. As Takeda et al. (1996, p.187) have pointed out, function is "a description of behaviour abstracted through recognition of behaviour for utilisation". This implies that different interpretations of interpreted function could be derived from the same behaviour by different people.

Despite the above differences between function and behaviour, these two concepts are closely related. As Qian and Gero (1996) have pointed out, function can be accomplished by static or dynamic behaviour, or by a set of behaviours occurring concurrently or sequentially. Moreover, according to Iwasaki et al. (1995), to fully understand how an artefact works, especially to evaluate a design based on the expected function and behaviour, the function of the artefact should be represented in a way with interpretation of behaviour. In order to reason how an artefact works in an unexpected environment, the interpreted behaviour knowledge alone is insufficient. This is because in order to predict how an artefact will behave under a given environment, artefact structure knowledge and general physical principles might be sufficient. However, without the expected function knowledge, it is impossible to determine the desirability of the predicted or observed behaviour (Deng et al. 1999). As Takeda et al. (1996) argued, this is because although an artefact can exhibit a number of behaviours, but not all behaviours are meaningful for designers.

3.3.2.4 Structure

Structure, or as others (e.g. Matousek 1963; Zeng and Cheng 1991) put, "form", describes distinctive variables that identify the artefact, and their interactions (Kuipers 1984). Artefact structure can be represented by its components, attributes of components, and relationships among these components or their configuration (Gero 1990; Takeda et al. 1996).

The components of structure are a finite set of element variables that could be either physical or logical. For example, it could be a physical bolt in a roadside barrier or a software program embedded in chip. In addition, an element could also include primitive elements and structure elements (Qian and Gero 1996). While the former refers to the element that cannot be further divided, the latter refers to a group of elements that form a sub-structure. Accordingly, a structure element can consist of a combination of primitive elements or other structural elements. The attributes of components are their properties, such as their material, energy, information state, shape, colour, to name but a few. The attribute itself or when it is combined with other attributes, can play a key role in forming and obtaining behaviours. In this respect, the visual effect of a combination of colours can be regarded as an example. The relationships between the elements here refer to either a physical-link (which can be a physical interconnection that could be represented with topological or geometrical data), or containing a relationship such as has-part and a-part-of between primary and structural elements. Generally, the has-part and a-part-of relationships are described by hierarchical representation. In addition, different relationships could lead to different function of an artefact.

With a post-positivism viewpoint, the artefact structural knowledge exist in two states, either in relation to the designers' expectation towards what the artefact structure will or should be, or in relation to the state that has been specified by designers for the current artefact. Therefore, structural knowledge is limited to the two existing design spaces, i.e., ES and IsS. Consequently, an artefact's structure can be classified into expected structure (S_e) in ES and instantiated structure (S_{is}) in IsS. While the former refers to designers' expectation of the components of the artefact and relationships among them, the latter refers to the actual structure of the artefact being instantiated and specified at a particular point in time. The instantiated artefact structure remains consistent regardless of a human being's interpretation.

Finally, based on different viewpoints, Nguyen and Rieu (1992) and Tichem and Storm (1995), among others, take the above discussion further by explaining the multiple descriptions of artefact structure, i.e. artefact aspects. This view, as its title indicates, describes different aspects of an artefact, such as its thermodynamics, kinetics, or electrodynamics.

3.3.2.5 Motivations and requirements

Design motivations (M) stimulate a design, which can be customers' needs or desires (Smithers 1998; Varejao et al. 2000), they can also be designers' will of changing the state of something in their surrounded environment. Strictly speaking, the motivations are still outside of the design space, though it is the origination of the designii . Therefore, it is attributed as a type of contextual knowledge of the artefact.

The design requirements (Rq) formalise the motivation in the design space, which are characteristics expected to be fulfilled by designers through the design solution (Varejao et al. 2000; Chakrabarti et al. 2004). They are served as agreement of what the desired artefact would be, and provide a basis for designers to proceed with the design (Darlington and Culley 2004). Therefore, requirements are addressed throughout the development process of an artefact. The requirements of a design is normally "incomplete, inconsistent, imprecise, ambiguous and/or impossible" at the beginning of the design process (Smithers 1998), and need to be revised in the design process so as to be clarified (Brazier et al. 1998). The extent of how well the requirements are clarified affect the quality of the design solution (Chakrabarti et al. 2004). Because requirements reflect human being's teleology concepts, they exist in the ES of design knowledge. Similar with motivations, they are also a type of contextual knowledge of the design artefact, and not fundamental knowledge elements of the artefact per se.

3.3.2.6 Causal relationships

Among the aforementioned artefact knowledge elements, i.e. function (F), behaviour (B), structure (S), design motivation (M), and requirement (Rq), there exist cause-effect links, which are causal relationships (CR) that can reflect the evolution of design artefact knowledge. Knowledge of causal relationships is considered as relational knowledge by Gero (1990). It provides, and makes explicit, the dependencies between the variables in the functional, structural, and behavioural knowledge and can be represented as a dependency network (Gero 1990; Gero and Kannengiesser 2004). A list of causal relationships among design knowledge elements is given in Section 3.3.2.8.

Causal relationships become design constraints in particular situations when the relationships must be realised. While the chunk of knowledge belongs to causal relationship knowledge, it also belongs to constraint knowledge in that situation.

3.3.2.7 Constraints

Designing is a constrained activity (Gero 1990). Throughout design development, designers need to specify and simultaneously satisfy various design constraints (Chandrasekaran 1990; Thornton 1996). For example, designers set function constraints from the beginning of design and continuously introduce other additional constraints whenever it is necessary throughout designing.

By definition, constraints (Ct) of a design artefact are restrictions on an accepted design solution (Suh 1990). For Chen and Lin (2002), constraint is a relation that links design variables. Normally, constraints on function may appear as expected behaviours and constraints on structure normally reduce the range of structure possibilities. As a result, constraints knowledge can guide designers in finding design solutions (Thornton 1996). For example, artefact constraints may include what form the artefact should have, or the cost of the artefact.

Design constraints are complex. For example, constraints knowledge could appear in either or both the qualitative knowledge and quantitative knowledge. According to Chen and Lin (2002), there are two types of constraints: one is domain constraints and the other is relation constraints. While the former defines the values or ranges allowable for design measures or parameters that could be either finite or infinite, the later refers to "equalities, inequalities, and rules" (p.170). Also, a majority of design constraints can be expressed as mathematical constraints. Of these mathematical constraints, while only some can be defined as equalities, a majority, however, define limitations on a design, rather than stipulating an exact relationship between variables. Moreover, most constraints are non-linear and many constraints may interact with each other during designing, which, in turn, makes the design even more complex.

3.3.2.8 A post-positivism view of function behaviour structure (P-FBS)

Having discussed the basic artefact knowledge elements, a model of function behaviour structure is presented from a post-positivism view in this section. This model is not only based on literature review, but also based on protocol study of a design project (Wang et al. 2007).

Gero (1990), Schulte and Weber (1993), and Chen and Lin (2002), among others, have observed the existence of a relationship between function and structure. Others (e.g. Gero et al. 1991; Qian and Gero 1996; Takeda et al. 1996; Gorti et al. 1998; Deng et al. 1999) take this argument further by stating that such a relationship is established through an artefact's behaviour. Umeda et al. (1990), for example, developed the FBS diagram that reveals the existence of a relationship between function and structure through behaviour (see Figure 3-9). A closer look at Umeda et al.'s FBS diagram, however, indicates that the model does not show the causal relationships among function, behaviour, and structure, and hence, the model could not answer the question of "which type of knowledge may result in change(s) in another?" To put it another way, which type of knowledge is the "cause" and which type is "effected".

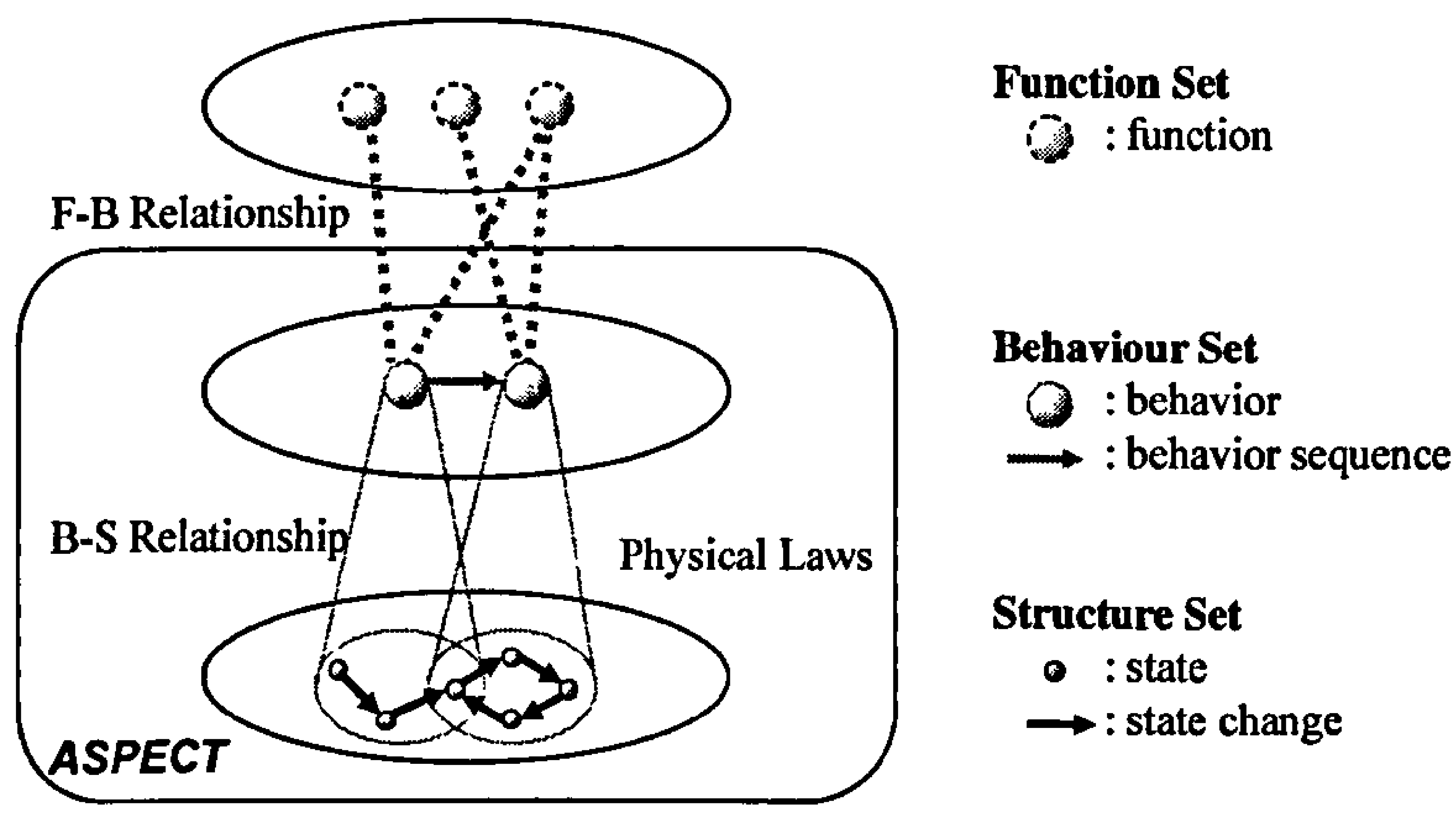


Figure 3-9: Relationships among F, B, and S (Umeda et al. 1990)

In his FBS framework, Gero (1990) revealed several causal relationships among function, expected behaviour, structural behaviour (behaviour derived from structure), structure, and design description (Figure 3-10). However, this only provided an initial description of causal relationships since it fails to fully consider function, behaviour, and structure in all of their forms. For example, the expected and working functions were not considered in the framework.

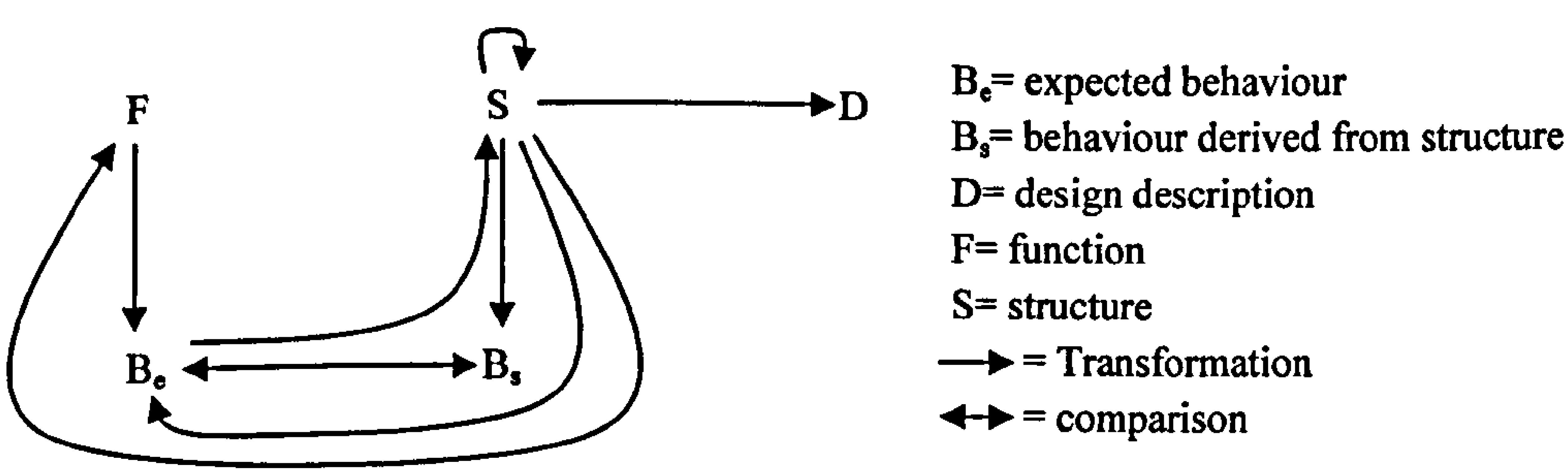


Figure 3-10: F-B-S framework (Gero 1990; Gero and Kannengiesser 2004, p.375)

Although in their situated function-behaviour-structure framework (Figure 3-11), Gero and Kannengiesser (2004) depicted a more detailed model of FBS with causal relationships, the framework does not reveal the relationship between requirements and designers' interpretation of current artefact behavioural and functional knowledge. In addition, function and structure were not actually reflected in their three design world description, i.e. external, interpreted, and expected, which in turn appended some causal relationships that didn't exist in the design world.

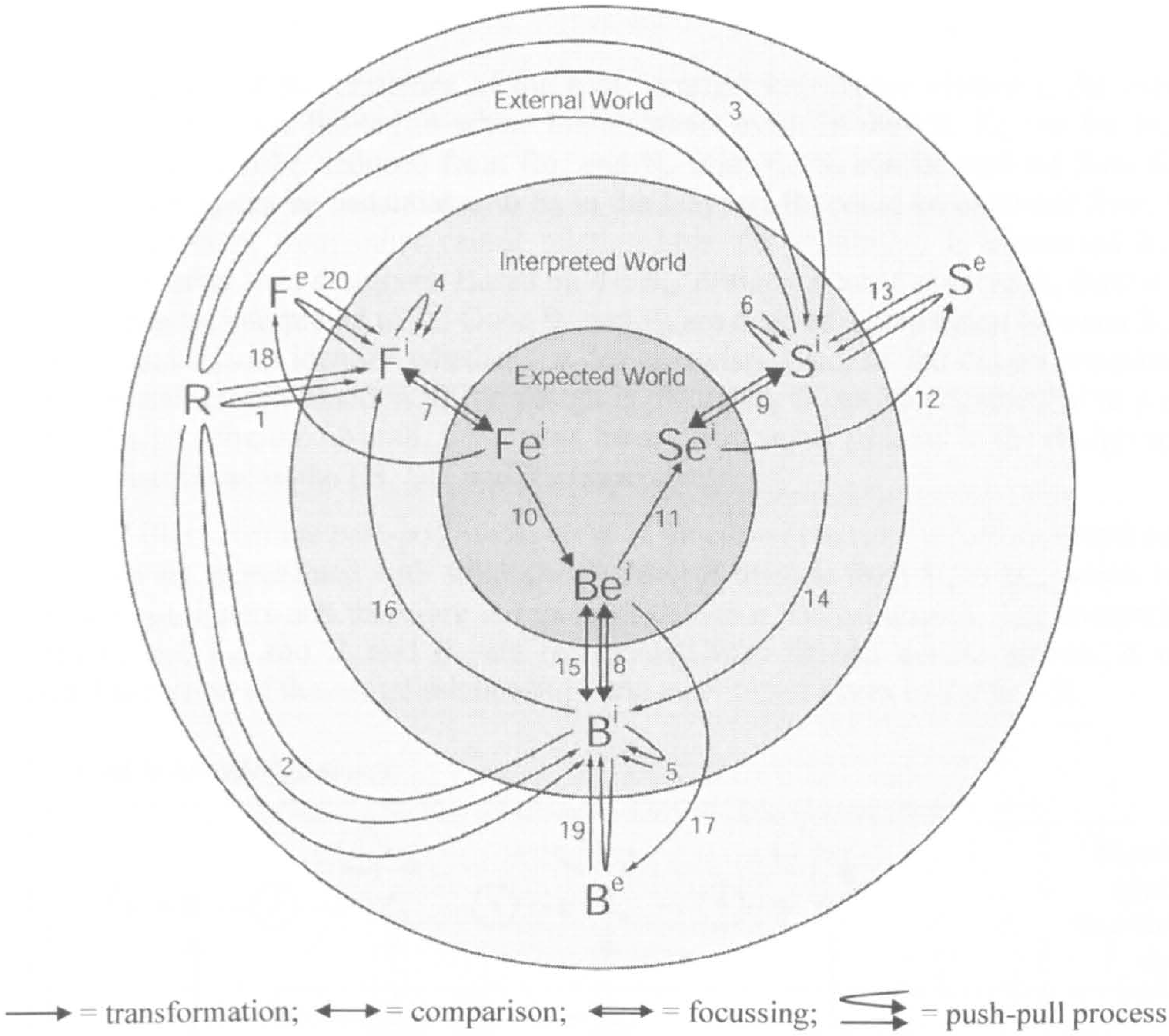


Figure 3-11: The situated FBS framework (Gero and Kannengiesser 2004, p.389)

From sections 3.3.2.1, 3.3.2.2, 3.3.2.3, and 3.3.2.4, it can be deduced from a post-positivism view that function and structure do not exist in all three artefact knowledge spaces (ES, IsS, and ItS). Specifically, *function* exists in the ES and ItS; *behaviour* could be derived entirely by objective qualitative physics or subjective observation so it exists in all the three worlds; and *structure* only exists in the ES and IsS. As a result, there seems to be seven fundamental knowledge elements of the artefact: F_e, F_{it}, B_e, B_{is}, B_{it}, S_e, and S_{is}. In addition, F_e is normally deduced from requirements (Rq), which exists in the ES and is derived from some motivating needs or the desires (M) of customers or the designers themselves. Moreover, as a result of designing, a design description (D) that can be used for producing the artefact is delivered in the IsS. Specifically, nine basic artefact knowledge elements distribute among the three design artefact knowledge spaces (As mentioned earlier, M does not belong to the design space): the ES comprises of Rq, F_e, B_e, and S_e; the IsS includes B_{is}, S_{is}, and D; and in the ItS, F_{it} and B_{it}. Further, design constraints set limitations to these artefact knowledge elements and the causal relationships across the three spaces. Table 3-2 lists the existence of the main artefact knowledge elements in the three design spaces.

Table 3-2: The existence of the artefact knowledge elements in three design spaces

	Requirements	Function	Behaviour	Structure	Description	Constraints
ES	√	√	√	√		√
IsS			√	√	√	√
ItS		√	√			√

As a consequence of the existence of the basic artefact knowledge elements, the existing causal relationships are limited to where the elements exist. In the ES, Rq can be derived from M. F_e then can be deduced from Rq, and B_e from F_e. S_e can be derived from B_e by synthesis. Then S_e can be instantiated to S_{is} in the IsS, and B_{is} could be exhibited from S_{is} in this space. Different from other causal relationships, the exhibition is conducted by the artefact itself rather than designers. Based on the B_{is}, designers could observe B_{it} from it, and this could then be interpreted to F_{it}. Once B_{it} and F_{it} are derived, comparison between B_e and B_{it}, and F_e and F_{it} can identify whether the design satisfies Rq, or the design provides the required behaviour and function. If the design is plausible, D can be documented as part of the final design solution. Overall, there exist three main causal streams in the design space, which are distributed in the ES, IsS, and ItS respectively.

Figure 3-12 illustrates the post-positivism view of function behaviour structure where causal relationships are represented with solid arrows (except the one from S_{is} to B_{is}, which is not triggered by designers and therefore is represented with a dashed arrow). The comparisons between F_e and F_{it}, and B_e and B_{it} are represented with dashed double arrows. A more detailed description of the causal relationships and activities is given in Table 3-3.

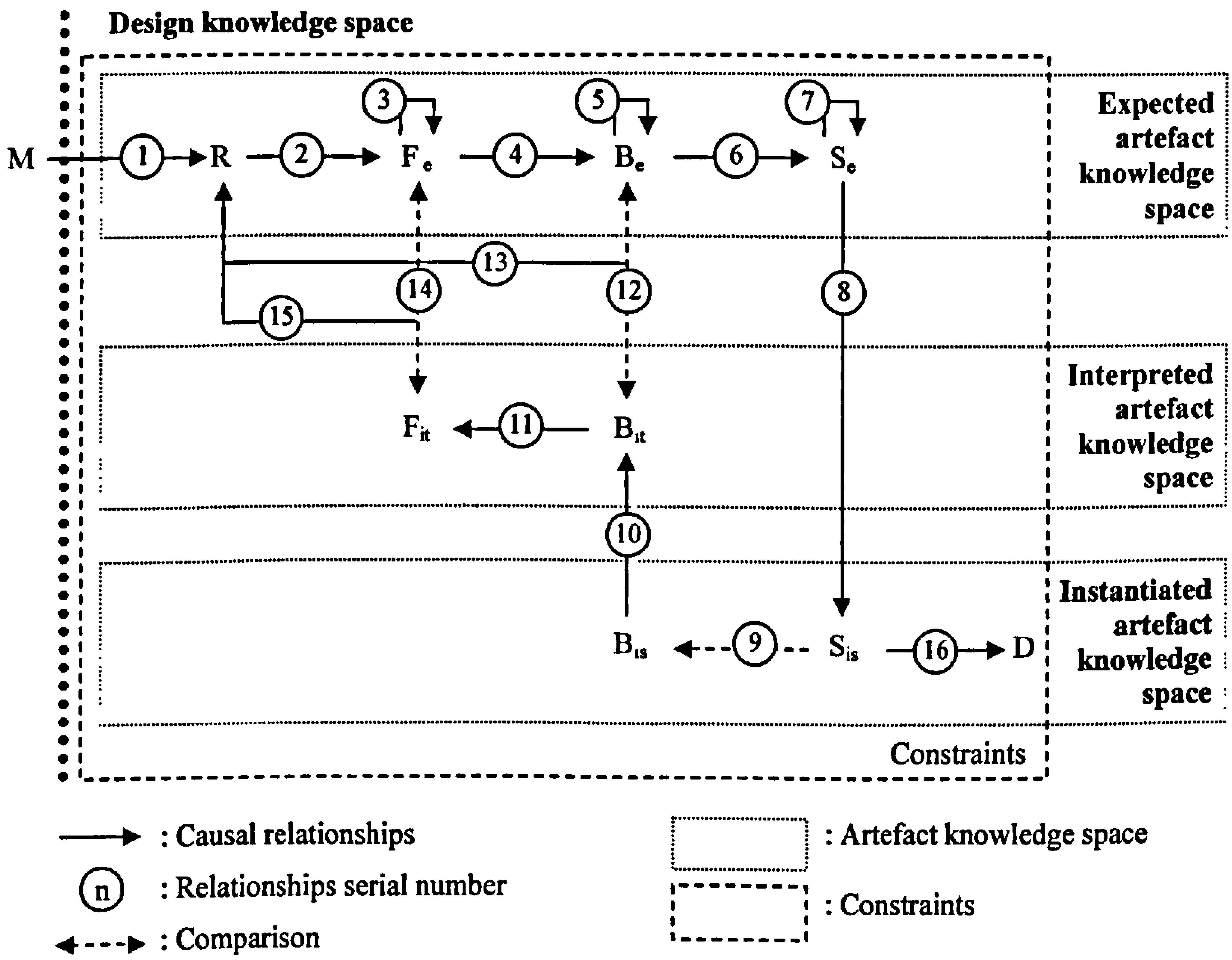


Figure 3-12: Post-positivism view of FBS (Derived from Wang et al. 2007)

Table 3-3: Causal relationships between artefact knowledge elements

Representation	Causal Relationships/ Activities	Explanation
1. M → Rq (from motivation to requirement)	Conversion	Design requirements are derived from some motivating needs or desires of customers or designers themselves.
2. Rq → F_e (from requirement to expected function)	Deduction	This relationship reveals the deduction of the expected function of the artefact from design requirements. The F_e indicates the designers' expectations towards the design, i.e. what the design is for.
3. F_e → F_e (decompose expected function)	Function decomposition	Function decomposition creates sub-functions or detailed functions by analysing the primary expected functions (Pahl et al. 2007). It normally creates a function tree with function dependency relationships among functions. By decomposition, the problem can also be divided to sub-problems that to design the artefact to satisfy the sub-functions (Deng et al. 1999). Umeda and Tomiyama (1997) believe that the design results rely entirely upon the function decomposition.
4. F_e → B_e (from expected function to expected behaviour)	Deduction	Expected behaviour of the artefact could be predicted and described through expected function knowledge (Iwasaki et al. 1995). By this causal link designers presume that the expected functions could be realised through exhibition of expected behaviours.
5. B_e → B_e (decompose expected behaviour)	Behaviour decomposition	Similar to F_e, B_e could also be decomposed to sub-behaviours. Therefore, a primary B_e could be realised through a set of sub-behaviours exhibited by the artefact either concurrently or sequentially.
6. B_e → S_e (from expected behaviour to expected structure)	Mapping/Synthesis	Based on knowledge of achievable behaviours produced by some specific structures, S_e is defined, which is expected to exhibit B_e so that the F_e could be realised.
7. S_e → S_e (decompose expected structure)	Structure decomposition	Sometimes, for a structural element that is required to realise an expected behaviour, the structural element can be decomposed into more primitive elements. This structure decomposition refers to the causal relationship between the structural element and its more primitive elements.
8. S_e → S_{is} (from expected structure to instantiated structure)	Instantiation	Instantiated structure is created once the S_e including all the primitive elements have been decided and instantiated by the designers, such as with a computer model.
9. S_{is} → B_{is} (from instantiated structure to instantiated behaviour)	Exhibition	Instantiated structure's attributes, relationships among elements, and certain external effects interacting with the structure at a particular time determine the structure's exhibited behaviour.

Representation	Causal Relationships/ Activities	Explanation
		Affected by qualitative physics and physical laws, B_{it} can be exhibited by a structure.
10. $B_{is} \rightarrow B_{it}$ (from instantiated behaviour to interpreted behaviour)	Observation	With regard to all B_{is} that could be exhibited by the artefact, designers obtain B_{it} within a specific working environment according to their own observation.
11. $B_{it} \rightarrow F_{it}$ (from interpreted behaviour to interpreted function)	Interpretation	As part of human beings' ideology, F_{it} is designers' interpretation of an artefact according to their expectation of the design. It can be derived through designers' interpretation of B_{it}. In other words, F_{it} can be accomplished by interpreted behaviour.
13. $B_e \leftrightarrow B_{it} \rightarrow Rq$ (evaluation by comparing expected behaviours with interpreted behaviours, to refine requirements)	Refinement	Since the initial requirements might be "incomplete, inconsistent, imprecise, ambiguous and/or impossible" (Smithers 1998), they need to be refined by reformulation and/or modification. If any inconsistency between B_e and B_{it} is found through evaluation, designers can refine design requirements.
15. $F_e \leftrightarrow F_{it} \rightarrow Rq$ (evaluation by comparing expected function with interpreted function, to refine requirement)	Refinement	Meanwhile, in case of any inconsistency between F_e and F_{it}, requirements can also be refined.
16. $S_{is} \rightarrow D$ (from instantiated structure to design description)	Documentation	Following evaluation, if the design requirements are satisfied by the S_{is}, the design description could be documented for the design. Generally, a design description, as a detailed depict of the artefact structure, contains structural and functional information, as well as its detailed manufacturing information.

In addition, the two comparison activities involved in this P-FBS model are listed in Table 3-4.

Table 3-4: Activities involved in P-FBS model

Representation	Activities	Explanation
12. $B_e \leftrightarrow B_{it}$	Comparison/Evaluation	In order to discover whether the S_{is} of current design is plausible or not, B_{it} needs to be compared with B_e to find out whether B_{it} match B_e.
14. $F_e \leftrightarrow F_{it}$	Comparison/Evaluation	Similarly, F_{it} needs to be compared with F_e to find out whether they match.

The P-FBS describes the existence of the basic artefact knowledge elements and the relationships among them. Though, it is not a prescriptive model that foresees the next step in the design process.

3.3.3 Evolution

As mentioned in Section 3.3.1, one of the artefact knowledge features is that it evolves during the design process (Hybs and Gero 1992; Shen and Barthes 1994; Ullman 1997; Gorti et al. 1998; Leeuwen and Wagter 1998; Zeng and Gu 1999; Deneux and Wang 2000; Chan et al. 2002; Maher and Tang 2003; Vajna et al. 2005).

Engineering design generally commences with incomplete knowledge of a required artefact or a rudimentary form, and ends with a detailed description of a desired artefact ready for manufacturing. Artefact knowledge, until the design is considered finished, is therefore in the state of dynamic evolution (Shen and Barthes 1994). The majority aspects of design artefact knowledge evolve during the design process, such as requirement (Maher and Tang 2003; Almefelt et al. 2006), function (Chandrasekaran 1990), behaviour, and structure (Ullman 1993; Tomiyama 1994; Takeda et al. 1996; Poon and Maher 1997; Braha and Reich 2003; Maher and Tang 2003; Gero and Kannengiesser 2004), and constraints (Chandrasekaran 1990). More specifically, at the beginning of design, not all the requirements are known by designers a priori and they are refined during the design process. For example, less than 50% of the original requirements remained unchanged during a project developing cellular telephone features for the Japanese market. The rest were either new, changed, or removed during the design process.

In respect of evolution in design, its formal model was first introduced by Woodbury (1989). Since then, there has been considerable research focused on this characteristic of artefact knowledge. However, a review of the previous research pertinent to artefact knowledge evolution indicates that most research has focused on how to develop frameworks or models to support evolving artefact knowledge rather than this characteristic itself. For example, SHOOD (Nguyen and Rieu 1992), a model based on object-oriented and frame-based knowledge representation, supports dynamic artefact knowledge evolution. The object-oriented representation model proposed by Shen and Barthes (1994), PDM, represents the evolution of design by providing versions for each object. Similarly, Gorti et al. (1998) proposed an object-oriented model with a layered schema. The model supports evolving an artefact by defining objects recursively and step-wise refining its knowledge base. The Cambridge Product Data Model (CPDM) (Ball et al. 1996) enables the representation of an evolving artefact with new classes and new characteristics by building and capturing class prototypes during the design process. Moreover, taking into account of the dynamic nature of design, Leeuwen and Wagter (1998) proposed an information model with a layered schema that supports dynamic information evolves along with the development of the design.

In addition to the aforementioned frameworks and models for supporting evolutionary artefact knowledge, there is also some research that has investigated the evolution phenomenon. For example, Gero (1996) proposed evolution as one characteristic in creative design. Smithers (1990) pointed out that the construction of design requirements and design specifications are tightly interactive in terms of the knowledge used and generated. In a similar vein, the co-evolution proposed by Poon and Maher (1997), reveals that a design process does not begin with an exhaustive problem specification. In contrast, the initial problem specification is usually vague and unclear, and the evolution of the design problem and solution alternates through designers' searching in two parallel search spaces: the problem space and the solution space (See also Dorst and Cross 2001; Maher and Tang 2003). Chakrabarti (1993), Braha and Reich (2003), and Brissaud et al. (2003) also observed that the functional description of the design problem and solution evolve together through criteria and conjecture.

As Gorti and Sriram (1996) have pointed out, design evolution is guided by knowledge, such as knowledge about the components used during the design, process knowledge used in a particular task, the current context conditions, and user decisions and preferences. They also suggest that this evolution is triggered by the outside environments, such as new material, new techniques, and new information systems. However, despite the close relationship between the artefact evolution and design process knowledge, little research has been focused on such relationship. For example, the following questions are still remaining unanswered by the current research:

- The basic artefact knowledge elements involved in the coupling: What artefact knowledge elements are involved in the coupling during the design development?
- The development of the evolutionary artefact knowledge elements: How the artefact knowledge elements develop during the design process?
- The triggers of the evolution: What caused the artefact knowledge elements to evolve? i.e. what are the links between the artefact knowledge elements and other design knowledge elements, which cause the evolution?

Since the design process knowledge is the manipulation knowledge of the artefact knowledge. As some researchers observed (e.g. Zhang 1999; Huang and Gu 2006a), artefact knowledge evolution is closely associated with the design process knowledge. This suggests that a coupling exists between artefact knowledge and design process knowledge. To understand the artefact knowledge evolution as well as answer the above questions, it is necessary to unveil their coupling. However, before further discussion of such coupling, the next section presents design process knowledge, its fundamental elements, and its evolutionary characteristics.

3.4 DESIGN PROCESS KNOWLEDGE

According to Gorti et al. (1998), design process is a sequence of mappings from one design state to another until one or more acceptable artefacts are found. During this process, design activities responsible for the mappings are applied to design objects. From a knowledge perspective, the design process is a process of utilising and evolving design knowledge.

Research on the design process has grown over the past few decades, and the research community has obtained more understanding of it (Mostow 1985; Ullman et al. 1988; Finger and Dixon 1989; Takeda, Veerkamp et al. 1990; Blessing 1996; Braha and Maimon 1997; Ullman 1997; Gorti et al. 1998; Smithers 1998; Pavkovic et al. 2001; Brissaud et al. 2003; Vajna et al. 2005; Reymen et al. 2006). By exploring the nature of the design process, this section first elucidates the features that distinguish designing from other activities. It then presents the following five fundamental knowledge elements of design process: design goals, activities, resources, input knowledge, and output knowledge, and two contextual design process knowledge elements: issues and contexts. One conspicuous characteristic of the design process, evolution, is then discussed at the end of this section, which builds the basis for later discussion of coupling evolutionary artefact and design process knowledge (Chapter 4).

3.4.1 Features

According to Gero (1990), designing is a purposeful, goal-oriented, constrained, decision-making, exploration and learning activity, which operates within a context that depends on the designers' perception of it. Designing is different from other similarly described human activities such as problem solving and planning. This difference is not only because of its domain, but also because of some additional necessary features (Gero 1990). Moreover, what make designing different is that it neither starts with something that specifies what is required nor defines a problem to be solved. However, it must arrive at a design for a perceived need. When it is realised or implemented, it should satisfy the motivating needs or desires (Smithers 2002). Different researchers view design process differently from different viewpoints, for example, as planning, search, or exploration. The key features of the design process are identified in this section by rationalising some of the work in the area.

3.4.1.1 Dynamics

Evolutionary

As mentioned in Section 3.3.3, design artefact knowledge evolves throughout the design process, and is manipulated by the design process knowledge. Hybs and Gero (1992) present designing as an evolutionary process, which evolves from the initial problem statements, constraints, and goals to an ultimate artefact description through a series of transformation processes (Takeda, Hamada et al. 1990; Tomiyama 1994; Pavkovic and Marjanovic 2001). Strictly speaking, by saying designing as is an evolutionary process, Hybs and Gero really mean that the design artefact knowledge, which is manipulated by the design process, is evolutionary. This reveals that the artefact knowledge evolution is closely related with the design process.

The design process is constituted by a sequence of design activities. The complete design activities are not formulated a priori but rather, they are specified gradually along with the evolution of design artefact knowledge. In this thesis, the evolution of the design process is considered as the evolution of the fundamental knowledge elements of the design process itself, rather than the evolution of the artefact knowledge.

Iterative

The design process is not a straightforward one, but an recursive one and is composed of a series of stages with iterations (Chandrasekaran 1990; Roozenburg and Eekels 1995; Braha and Reich 2003). During designing, designers need to go back to one or more previous stages to revise the design if the current artefact does not satisfy the requirements or constraints. However, this iteration does progress design and cause the design from vague specifications to a description of a design (Asimov 1962).

Mapping

Designing has also been considered as a mapping from functional requirements in a "functional space" to a physical embodiment characterised in terms of design parameters in a "physical space" or "attribute space" (Suh 1990; Tomiyama 1994). This is the core idea of the "General Design Theory" proposed by Yoshikawa (1981), which describes designing from a macro point of view with a start and finish. The real design process is a stepwise transformation process and there exist some micro processes between this mapping process. The meta-model space presented by Takeda et al. (1990) reveals this stepwise mapping process.

Transforming

As mentioned earlier, design progresses through a series of transformation processes. Thus, the design process can be regarded as a series of transformations of function, structure, and behaviour towards the design description (Hybs and Gero 1992; Tomiyama 1994). According to Gero (1990), the ideal transformation would be deriving the design description from the functional requirements directly. This is actually the "Design as mapping" mentioned earlier. However, a direct transformation just occasionally exists between function and structure, which is capable of achieving the desired result. In general, there is another element that exists in this transformation as a means of connection between function and structure, which is behaviour. In this sense, Gero (1990) depicted the actual transformations from function to structure through behaviour. These transformations are analogous to the causal relationships presented earlier in Section 3.3.2. However, they reveal the dynamic activities during designing.

3.4.1.2 Process based

Planning

For Gero and Coya (1985), designing is a type of planning that determines the sequence of design activities required to achieve a goal state from a starting state of a design. However, this assumes that the state space of designing is defined a priori. Therefore, as Gero (1998) argued, it could be used to describe detail design or routine design where the space is defined. However, according to Smithers (2002), designers just know the needs or desires at the beginning of designing. These needs or desires are not specifications of what to be designed. Thus, from this point of view, designing is not exactly planning since a specification of what is to be achieved should be known before executing the plan.

Search

As discussed by some researchers (Simon 1981; Howe et al. 1986; Chandrasekaran 1990; Thornton 1996; Gero and McNeill 1998), designing can be viewed as a search process. In this view, the solutions of artefacts or their components can be represented as states and there are a number of possibilities of states that can fulfil each design goal. Design goals and constraints could be fulfilled by searching this states space and applying operators to the problem specification. Normally, only a small number of possibilities in this space constitute satisfying solutions. Moreover, not only the artefacts and their components, the design activities could also be represented as state spaces. By searching the activities space, a sequence of activities are executed to obtain the desired design.

However, the basic and often implicit assumption in designing as search is that the state space of possible artefacts or their components or possible activities is defined a priori and is bounded. According to this view, prior to designing, the design space should also be defined. Therefore, similar to viewing designing as planning, this model tends to suit detail or routine design (Gero 1998) in which the state space is usually predefined. Moreover, by viewing designing as a search, goals of the design activity should be well defined before the design process begins and the focus of designing is not changed during design process. In addition, according to Howe et al. (1986), many issues that limit search as a technique for planning also limit this view of designing, such as mutually constraining goals, i.e. control of explosive search spaces.

Exploration

Considering the problems involved in regarding designing as a search, i.e., the design state space should be defined at the outset of the design process and the design focus should not change during designing, designing could be viewed as exploration (Chandrasekaran 1990; Gero 1990; Smithers 1990; Qian and Gero 1996; Rosenman and Gero 1998; Smithers 2002; Braha and Reich 2003). That is, designing explores what variables may be appropriate for the design. In this view, the states or solution space could be expanded through a change in the focus of the design during designing. Thus, the space of possible designs to be searched is not necessarily available at the outset of the design process. By exploration, design goals or decisions are explored. In the mean time, artefact behaviours, possible structures and the means of achieving them are decided as a consequence of exploration.

3.4.1.3 Cognitive based

Designing is typically a human activity, an endeavour that is mainly about what people do when they design, as well as why, when, and how they do it (Mostow 1985; Smithers 1996; Darlington et al. 1998). Thus, designing could be considered as a cognitive process that is executed purposely to achieve an objective (Adelson 1989; Darlington et al. 1998; Varejao et al. 2000; Maher and Tang 2003). According to Kurakawa (2004), design development is composed of a cognitive problem solving process. In a similar vein, Hubka and Eder (1996) regard designing as a rational cognitive activity, which can be decomposed into smaller design stages or phases. As Sim and Duffy (2003) pointed out, design cognation could be depicted in terms of goals, actions, knowledge, and intended rational behaviour at the knowledge level. However, there is no well-established theoretical understanding of the cognitive capabilities used during design. Therefore, the development of cognitive theories of design is untenable at the moment.

Learning

Designing involves learning (Gero 1990; Persidis and Duffy 1991; Duffy and Duffy 1996; Duffy et al. 1998; Sim and Duffy 1998, 2004; Wu 2004). Designing and learning are two interlinked activities because learning is part of the design exploration activity. Designers obtain new knowledge through learning during the design process when they encounter knowledge that is sufficiently different from their present state of knowledge (Persidis and Duffy 1991). Through learning, designers improve their problem solving ability. In addition, learning happens not only through single designer designing, but also among different designers through collaborative designing, termed collective learning (2004).

Problem solving

Designing could be characterised as a problem solving process (Simon 1981; Chandrasekaran 1990; Dorst and Dijkhuis 1995), which starts with a problem specification, a set of functions and constraints to be satisfied and ends with a problem solution (Hillier et al. 1984; Mostow 1985; Leeuwen and Wagter 1998). Simon and Newell (1958) suggest that there are three criteria of a well-structured problem: first, it can be completely described in quantitative terms; second, the goal can be described by an objective function, and last, the problem could be stated quantitatively and solved by algorithms. Design problems, therefore could be viewed as a wicked or ill-defined problems as they are not known in full detail from the outset of designing (Rittel and Webber 1973; Leeuwen and Wagter 1998; Coyne 2005). Though, there are still some other researchers who object to this view, they agree that designing does involve problem solving, but that it does not account for the overall process. Smithers (2002) considers that designing does not start with a problem to be solved, because a problem should specify what can be a solution. However, as the input of designing, needs and desires of a design do not specify what can satisfy them, they simply identify what we would like to be different, or what we need to be different.

Reasoning

Since the second half of the eighties, design as a reasoning process has gained considerable consideration (Brazier et al. 1994). As Rzevski (1981) and Takeda (1990) mentioned, a design process is regarded as an iterative logical process realised by reasoning. During designing, reasoning takes place at various levels and various types of reasoning are involved, such as deduction, induction, abduction (Gero and Rosenman 1990; Yoshioka 1993; Brazier et al. 1994; Takeda and Nishida 1994; Roozenburg and Eekels 1995), circumscription (Yoshioka 1993), and recursion (Zeng and Cheng 1991).

Reflection-in-action

The view of design as problem solving deals with design in a positivism way in which designers act as information processors and the design process is a rational search process (Dorst and Dijkhuis 1995). However, to some researchers, designing is an activity that designers act in. That is, during designing, designers encounter difficulties, when they will switch to reflective thinking, analysing or learning. Schon (1983) uses reflection-in-action to describe activities such as design, where the design process becomes a reflective conversation :tween designers and the situation, in which designers set problems and then take actions tc improve the current situation.

3.4.1.4 Knowledge intensive

The design process is a knowledge intensive activity in which designers use diverse knowledge throughout designing (Takeda, Hamada et al. 1990; Smithers 1998; Klein 2000; Braha and Reich 2003). In respect of the content of design knowledge, design artefact, process, management, and supplementary knowledge are considered as its main types. Following the Knowledge Level (Newell 1982) theory of the design process (Smithers 1996), there has been more and more research focussing on the knowledge level of designing. For example, Tomiyama (1994) and Nomaguchi and Tomiyama (2002) proposed knowledge intensive engineering, which assists engineering activities in various product life cycle stages based upon intensive use of the accumulated engineering knowledge.

The above discussion of the main features of the design process reveals that it is a complex activity evolving various elements, and possessing dynamic and cognitive characteristics. The next section presents the main design process knowledge elements.

3.4.2 Elements

According to Reymen et al. (2006), the design process can be viewed as a finite sequence of design activities necessary for achieving design goals. Referring to various discussions on the design process (Mostow 1985; Ullman et al. 1988; Treur and Veerkamp 1992; Gorti et al. 1998; Li et al. 2004; Reymen et al. 2006), five fundamental knowledge elements are considered here to define the design process: *goals, activities, resources, inputs,* and *outputs*. These elements are closely related and interconnected throughout designing. In addition, the design process also involves two types of contextual knowledge, i.e., *design context* and *issues*.

3.4.2.1 Goal

Designing is a purposeful activity and the design problem has been described as a goal-oriented problem (Mostow 1985; Gero 1990). Goals in design are the objectives that reflect desires, needs, and/or requirements of designers or customers (Roozenburg and Eekels 1995; Duffy 2002). Throughout designing, a series of design goals are set and achieved by designers. For example, they could be to determine functional, behavioural, or structural elements for the artefact. They could also introduce constraints, introduce new artefact elements, or create further sub-goals that will be met individually. The pursuit of sub-goals then impels the progression of design (Gorti et al. 1998).

Goals derived from the current state of design guide how the design process should proceed. Therefore, goals link the artefact and process knowledge. They can prescribe how the artefact knowledge should be manipulated (Mostow 1985) hence to direct and set constraints on designers' activities.

During the design process, designers set tasks to meet goals, and the goals can be achieved through accomplishing the tasks. Thus, a task is an undertaking specified a priori (Duffy 2002).

3.4.2.2 Activity

It should be noted that the design activities, rather than tasks, are treated as fundamental knowledge elements of the design process, because the activities are the actions that take place in order to evolve the design process. To Sim and Duffy (2003, p.202), the design activity is "an action or cognitive process taken by a design agent to achieve a knowledge increment in the state of the design and/or its associated design process in order to achieve some design goal". Hence, design activities can be thought of as the operations enacted on artefact or process knowledge elements by designers, through which a knowledge transformation towards the design goal is made. This in turn results in a transition of the state of the artefact or design process (Reymen et al. 2006). A basic model of an unplanned design activity may involve the following basic elements: Design activity (A), Input activity knowledge (I_{kA}): the knowledge present prior to the activity; Output activity knowledge (O_{kA}): the knowledge present as the result of carrying out the activity; Activity goal (G_A): the knowledge that directs and constrains the activity; And Activity resource (R_A): the knowledge that acts on the input to produce the output. They are depicted in Figure 3-13.

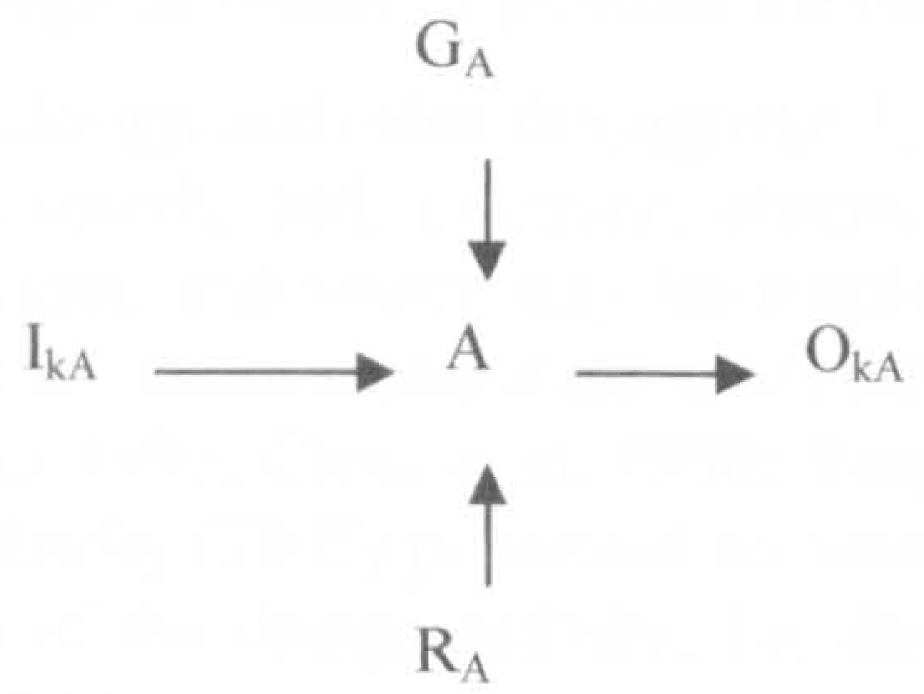


Figure 3-13: Un-planned design activity (Adapted from O'Donnell and Duffy (2005))

In order to accomplish design tasks, given the availability of resources, directed and constrained by the goal of design tasks, designers choose design activities by comparing the goal, available input, and desired output knowledge of the design task with those of the design activity. If the goal, input, and output knowledge of design activity match those of the design task, and there are available resources for executing the design activity, it is chosen to accomplish the design task. Or even if there are not the available resources at the required time, design activities can also be defined with the resources to be determined. This combination of design tasks, activities, goals, resources, input, and output form part of the design plan and consequently, the activities become planned activities that build the fundamental knowledge elements of the design process. Figure 3-14 shows the model of a planned design activity.

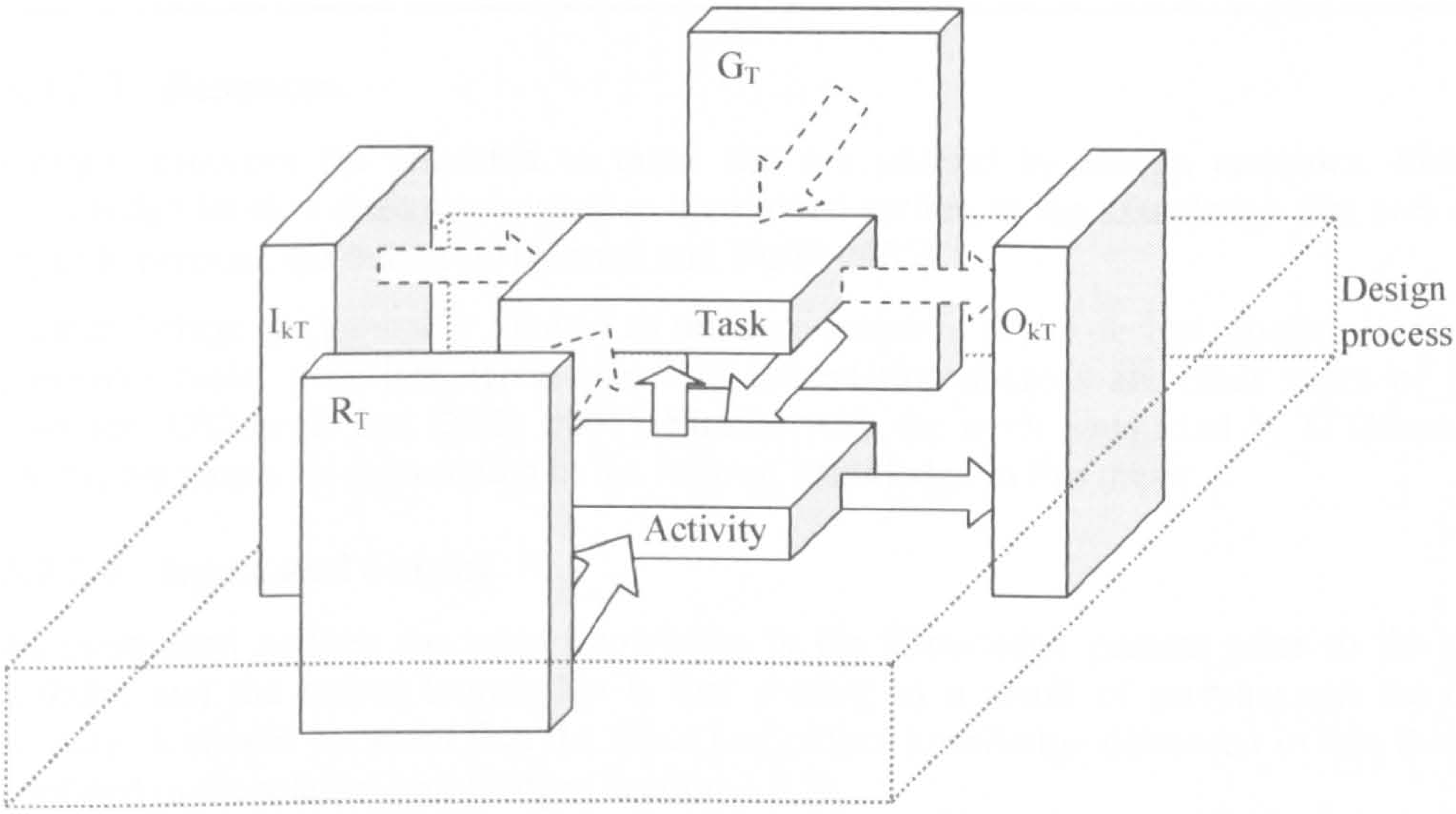


Figure 3-14: Planned design activity

In this mode input knowledge (I_{kT}) is the knowledge available prior to the design task and output knowledge (O_{kT}) is the knowledge expected resulting from accomplishing the design task by carrying out the design activity. They represent the initial and final states of knowledge, related to both the artefact and the design activity. For example, the input could be a vague concept with an output being a more detailed description of the design. Moreover, the input could be knowledge of current expenditure related to the resources used in activities prior to the start of the activity. The output will also have a value of expenditure, which will represent an increase on the input value, as further resources will have been used during an activity. Design goals (G_T) in planned design activities, as mentioned earlier, are the knowledge that direct and constrain the design activities. Design resource (R_T) represents the resource that is used by design activities to produce the output knowledge.

Designers perform a range of design activities throughout designing. For example, to create the artefact, activities such as search, add, calculate, choose, combine, decide, decompose, define, delete, evaluate, represent, and select may be employed (de Roode 1998). Design activities have been discussed by some researchers from different views at different levels (Pugh 1986; Dorst and Dijkhuis 1995; Cross et al. 1996; Yang and Epstein 2005). Based on the knowledge level, Sim and Duffy (2003) presented an ontology of design activities, which include three main categories of the design activity, i.e. design definition, evaluation, and management activities (Table 3-5).

Table 3-5: Design activity ontology (Derived from Sim and Duffy 2003)

Activities categories	Design activities
Design definition activities	Abstracting, associating, composing, decomposing, defining, detailing, generating, standardising, structure/integrating, synthesising, formulation, modification.
Design evaluation activities	Analysing, decision making, evaluating, modelling, selecting, simulating, testing/experimenting, validation and verification.
Design management activities	Constraining, exploring, identifying, information gathering, planning, prioritising, resolving, searching, selecting, scheduling, communication, guiding, information archiving,

3.4.2.3 Resource

Design resources are allocated to tasks and are utilised by design activities. From the knowledge level, a design resource, as mentioned earlier, is the knowledge that acts on the input to produce the output (O'Donnell and Duffy 2005).

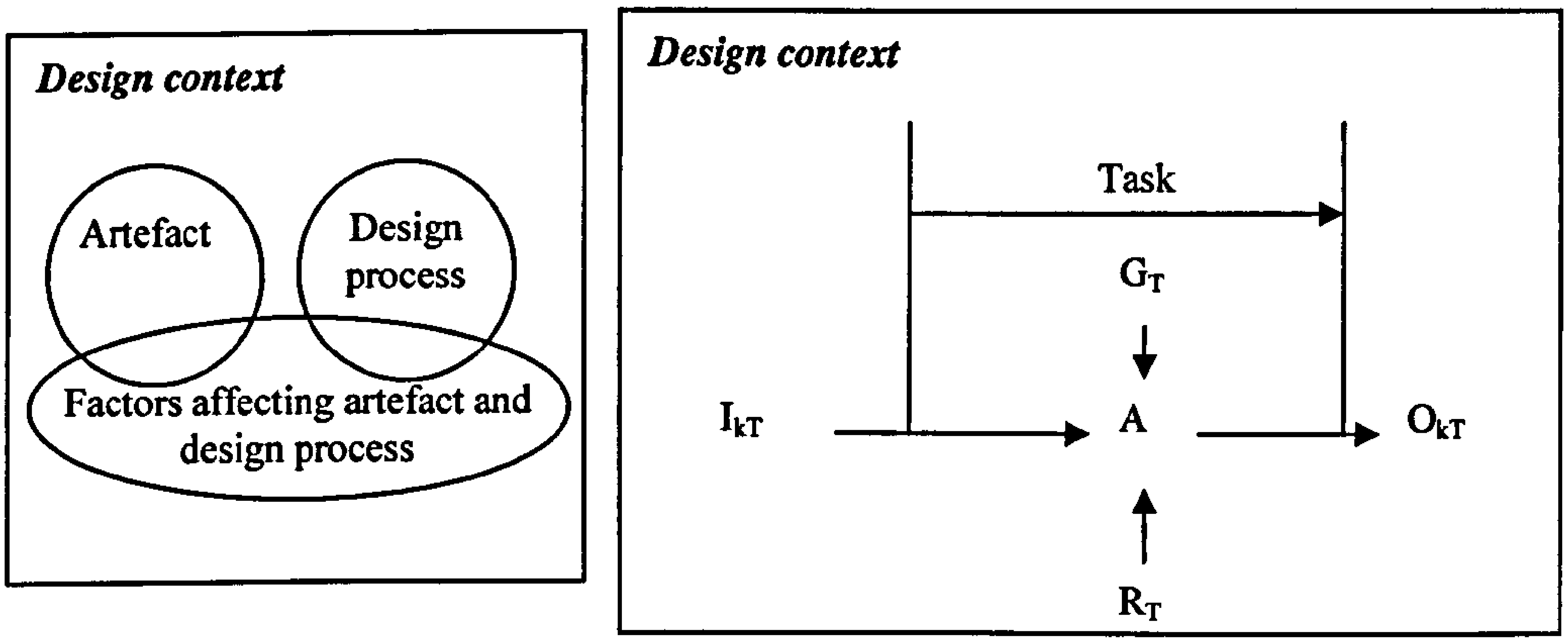
Human beings are generally viewed as the core resource in the design process. In addition, computer tools, materials, techniques and information sources are other types of design resource (O'Donnell and Duffy 2005). Similar with the work conducted by O'Donnell and Duffy, resources are represented in the form of knowledge in this thesis.

3.4.2.4 Input and output

As mentioned earlier, the input knowledge is the knowledge present prior to the design activity, and the output knowledge is that present as a result of carrying out the design activity. It should be noted that the input and output knowledge discussed in this thesis are confined to the artefact knowledge (Section 3.3.2).

3.4.2.5 Context

During the design process, before designers specify a design goal or carrying out a design activity, they should be familiar with the state of both the artefact and design process (Mostow 1985; Ullman et al. 1988). Further, the current state of project environment variables, such as available resources and company strategy, should also be acknowledged by designers to execute design activities. Design context is adopted here to describe the set of the knowledge factors influencing the design artefact, which include not only description of the current design artefact and process knowledge but also the factors influencing the artefact being designed and the design process (Brissaud et al. 2003; Reymen et al. 2006). These factors are of various types of knowledge, such as constraints, specifications, requirements, needs, performance measures, and objectives (Ullman et al. 1988). Figure 3-15 (a) illustrates the composition of design context. Throughout the design process, designers carry out every design activity in specific design contexts. Figure 3-15 (b) shows the relationship between design context and a planned design activity.



(a) Design context

(b) Relationship between design context and design activity

Figure 3-15: Design context

Any change to the current design, such as changes to the artefact attribute, the relationships, or artefact elements, changes the design context. Moreover, designers' perceptions of the design also affect what is included in design context (Gero 1990). Therefore, design context is a dynamic knowledge set. Knowledge is added to and removed from this set at anytime throughout designing with the development of design and change of designers' perception.

3.4.2.6 Issues

During the design process, various issues arise from the context, which formulate the design problem to be solved by designers (Ullman 2001). Design issues can be of the artefact being designed, or the design process itself. Design goals are to solve these issues, which is achieved through executing design activities. Thus, design issues are closely related to design context, design goals, and activities. Though design issues are not considered as a fundamental knowledge element of the design process, it constitutes the contextual knowledge of the design process.

3.4.3 Evolution

As mentioned earlier, the design process is constituted by a sequence of design activities, and the detailed design activities are formulated gradually within a design context, within which the design artefact knowledge evolves. In addition, with the evolution of the artefact knowledge, the input, output of the artefact evolves. Therefore, evolution pervades every aspect of a design ~roject. Not only the designed artefact manipulated by the design process evolves, the desi process itself also evolves throughout designing (Demaid and Zucker 1993; Gorti et al. 1998; Wallace et al. 1999; Braha and Reich 2003; Maher and Tang 2003).

The evolutionary feature of the design process is exhibited through the dynamic evolution of its knowledge elements, i.e. design, goals, activities, resources, inputs, outputs knowledge, contexts and issues (Gero 1996; Wallace et al. 1999; Chan et al. 2002; Pavkovic et al. 2002). Each of them dynamically evolves throughout designing, either individually or co-related. More specifically, during designing, the ***design goal*** could be decomposed into sub-goals. To put in another way, a design goal can evolve to more detailed sub-goals that can compose a goal tree of the design. In addition, new design goals can also emerge as design requirements change. As design goals evolve, new design tasks are assigned to achieve them. Accordingly, new ***design activities*** then may be required to be carried out to accomplish the tasks that could achieve the goals. As a result, ***design resources*** used by the activity evolve. In addition, with the evolution of artefact knowledge, the ***input*** and ***output knowledge*** of the activity evolves. As mentioned earlier, ***design context*** is composed of the description of the current design artefact and process knowledge as well as all the factors influencing the development of the artefact being designed and the design process. Therefore, as any of the aforementioned elements evolves, a new design context emerges (Reymen et al. 2006). Consequently, the evolution of design context causes design issues' evolution. Throughout the design process new issues are identified, old issues are revisited, and some issues abandoned (Ullman 2001). Figure 3-16 gives a depiction of the evolution of the design process.

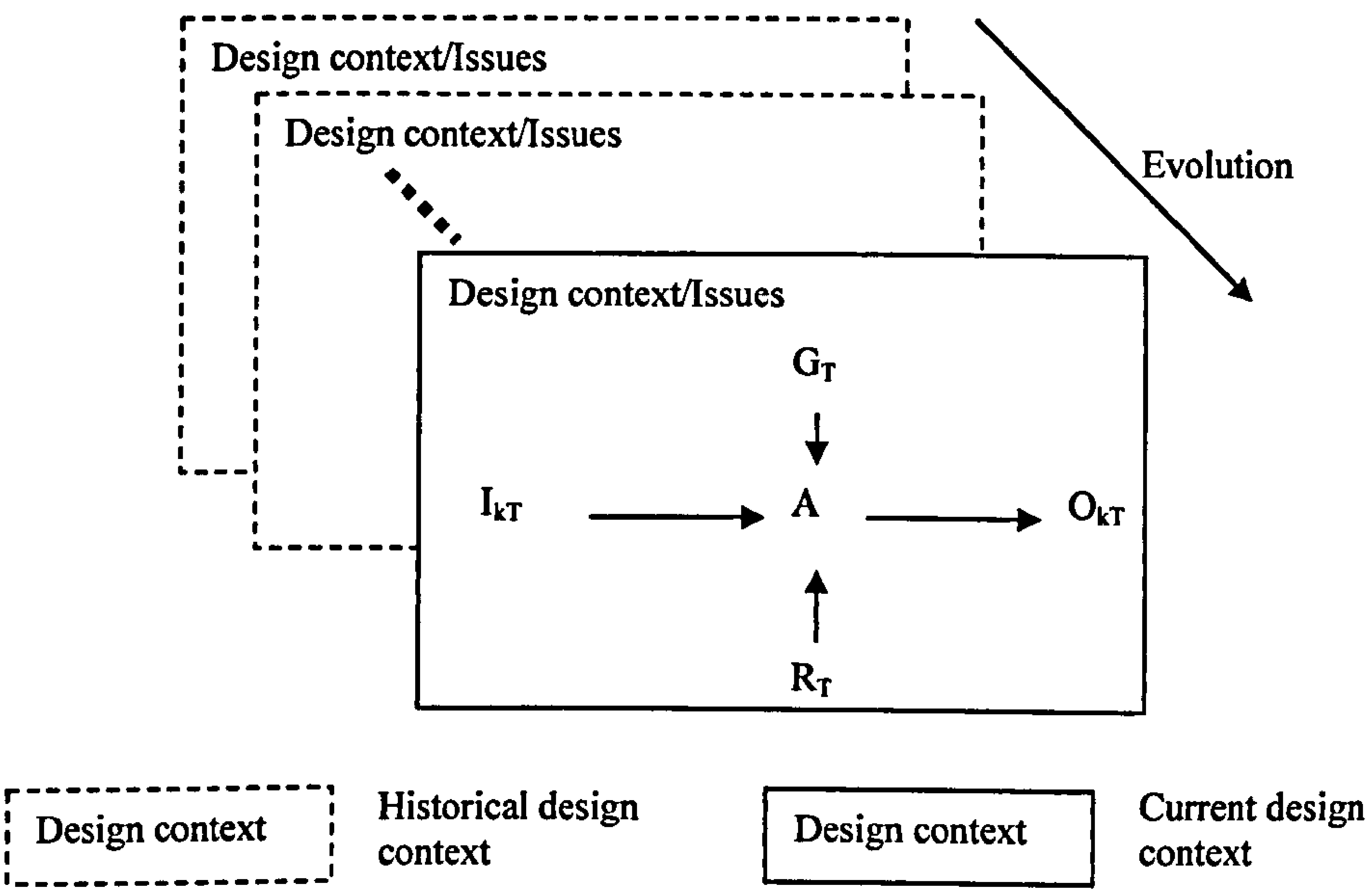


Figure 3-16: Design process evolution

Although there has been some research that has focused on the dynamic evolutionary character of the design process, the majority has referred to the evolutionary character of the design artefact manipulated by the design process. Of these, for example, the evolutionary design process model presented by Hybs and Gero (1992), commences with intentions and ends up with the artefact and embeds design into it. Chan et al. (2002) developed an evolutionary computation framework with a dynamic hierarchical structure of the artefact, which supports dynamic evolutionary design. Some more examples could be found in (Takeda, Veerkamp et al. 1990; Gero 1996; Shimomura et al. 1998; Dorst and Cross 2001; Maher and Tang 2003). The evolution of design process knowledge is closely related to the artefact knowledge. However, little research has focused on this topic. For example, the following questions are still remaining unanswered by the current research:

- The basic design process knowledge elements involved in the coupling: What design process knowledge elements are involved in the coupling?
- The development of the evolutionary design process knowledge elements: How do the evolutionary design process knowledge elements develop during the design process?
- The triggers of the evolution: What causes the design process knowledge elements to evolve? i.e. what are the links between the design process knowledge elements and other design knowledge elements, which cause the evolution?

From the earlier description of the design artefact and process knowledge evolution, it can be deduced that they are closely related. Therefore, it is hypothesised that there is a coupling exists between them. To understand such a coupling can contribute to our understanding of the evolutionary nature of artefact and design process knowledge. To this end, previous work closely related to the coupling of evolutionary artefact and design process knowledge will be reviewed in the next chapter.

3.5 SUMMARY

The purpose of this chapter is to provide a review of design artefact and process knowledge, which resulted in: enhanced understanding of the domain, a basic set of artefact and knowledge elements, and identification of the design problem, i.e., a lack of knowledge between the artefact and design process. Specifically, a knowledge pyramid in design research is given at the beginning of the chapter, which shows a layered structure of design research, with design knowledge, design knowledge models, knowledge-based design supporting systems from bottom to top. A design knowledge classification based on its content is then presented, which includes design artefact, process, management, and supplementary knowledge. Two topologies of design knowledge are presented including teleology and evolutionary. Design artefact knowledge and design process knowledge were then discussed in chapter 3.3 and 3.4, focusing on their basic knowledge elements and their evolutionary character. The fundamental elements of artefact knowledge include: function, behaviour, and structure, and those of design process knowledge are design goal, activity, resource, input, and output knowledge. In addition, design motivations, requirements, causal relationships, and constraints of the design artefact, and context and issues of the design process constitute the contextual knowledge of the artefact and design process.

Following the discussion of the evolutionary characteristic of the artefact and design process knowledge, it was concluded that they are closely related, i.e. the artefact and design process knowledge are coupled. However, the questions such as what are the evolutionary knowledge elements, how the knowledge elements develop, and what are the relationships of the evolutionary elements, are still unanswered. Before presenting the work addressing these questions, the next chapter will take a closer look at the literature on coupling of the design artefact and process knowledge.

Chapter 4 REVIEW OF ARTEFACT AND DESIGN PROCESS KNOWLEDGE COUPLING

Chapter 3 presented the features and ontologies of the artefact and design process knowledge. Specifically, it highlights that both of them evolve during design development. It was hypothesised that their evolution closely relates to the coupling of the artefact and design process knowledge. This chapter presents the literature pertinent to the coupling, thereby leading to the identification of the research challenges of the thesis.

In Section 4.1, four research topics related to coupling of the artefact and design process knowledge are presented. The research gap is identified in Section 4.2, which provide a review of the research related to coupling of the artefact and design process knowledge. Section 4.3 presents a number of problems encountered by industry that relate to coupling of the artefact and design process knowledge. Finally in Section 4.4, the research focus of this thesis is derived based on the review, i.e. to explore the nature of the coupling of evolutionary artefact and design process knowledge.

4.1 RELATED RESEARCH TOPICS

There are several research topics in the engineering research domain that are closely related to the coupling discussed in this thesis, such as "integrated product development", "concurrent engineering", "product lifecycle management", and "total design". To clarify coupling and these related research topics, this section introduces the research focus of each topic.

These research topics emphasis different aspects of product development, though product development is regarded to be the core concept, which covers part of the product lifecycle beginning from the marketing of a product to its design and manufacturing process. To clarify, a short discussion of these approaches is given below.

In the early 1980s, based on the idea that

> *"the product development cannot be carried out in the best possible way if it is allowed to disintegrate into different areas of specialisation, areas of activity or areas of responsibility." (Andreasen and Hein 2000, p2)*

Integrated Product Development (IPD) was formulated as an idealised model of a new product development paradigm (Andreasen and Hein 2000). The aim of IPD was to build proper interactions for the isolated activities within the company. To achieve this, it takes a holistic view that focuses not only on integrating the market, product, and production, but also on the project and management, and integrating with other development activities (See Figure 4-1). The coupling of the artefact and design process was not explicitly stated within the IPD. However, it is integrated within the middle stream of the IPD, i.e., "Engineering design".

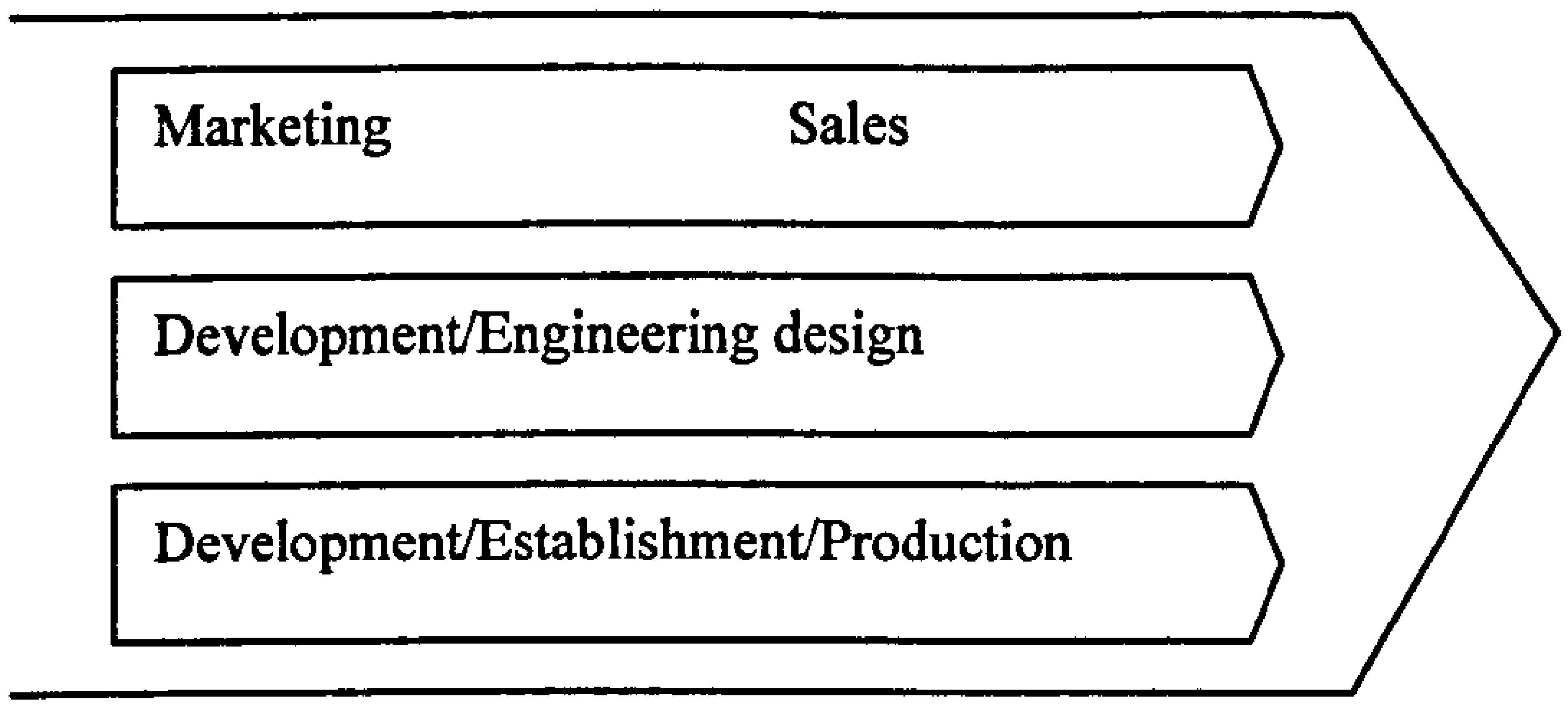


Figure 4-1: Integrated Product Development (Andreasen and Hein 2000)

In order to overcome some shortcomings of traditional sequential "over the wall" approach, ***concurrent engineering*** (CE) was proposed in 1988. CE is a systematic solution conducted by a team, which aims to minimise product development time by means of integrated, concurrent design of products and their related processes (Prasad 1996). It mainly focuses on parallel engineering and considers mostly the perspectives of product life-cycle, such as the quality, cost, schedule, and customer expectations (Winner et al. 1988). As an approach to IPD, CE was observed by many researchers that its narrow meaning is "integrating product and process" (Winner et al. 1988; Prasad 1996). It should be noted that the term "process" here not only includes the design process but also include processes of such as the manufacturing and supporting. Other researchers such as Finger et al. (1993) provided a broad meaning of CE, which is integration within the whole enterprise. Therefore, the core idea of CE is two-fold: first, to integrate product and its related processes in a parallel holistic way, and second, to establish a coherent co-operation within the enterprise.

Product Lifecycle Management (PLM) is

> *a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information across the extended enterprise from concept to end of life – integrating people, processes, business systems, and information (CIMdata 2002).*

This implies that PLM is neither a tool nor a packaged suit of applications. Rather, it is a concept and vision of a way that can be operated in an enterprise. It integrates enterprise resources together to make the business processes run more smoothly and more efficiently. Specifically, its scope not only covers Product Data Management (PDM), but also shares some mutual benefits with Supplier Relationship Management (SRM), Enterprise Resource Planning (ERP), and Customer Relationship Management (CRM).

Total design (1990) is the systematic activity that contains product, process, people and organisation. It is a general management concept that covers the product from the marketing investigation until it is sold to the market. In the total design model, Product Design Specification (PDS), after being formulated, will constrain the design development through all the design stages. Similar with PLM, total design is an enterprise approach that considers related information from the outset of the design.

All the aforementioned four topics emphasise on integration of different design related aspects, such as marketing, product, design process, sale, and enterprise operation management. As two core aspects of design, artefact and design process are integrated into these approaches accordingly. However, these approaches do not reveal the nature of the coupling of the artefact and design process on a knowledge level.

4.2 REVIEW OF COUPLING RELATED RESEARCH

As some researchers have observed, the closely related relationship, i.e., coupling, exists among elements of design knowledge, for example, between function and behaviour (Sasajima et al. 1996), requirements and design solutions (Maher and Tang 2003), function and structure (Schulte and Weber 1993), and behaviour and structure (Umeda et al. 1990). A number of related research work has been conducted to reveal this phenomenon, for example, research work by Marples (1960), Blessing (1994), Klein (2000), and Wynn and Clarkson (2008). Marples (1960) maps the design process through decision trees that follow the product hierarchy. Blessing (1994) proposes a framework for design process data based on a design matrix, which relates activities to product data. Klein (2000) discusses the relation between product and design process and argues that there exists a close interaction in design between design object level knowledge and problem solving knowledge. Similarly, Wynn and Clarkson (2008) defined a linkage meta-model that represents the knowledge elements of artefact and design process, as well as their relationships between them.

Overall, the relationships that were discussed by researchers can be grouped into the following three main categories, which include: 1) between artefact and artefact, 2) between process and process, and 3) between artefact and design process. Following a review of the research related to the coupling, Table 4-1 shows the research (with the reference number) distributed in these three categories based on the knowledge ontology discussed in Chapter 3. If there are research about the relationship between two elements, the index numbers of the research are listed in corresponding intersection cell of the column and row of the two elements. A list of the research with their reference numbers can be found in Table 4-2. The review shows that these research involve relationships not only between specific knowledge elements, but also between elements and general artefact and process, and between artefact and design process. The knowledge elements reviewed here include motivations (M), requirements (Rq), function (F), behaviour (B), structure (S), constraints (Ct), causal relationships (CR), activity (A), goal (G), input (In), output (Out), resource (R), context (C), and issues (I). In addition, domain artefact knowledge (DK) also listed because there was some research dedicated for domain knowledge reuse. Research conducted in these three categories are discussed in the following sub-sections.

Table 4-1: Review of coupling artefact and design process

	Artefact	M	Rq	F	B	S	Ct	CR	DK	Process	A	G	In	Out	R	C	I
Artefact																	
M																	
Rq	[1, 2]	[3]	[4]														
F		[5]	[4, 6]	[7]													
B			[6]	[5, 6, 7, 8, [illegible]													
S		[illegible]				[28, 29]											
Ct							[30]										
CR																	
DK	[31]																
Process	[2, 4, 31, 32, 33, 34, 35, 36, 37,38]		[2, 39]						[31]								
A	[1, 31, 40]	[3]	[1, 3, 4, 17, 41. 42]	[3 [illegible]				[8, 10]	[17, 31, 43, 44]								
G	[45]										[44, 46]						
In											[44, 46]						
Out											[44, 4[illegible]						
R											[4, [illegible]				[4]		
C	[40, 45]		[17, 47]	[13, 17]	[13, 17]	[17]	[45]			[40]	[40]						
I	[41]		[48]								[41, 48]	[illegible]					

1. Artefact - Artefact

2. Process - Process

3. Artefact - Process

Table 4-2: A list of research related to coupling

Ref No.	Research
[1].	Design tasks specification (Brazier et al. 1994)
[2].	Strategic knowledge (Brazier et al. 1998)
[3].	Ontological framework (Varejao et al. 2000)
[4].	Relation network (Pavkovic et al. 2002)
[5].	Evolutionary design process model (Hybs and Gero 1992)
[6].	Situated FBS (Gero and Kannengiesser 2004)
[7].	Functional evolution process model (Takeda et al. 1996)
[8].	Design prototype (Gero 1990)
[9].	Bridging function and behaviour (Iwasaki and Chandrasekaran 1992)
[10].	FBS paths (Qian and Gero 1996)
[11].	CFRL (Iwasaki et al. 1995)
[12].	FBRL (Sasajima et al. 1996)
[13].	FEBS (Deng et al. 1999)
[14].	Function behaviour representation (Deng 2002)
[15].	Function, behaviour, and structure (Umeda et al. 1990)
[16].	QFD (Akao 2004)
[17].	MOKA (Klein 2000)
[18].	Co-evolution (Maher and Tang 2003)
[19].	Modelling design process (Takeda, Veerkamp et al. 1990)
[20].	Functional reasoning (Chawla and Sangal 1992)
[21].	Function & shape relationship (Schulte and Weber 1993)
[22].	Structures mapping (de Roode 1998)
[23].	Function-to-form mapping (Roy et al. 2001)
[24].	Concept decision using function and constraints coupling (Chen and Lin 2002)
[25].	Topological structures for modelling design process (Braha and Reich 2003)
[26].	Function representation for inspiration new ideas (Chakrabarti et al. 2005)
[27].	YMIR (Alberts 1994)
[28].	DSM (Steward 1981)
[29].	Identifying shape relationships (Orsborn et al. 2008)
[30].	Knowledge model for functional re-design (Deneux and Wang 2000)
[31].	CWK evolution support (Zhang 1999)
[32].	Rationale capture and support (Brissaud et al. 2003)
[33].	Interactions between factors influencing design system (Robin et al. 2005)
[34].	Design knowledge reuse using process modelling (Baxter et al. 2007)
[35].	Support design learning (Giess et al. 2007)
[36].	Aligning process product and organisational architectures (Sosa 2007)
[37].	Development mode based on integration product and process (Huang and Gu 2006a)
[38].	Linkage meta-modelling (Wynn and Clarkson 2008)
[39].	Development based on information feedback (Huang and Gu 2006b)
[40].	Domain-independent design model (Reymen et al. 2006)
[41].	Design matrix (Blessing 1994)
[42].	Requirements management (Almefelt et al. 2006)
[43].	Evolutionary design case adaptation (Gomez de Silva Garza and Maher 2000)
[44].	Learning in design (Sim and Duffy 2004)
[45].	CONGEN (Gorti and Sriram 1996)
[46].	Design performance (O'Donnell and Duffy 2005)
[47].	Factors influencing design requirement (Darlington and Culley 2004)
[48].	Ideal decision support system (Ullman 2001)

4.2.1 Artefact and artefact

Table 4-3 lists the first research category that is related to the relationships between the artefact knowledge elements (grey cells) and between the elements and general artefact knowledge (dark grey cells) with their reference numbers (see Table 4-2 for the research related to those particular numbers).

Table 4-3: Research related to artefact knowledge relationships

	Artefact	M	Rq	F	B	S	Ct	CR	DK
Artefact									
M									
Rq	[1, 2]	[3]	[4]						
F		[5]	[4, 6]	[7]					
B			[6]	[5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]					
S		[16]	[4, 17, 18]	[9, 19, 20, 21, 22, 23, 24, 25, 26]	[5, 6, 7, 8, 10, 13, 15, 26, 27]	[28, 29]			
Ct							[30]		
CR									
DK	[31]								

In addition to some research about the relationship between artefact and requirements (Brazier et al. 1994; Brazier et al. 1998), artefact current working knowledge and domain knowledge (Zhang 1999), motivations and requirements (Varejao et al. 2000), motivation and function (Hybs and Gero 1992), requirements and requirements (Pavkovic et al. 2002), requirements and function (Pavkovic et al. 2002; Gero and Kannengiesser 2004), requirements and behaviour (Gero and Kannengiesser 2004), requirements and structure (Klein 2000; Pavkovic et al. 2002; Maher and Tang 2003), structure and structure (Steward 1981; Orsborn et al. 2008), and constraints and constraints (Deneux and Wang 2000), it can be found that most of the research listed in Table 4-3 are about relationships between the function, behaviour, and structure (Gero 1990; Takeda, Veerkamp et al. 1990; Chawla and Sangal 1992; Hybs and Gero 1992; Iwasaki and Chandrasekaran 1992; Schulte and Weber 1993; Alberts 1994; Iwasaki et al. 1995; Qian and Gero 1996; Sasajima et al. 1996; Takeda et al. 1996; de Roode 1998; Deng et al. 1999; Roy et al. 2001; Chen and Lin 2002; Deng 2002; Braha and Reich 2003; Gero and Kannengiesser 2004; Chakrabarti et al. 2005). As discussed in Chapter 3, behaviour connects function and structure in the transformation from function to structure. Of the relationships between function, behaviour, and structure, two research groups have actively contributed to this research topic. One is Gero and his colleagues, the other is Umeda and his colleagues.

The FBS model presented by Gero and his colleagues includes a basic one (Gero 1990) and an extended one (Gero and Kannengiesser 2004). It does combine design artefact knowledge with design process knowledge. To this end, the design process was modelled as a series of transformations among design artefact knowledge elements. This, in turn, reflects the evolutionary characteristic of design artefact knowledge. However, the design process knowledge, which includes design goal, activity, input, output, resource, context, and issues, has not been considered in this model. Consequently, the interrelationships between the artefact and design process knowledge, i.e., the coupling between them, has not been clarified.

Similar to the FBS model presented by Gero, the FBS presented by Umeda and his colleagues (1990) also has extended versions, for example, the functional evolution process model (Takeda et al. 1996) and the design methodology (2005) that aims to facilitate product upgrade based on the FBS diagram. However, the FBS diagram only illustrates the static relationships among function, behaviour, and structure. Furthermore, design process knowledge was not discussed in this diagram, and there was no obvious coupling between the function, behaviour, and structure and the design process knowledge. In short, both FBS models do not reveal the coupling of the artefact and design process knowledge. They also fail to reveal how the coupling affects their evolution throughout designing.

From the research presented in this section, it can be seen that the transformations between the artefact knowledge elements are revealed. However, the research does not address how these transformations related to the design process elements, especially goal, input, output, resource, context, and issues.

4.2.2 Design process and design process

The research related to the relationships between the process knowledge elements (grey cells) and between the elements and general process knowledge (dark grey cells) are shown in Table 4-4 with their reference number as listed in Table 4-2.

Table 4-4: Research related to process knowledge relationships

	Process	A	G	In	Out	R	C	I
Process								
A								
G		[44, 46]						
In		[44, 46]						
Out		[44, 46]	[46]	[44, 46]				
R		[4, 41, 46]				[4]		
C	[40]	[40]	[45]	[45]				
I		[41, 48]	[48]					

Design process knowledge is a part of the design context (Reymen et al. 2006), which also includes the activity, goal, and input of the design process (Gorti and Sriram 1996).

The research related to the relationships of process knowledge elements is mostly based on the activity model, within which the activity relate to other elements of the design process. For example, the relationships between the activity and goal, input, output, and resource are depicted by Duffy and his colleagues (Duffy 2002; Sim and Duffy 2004; O'Donnell and Duffy 2005). Moreover, the relationships between the input and output, and the goal and output could be used to model design performance (O'Donnell and Duffy 2005).

In addition to the activity-related research, there are also research related with the relationships of other elements. The relation network presented by Pavkovic et al. (2002) built the relationship between designers, design task, and software tools, which revealed the relationships between the resource and activity, and resource and resource. Blessing proposed the design matrix (Blessing 1994), which linked issues of different artefact knowledge with activity and goal. In the decision system presented by Ullman (2001), he connected "issues" with "goals".

It could be found that while these research focus on the process knowledge elements, the artefact aspect was not covered in a detailed level such as the relationship with the function, behaviour, and structure, hence the coupling of the artefact and design process on a knowledge level was left untouched by this category of research.

4.2.3 Artefact and design process

The third category of the research is related to the relationships between the artefact and design process knowledge elements, as well as between the general artefact and design process. A number of research in this category are shown in Table 4-5 in the grey cells and dark grey cells with their reference number as listed in Table 4-2.

Table 4-5: Research related to relationships between artefact and design process

DK	Artefact	M	Rq	F	B	S	Ct	CR	DK
Process	[2, 4, 31, 32, 33, 34, 35, 36, 37,38]		[2, 39]						[31]
A	[1, 31, 40]	[3]	[1, 3, 4, 17, 41, 42]	[3, 6, 8, 9, 22, 41]	[3, 6, 8, 9]	[3, 8, 9, 10, 17, 22, 41]		[8, 10]	[17, 31, 43, 44]
G	[45]			[45]	[45]	[45]			
In									
Out									
R									
C	[40, 45]		[17, 47]	[13, 17]	[13, 17]	[17]	[45]		
I	[41]		[48]						

The research related to the relationship between the artefact and design process can be roughly categorised into four groups as between 1) general artefact and process elements, 2) artefact elements and general process, 3) general artefact and general design process, and 4) artefact elements and process elements.

With regard to the first two groups, the artefact was considered as part of the design context (Gorti and Sriram 1996; Reymen et al. 2006). It is related to the design activity (Brazier et al. 1994; Zhang 1999; Reymen et al. 2006), goal (Gorti and Sriram 1996), and issues (Blessing 1994). The design process is closely related to the design requirements, which is used to check the design process throughout the design (Brazier et al. 1998; Huang and Gu 2006b). Moreover, domain knowledge is utilised by the design process, which contributes the current design evolution (Zhang 1999).

The artefact is considered to be closely related to the design process (Brazier et al. 1998; Zhang 1999; 2002; Brissaud et al. 2003; Robin et al. 2005; Huang and Gu 2006a; Baxter et al. 2007; Giess et al. 2007; Sosa 2007; Wynn and Clarkson 2008). Within the third group, the research recognised such close relationship and tried to model them in different ways. However, some of them are still on the high level of the coupling, for example, the knowledge evolution through interactions between the artefact and design process (Zhang 1999), the development mode proposed by Huang and Gu (2006a) that integrates the artefact and design process, the knowledge reuse framework (integrating artefact and design process knowledge) proposed by Baxter et al. (2007). Though, there have some research been conducted in integrating the artefact and design process. For example, the generic model of design proposed by Brazier (1998) linked requirements, artefact, and design process through some information links. Pavkovic et al. (2002) built a relation network that includes relations (dependency, generalisation, association, and realisation) between different elements of the artefact and design process, such as between designers (a type of resource) and activities, requirements and product components (structure), and requirements and activities. Similarly, Wynn and Clarkson (2008) presented a linkage meta-model that includes elements across different domains and their relationship. Despite these research, a detailed description of the relationships between the artefact and design process knowledge elements were still not presented.

Within the last group, research involved in different relationships between the artefact and process knowledge elements. It can be seen that most of the research in this group focused on how the activity, goal, and context are related to the artefact elements. Generally, the activity is closely related to most artefact knowledge elements, such as the motivations (Varejao et al. 2000), requirements (Blessing 1994; Brazier et al. 1994; Klein 2000; Varejao et al. 2000; Pavkovic et al. 2002; Almefelt et al. 2006), function (Gero 1990; Iwasaki and Chandrasekaran 1992; Blessing 1994; de Roode 1998; Varejao et al. 2000; Gero and Kannengiesser 2004), behaviour (Gero 1990; Iwasaki and Chandrasekaran 1992; Varejao et al. 2000; Gero and Kannengiesser 2004), structure (Gero 1990; Iwasaki and Chandrasekaran 1992; Blessing 1994; Qian and Gero 1996; de Roode 1998; Klein 2000; Varejao et al. 2000; Gero and Kannengiesser 2004), and causal relationships (Gero 1990; Qian and Gero 1996). In addition, the activity also utilises or creates domain knowledge (Zhang 1999; Gomez de Silva Garza and Maher 2000; Klein 2000; Sim and Duffy 2004). In addition, the goal was considered by Gorti and Sriram (1996) to create or modify artefact that includes the function, behaviour, and structure. The context is considered to contain both the artefact and design process. Consequently, it contains the requirements, function, behaviour, structure, and constraints (Gorti and Sriram 1996; Deng et al. 1999; Klein 2000; Darlington and Culley 2004). Moreover, in addition to being related to the general artefact knowledge, the design issue (Ullman 2001) was considered to be related to the requirements. In all, the last group of research addresses more detailed relationships between the artefact and design process knowledge elements. However, most of them did not clarify the type of the relationships. There is lack of a comprehensive view of the relationships between the artefact and design process knowledge elements, which, according to Robin et al. (2005), trigger the evolution of design knowledge.

From the research presented in this section, it can be found that out of a number of research related to the relationships between the artefact and design process knowledge, some of them concern the relationships between the artefact elements, some of them concern the relationships between the design process elements. Though some of them relate to the relationships between the artefact and design process knowledge, they are either still on a high level coupling, or covered only part of the relationships between the artefact and design process knowledge elements. Hence there is lack of such a model that shows how the elements of artefact and design process are linked during the design development.

4.3 PROBLEMS IN INDUSTRY RELATED TO THE COUPLING

While participating the PLM project in Company A, a workshop was conducted in order to explore the opportunities, drivers, and problems of PLM. In order to identify the research problem of this work, results obtained from the workshop were analysed focusing on the artefact and design process knowledge. Though the workshop was conducted in the context of PLM, and most of the obtained results focused on management issues, there were some problems and drivers raised by designers that were considered to be caused by a deficiency of coupling of the artefact and design process. For example, some problems and drivers are "In-service feedback to support design decisions, missing link between engineering and support", "Enable early visibility of requirements", "Provide a global set of information & data & decisions", "Use product data to understand program completion", and "Required process structure at company level". These problems and drivers showed that industry still lacked a well integrated artefact and design process, which revealed an insufficient knowledge of the coupling of the artefact and design process in industry.

A follow-up visiting to Company A was made in November 2005 in order to further identify the research problem. During an informal discussion with three designers from the company, it was found that there were problems concerning the integration of the artefact and design process. The problems were mainly caused by change propagation because considerable changes were made to the artefact as well as its related design process throughout designing. Problems raised during the discussion included: "Change of the artefact could not be followed with the up-to-date change of the design process", "The knowledge of artefact and the process is not integrated enough", and "Process transition propagation". Such problems also reveal the insufficient knowledge of the relationships between the artefact and design process in industry. As a result of such insufficient knowledge, problems such as "change of the artefact could not be followed with the up-to-date change of the design process" are still difficult to tackle in industry. These observations suggest that, to solve the above-mentioned problems, not only the artefact and process knowledge, but also their coupling needs to be understood.

A review of the literature pertinent to the practice of design also indicates that there are problems caused by loosely integrating artefact and its design process. For example, the case study conducted by Ranta (1999) highlighted problems such as conformance, rationale, dynamics, re-use, and milestone integration to be originated from the insufficient knowledge of coupling of artefact and design process. Therefore, to counteract the above-mentioned problems, knowledge of the coupling of the artefact and design process knowledge is needed, which could provide a more comprehensive view of the relationships between artefact and design process knowledge.

4.4 RESEARCH FOCUS

Following the identification of the research gap from the literature review and problems faced by industry related to the coupling of the artefact and design process knowledge, this section clarifies the research problem to be tacked by this research work.

"Technical systems" was proposed by Hubka and Eder (1988) to represent the concept of "abstract machine" or "technical means". Viewed in this way, the design artefact is a technical system conceived by a human being. Broadly speaking, design process, of which its purpose is to derive a desirable artefact, can be considered as an artefact devised by process designers. Therefore, both of the artefact and design process can be treated as two systems with interaction relationships. The links between the two systems can be categorised into material (e.g., documents, prototype), energy (designer's effort), and information (artefact and process knowledge) accordingly.

More specifically, a design artefact system is composed of the artefact being designed in the material world and its knowledge representation in the ideology world. Similarly, a design process system is composed of the design process and its knowledge representation. Of the three types of link between the artefact and design process system, energy and material links exist in the material world, and information link exists in the ideology world (the artefact and design process knowledge are regarded as information transmitted in this link). Therefore, a general coupling of the artefact and design process could be represented within two worlds: a material one and an ideology one. Energy and material couple artefact and design process in the material world and information couples artefact and design process in the ideology world. Moreover, knowledge transmitted in the ideology world is composed of function (F), behaviour (B), structure (S), motivations (M), requirements (Rq), causal relationships (CR) and constraints (Ct) of the design artefact, and goal (G), activity (A), resource (R), input (In), output (Out), design context (C), and design issues (I) of the design process. Figure 4-2 depicts this general coupling of the artefact and design process system. The design agent located in the centre belongs to the resource of design process, which could be either human or a computer aided intelligent design system.

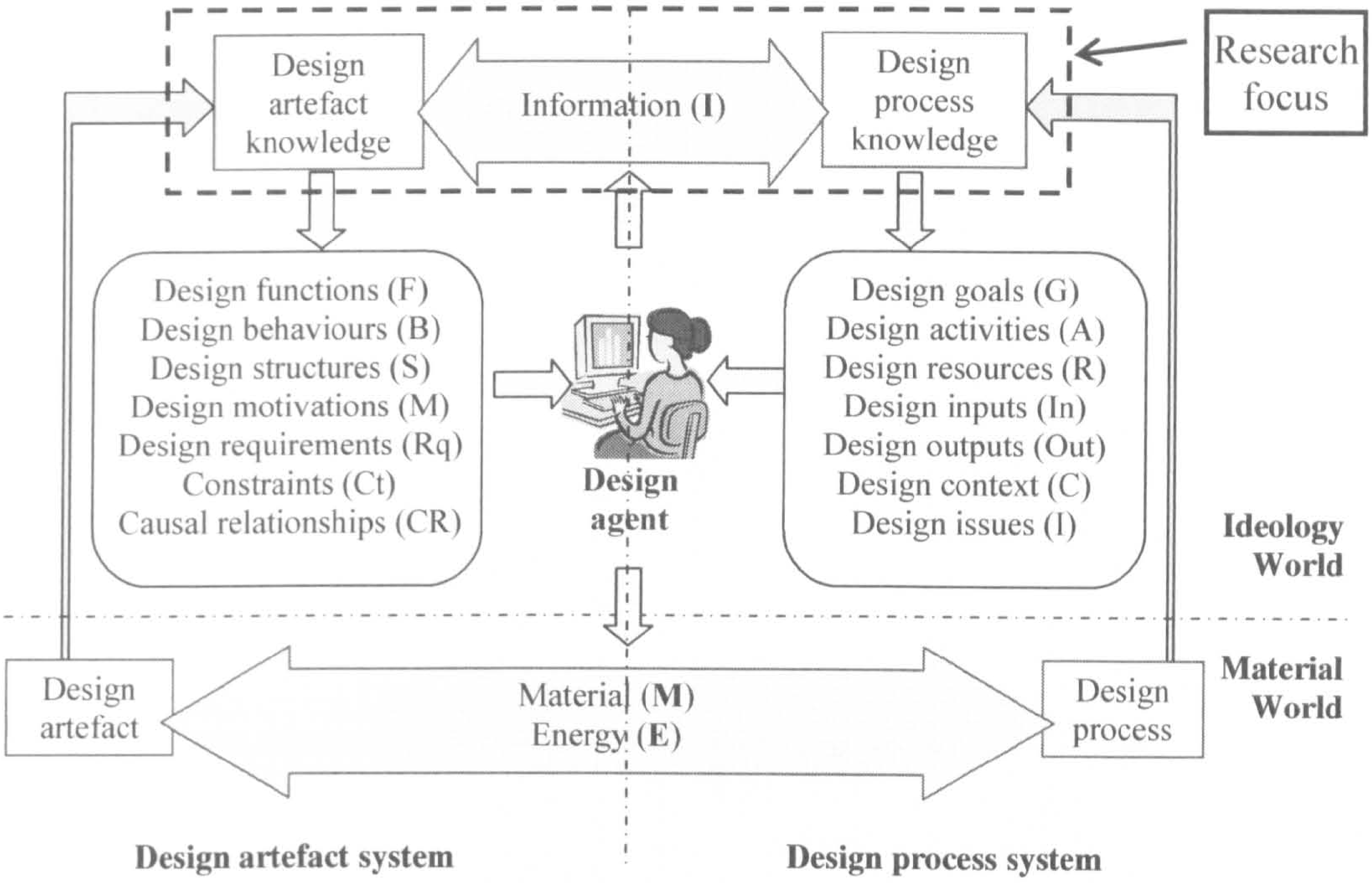


Figure 4-2: General coupling of artefact and design process

To bridge the research gap identified in Section 4.2, as well as potentially tackle the problems faced in industry, the research presented in this thesis focuses on the ideology world coupling, i.e., the knowledge level of the coupling of the artefact and design process (highlighted by the dashed rectangle in Figure 4-2). Specifically, the research is going **to focus on the nature of the coupling of evolutionary artefact and design process knowledge by modelling the knowledge elements involved in the coupling, as well as different relationships between these knowledge elements**. By doing so, the potential research contribution would increase our knowledge of design development by identifying the nature of such coupling.

4.5 SUMMARY

In order to identify the research focus, this chapter has reviewed research work by peer researchers that is pertinent to the relationship between artefact and design process knowledge. A number of problems faced by industry that are related to the coupling were also identified in this chapter.

Much of design research has been concerned with either artefact knowledge, such as function, behaviour, structure, and transformation between them, or the process knowledge, such as activity, resources, and issues. Though there is research that has been done involving relationships between the artefact and process knowledge, they are either still on a high level of the coupling, or only cover part of the relationships between the artefact and design process knowledge elements. Hence there still lack such a model that shows how the elements of artefact and design process are linked during the design development. In addition, problems identified in industry also shows that artefact and design process knowledge were not well integrated, which reveals an insufficient knowledge of the relationships between the artefact and design process.

To bridge such research gap, the focus of the research is identified to be the nature of the coupling by modelling the knowledge elements involved in the coupling, as well as different relationships between these knowledge elements.

Part Two: Approach and findings

Chapter 5 COUPLING OVERVIEW

As discussed in Chapter 3, the artefact and design process knowledge constitute two main types of design knowledge. Both of them evolve during design development and their evolution affects each other. This inter-affection forms a close relationship between them. Such relationship was termed as the coupling of the artefact and design process knowledge, which was hypothesised as composing of links between the artefact and design process knowledge elements. The review in Chapter 4 shows that a number of research has been carried out to investigate the links between these two types of knowledge. While such research primarily focuses on different links or different aspects of the coupling, there is a gap in the current research in that it still lacks a model that represents such coupling from a knowledge level. In view of this, part II of this thesis presents the nature of the coupling of the evolutionary artefact and design process knowledge, which not only explores the knowledge elements involved in the coupling and their occurrence trends over task clarification, conceptual, and embodiment design phases, but also analyses main links between the artefact and design process knowledge elements that constitute such coupling.

In order to derive the coupling, based on the post-positivism philosophy and triangulation methodology (see Chapter 2), two methods were adopted in this work. Firstly, documents from Company A were analysed[7], which resulted in an initial finding of the coupling. Secondly, empirical protocol of a supervised student design project from the Department of Design, Manufacture and Engineering Management (DMEM), University of Strathclyde, was analysed in order to evolve the coupling.

The knowledge elements occurrence trends and coupling model are presented in Chapter 6 and Chapter 7 respectively. The objective of this chapter is to present initial insights of the coupling through content analysis of a number of design related documents. This chapter is organised as follows. Section 5.1 explains the content analysis process, which is followed with discussion of the evolutionary knowledge elements and coupling links that contribute to such evolution found through the content analysis in Section 5.2. Finally, Section 5.3 summarises the chapter and provides concluding remarks.

5.1 CONTENT ANALYSIS

Among 133 accessed design-related documents from Company A, eight of them were selected for analysis. The selected documents covered not only general description of the artefact and design process, such as artefact function, structure, system design process, system functions definition process, and requirements management, but also description of specific component design processes. Considering the focus being on the coupling of the artefact and design process knowledge, and the scope being task clarification, conceptual, and embodiment design, the justifications of choosing these eight documents were based on the following criteria:

- The documents should include description of both the artefact and design process.
- The documents should cover at least task clarification, conceptual, and embodiment design phases.

[7] Documents accessed during participating the PLM project in Company A were used as the basis of this chapter. All the documents and reference to the company are classified confidential. Consequently, only general reference can be ade to them in this thesis, i.e., the documents title and product name have been substituted with general words, such as artefact, design process, component, function, etc.

- The documents could include either those that describe the entire artefact, or those that describe specific component of the artefact.

The eight analysed documents were numbered 1 to 8 sequentially in this thesis. Among them, the first three documents are in the context of product lifecycle management. Document 4 describes artefact in scope of task clarification, conceptual, and embodiment design. While documents 5 to 8 describe the artefact and design process in terms of product development. Considering the research scope of this work, only contents related to the three design phases were analysed within these documents. Table 5-1 lists the eight documents' given reference number in this thesis, document title, pages, created date, focus, and covered design phases.

Table 5-1: List of analysed documents

Ref No.	Document title	Pages	Created date	Focus	Covered design phases
1	Artefact structure	129	Jan 2004	Artefact	Product life cycle
2	Artefact design phase	21	May 2001	Process	Product life cycle
3	Artefact information object	42	May 2001	Artefact	Product life cycle
4	System specification	40	Jun 2000	Artefact	Task clarification, Conceptual design, Embodiment design
5	Company operational process	5	Jun 2004	Process	Product development
6	Requirements management	52	Feb 2001	Artefact	Product development
7	Function definition process	46	Jan 2000	Process	Product development
8	Component level design process	103	Dec 2003	Process	Product development

It should to be noted that these documents describe company standard artefact knowledge that was accumulated from past designs and process knowledge of standard company working procedures. By analysing such documents, the knowledge being analysed were actually domain knowledge. However, the analysis was conducted in a hypothesis that the design was for a current project, and the design knowledge identified from these documents with such hypothesised scenario could, therefore, be hypothesised as current working knowledge of the design. Consequently, the analysis result of knowledge elements and coupling, obtained from the content analysis, could be considered as that of current working knowledge.

In order to obtain an initial insight of the nature of the coupling, the content analysis focused on descriptions of the artefact, design process, and relationship between them. To this end, the following two steps were taken.

Step 1:

The knowledge elements identified in sections 3.3 and 3.4 through the literature review were used as the basis for analysis, which included: Expected behaviour (B_e), Instantiated behaviour (B_{is}), Interpreted behaviour (B_{it}), Expected function (F_e), Interpreted function (F_{it}), Expected structure (S_e), Instantiated structure (S_{is}), Causal relationships (*CR*), Constraints (*Ct*), Motivations (*M*), and Requirements (*Rq*) of the artefact, and Design activity (*A*), Goal (*G*), Input (*In*), Output (*Out*), Resource (*R*), Context (*C*), and Issues (*I*) of the design process.

Although these terms were not explicitly used in the documents, there were some specific key words in the documents that were considered representing these elements.

In order to identify these elements, the key words were then extracted from each document. Table 5-2 shows an example of the analysis of knowledge elements in Document 1. The first column lists the design knowledge elements and the second contains the key words that represent these elements. "N/A" in the second column indicates that such element was not identified in the document. Since the analysis was based on the hypothesis of a current project, the current working knowledge elements were then represented with the aforementioned abbreviations (in the previous paragraph) following 'WK_A-' or 'WK_P-', depending on whether they were artefact or process elements. Though the documents were analysed in the hypothesis of a current design, there were some key words that could be identified as domain artefact knowledge, such as "company catalogue" relating to the coupling. Rather than describing specific artefact knowledge elements, such as function, behaviour, and structure, most domain artefact knowledge identified were company standard and catalogue. Hence, they were represented as DK_A in the analysis. A full description of the knowledge elements identified in all the eight documents can be found in the "Knowledge elements" part of Appendix B.

Table 5-2: Knowledge elements identified from Document 1

Knowledge elements	Key words
$WK_{A\text{-}Be}$	N/A
$WK_{A\text{-}Bis}$	N/A
$WK_{A\text{-}Bit}$	N/A
$WK_{A\text{-}Fe}$	Business catalogues, Standard specification, Functions, Elementary function, Contract
$WK_{A\text{-}Fit}$	Functional diagram, Performing functions
$WK_{A\text{-}Se}$	Contractual configuration, Constituent assembly, Configuration component, Business catalogues, Standard specification, Conception solutions, Design principles
$WK_{A\text{-}Sis}$	Configuration, 3D Models, 2D Drawings, Design solution, Mock-up, Chosen design principle, Parts
$WK_{A\text{-}CR}$	Category, Standard specification
$WK_{A\text{-}Ct}$	Constraints
$WK_{A\text{-}M}$	Company requirements, Customer needs
$WK_{A\text{-}Rq}$	Contract, Requirement program, Market requirement
$WK_{P\text{-}A}$	Way of working, Update/Creation of data, Build contract, Create specification, Means, Change, Evaluation
$WK_{P\text{-}G}$	Objective
$WK_{P\text{-}In}$	In
$WK_{P\text{-}Out}$	Out
$WK_{P\text{-}R}$	Catalogues, Standard specification, Department, Tools, Literature, Who
$WK_{P\text{-}C}$	Status, Interactions, Scenario, State of design, All functions/solutions
$WK_{P\text{-}I}$	N/A
DK_A	Standard specification, Business catalogue, Literature, Standards

Step 2:

After the knowledge elements were identified from the documents, the second step of the analysis was to find the links between the elements. Two types of links were identified: (i) *cause-effect link of creation* and (ii) *link of employment*. The former links two elements that one triggers the creation or occurrence of another, and the latter links two elements that one employs the other. These links were found, through this initial analysis, to be the basic types of links that constituted the coupling.

Table 5-3 shows the links identified from Document 1. In the upper "*Cause-effect link of creation*" part of the table, the elements listed in the second column represent the causing elements, and those in the second row represent caused elements. Symbol "✓" indicates that a creation link exists between the two intersected elements. In the lower "*Link of employment*" part, the elements listed in the second column represent the employing elements, and those in the second row represent employed elements. "✓" indicates that an employment link exists between the two intersected elements. A full description of the identified links from all the eight documents can be found in the "Coupling links" part of Appendix B.

Table 5-3: Links identified from Document 1

Cause-effect link of creation

Causing elements \ Caused elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}																			
	WK_{A-Bit}																			
	WK_{A-Bis}																			
	WK_{A-Fe}													√						
	WK_{A-Fit}													√						
	WK_{A-Se}													√						
	WK_{A-Sis}																			
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}													√						
	WK_{A-Rq}													√						
Design process	WK_{P-A}	√				√	√	√	√				√							
	WK_{P-G}																			
	WK_{P-In}																			
	WK_{P-Out}																			
	WK_{P-R}																			
	WK_{P-C}																			
	WK_{P-I}																			

Link of employment

Employing elements \ Employed elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}																			
	WK_{A-Bit}																			
	WK_{A-Bis}																			
	WK_{A-Fe}																			
	WK_{A-Fit}																			
	WK_{A-Se}																			
	WK_{A-Sis}																			
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}																			
	WK_{A-Rq}																			
Design process	WK_{P-A}																			
	WK_{P-G}					√		√	√				√							
	WK_{P-In}	√				√	√	√	√			√	√							
	WK_{P-Out}	√				√	√	√	√			√	√							
	WK_{P-R}	√								√										
	WK_{P-C}					√		√	√											
	WK_{P-I}																			

5.2 RESULTS

The analysis results of the eight documents, i.e. the identified knowledge elements that are involved in the coupling and initial findings of the coupling, are presented in sections 5.2.1 and 5.2.2 respectively. It should to be noted that due to the nature of the analysed documents, which contain high-level descriptions of the company product and procedure standards, the coupling presented in this chapter are based on high-level design knowledge elements. For example, the activities were identified at a higher level rather than the ontological level discussed by Sim and Duffy (2003). Therefore, such results will be accommodated with the results obtained from the protocol analysis presented in Chapter 7.

5.2.1 Evolutionary artefact and design process knowledge

Although the eight documents include descriptions of both the artefact and design process, the focus of each document is either the artefact or the design process. As a result, not all the aforementioned knowledge elements were identified within each document. However, with the exception of $WK_{A\text{-}Bis}$ and $WK_{P\text{-}I}$, the remaining elements were all identified from more than one document. Table 5-4 lists the number of documents within which the knowledge elements were identified. The analysed elements are presented in the remainder of this section.

Table 5-4: Number of documents within which knowledge elements were identified

Knowledge elements	Number of documents	Knowledge elements	Number of documents
$WK_{A\text{-}Be}$	5	$WK_{P\text{-}A}$	8
$WK_{A\text{-}Bis}$	0	$WK_{P\text{-}G}$	7
$WK_{A\text{-}Bit}$	5	$WK_{P\text{-}In}$	8
$WK_{A\text{-}Fe}$	8	$WK_{P\text{-}Out}$	8
$WK_{A\text{-}Fit}$	8	$WK_{P\text{-}R}$	8
$WK_{A\text{-}Se}$	8	$WK_{P\text{-}C}$	4
$WK_{A\text{-}Sis}$	8	$WK_{P\text{-}I}$	0
$WK_{A\text{-}CR}$	7	DK_A	5
$WK_{A\text{-}Ct}$	8		
$WK_{A\text{-}M}$	7		
$WK_{A\text{-}Rq}$	8		

Artefact knowledge

Domain artefact knowledge (DK_A)

As a result of the analysis, a number of DK_A were identified, mainly in forms of standard documents, such as "standard specification", "business catalogue", "literature", and "standards". These documents had been accumulated through past designs and were used in the current design for reference. Due to the nature of the analysed documents, DK_A was seldom presented on detailed element level, such as function and structure. Hence DK_A is treated as one item in the coupling analysis.

Expected current working behaviour ($WK_{A\text{-}Be}$)

Representing designers' expectation towards what the artefact can perform, $WK_{A\text{-}Be}$ was identified through key words such as "performances to be achieved" and "function requirements".

From the analysis, it was found that the identification of $WK_{A\text{-}Be}$ to be lower than other identified artefact elements (five out of eight documents). One explanation for this is that behaviour and function were often not differentiated in industry not least because function was sometimes used in the company to describe behaviour of the artefact. This can be verified from function definition in Document 7, which was "A task, action, or activity performed to achieve a desired outcome". In addition, "Functional requirements" was defined as an action to be performed by the aircraft/system/equipment in Document 7. This combination of behaviour and function might also verify the phenomena that function and behaviour were often debated by designers and researchers (see Chapter 3 for further details). The evolution of $WK_{A\text{-}Be}$ was revealed through its generation/emergence, decomposition, and evaluation.

Instantiated current working behaviour ($WK_{A\text{-}Bis}$)

As an intrinsic knowledge element of the artefact, $WK_{A\text{-}Bis}$ contains all the possible behaviours that an artefact could perform. As a result of the analysis, no $WK_{A\text{-}Bis}$ was identified from the documents. This could be explained that based on the definition of B_{is} and B_{it} (see Section 3.3.2.3), all artefact behaviours described in the documents were encoded as $WK_{A\text{-}Bit}$, because they were behaviours that were interpreted by designers.

Interpreted current working behaviour ($WK_{A\text{-}Bit}$)

Words labelling $WK_{A\text{-}Bit}$ were identified to be "simulations", "performance", "operations", and "function analysis". Similar to $WK_{A\text{-}Be}$, $WK_{A\text{-}Bit}$ was identified from five documents, which might also be explained as being often represented in combination with function. For example, "functions" in "Implementation of the functions performed by the system" (in Document 4) referred to interpreted behaviour according to its definition given in Chapter 3. The evolution of $WK_{A\text{-}Bit}$ was revealed through its generation.

Expected current working function ($WK_{A\text{-}Fe}$)

$WK_{A\text{-}Fe}$ was identified in all the eight documents, which was normally labelled "function in feasibility study", "contract", "standard specification", "function requirements documents", "configuration", or "function". The overall expected system function, derived from requirements, was normally decomposed into elementary functions, which were then allocated to different components or parts of the system. Hence, the evolution of $WK_{A\text{-}Fe}$ was revealed through its generation, decomposition, allocation to artefact structure, and its validation. The analysis showed that "requirements" were sometimes used in the documents representing $WK_{A\text{-}Fe}$. For example, it was mentioned in Document 6 that "A requirement describes a desired function or characteristic of any product, part of it, or service". In addition, "function requirements" and "artefact requirements" refer to the expected function in documents 2 and 4.

Interpreted current working function ($WK_{A\text{-}Fit}$)

$WK_{A\text{-}Fit}$ was generally used by designers for evaluating the artefact, after the artefact structure has been specified. It was therefore identified in the eight documents with key words such as "functional diagram", "system architecture description", "function analysis", and "performance analysis". Its evolution was revealed through its generation.

Expected current working structure ($WK_{A\text{-}Se}$)

The company's product development was normally based on some current configurations. In order to accomplish the expected function, designers initially need to clarify the artefact requirements and functions. Based on that, they will then choose components/parts from company catalogues and standard specifications, and make corresponding modification. The $WK_{A\text{-}Se}$ is normally specified in "contractual configuration", "proposed structure", "equipment specification", and "possibility of artefact design". Similarly, its evolution was revealed through its generation, decomposition, and evaluation.

Instantiated current working structure ($WK_{A\text{-}Sis}$)

In the analysed documents, as a result of instantiation of the artefact concept and system configuration, $WK_{A\text{-}Sis}$ is normally presented in the form of model. The key words that mark $WK_{A\text{-}Sis}$ include "2D drawings", "3D models", "physical geometry definition", and "solution". Its evolution was revealed from its generation and modification. The analysis showed that $WK_{A\text{-}Sis}$ was not transferred from $WK_{A\text{-}Se}$ at one instance. Rather, it was seen that they co-existed and the transformation occurred progressively in the designing.

Current working causal relationships ($WK_{A\text{-}CR}$)

Representing the cause-effect relationships among artefact knowledge elements, $WK_{A\text{-}CR}$ could be identified through "category", "standard specification", "design principles", "design evolution", and "design rationale". For example, the company category provides the mapping relationships between expected function and structure for the current design. The evolution of $WK_{A\text{-}CR}$ was revealed from its generation, which resulted in the creation of the effected elements.

Current working constraints ($WK_{A\text{-}Ct}$)

A number of constraints were identified in the eight documents, which were normally marked as "non-functional requirements", "restrictions", "regulations", or "constraints". Business and marketing as well as environmental constraints are some examples of such constraints. Similarly, the evolution of $WK_{A\text{-}Ct}$ was revealed from its generation.

Current working motivations ($WK_{A\text{-}M}$)

Two types of motivations were identified from the analysis, i.e., external and internal. The external motivation generally originated from market analysis and opportunity study, such as "customers' needs", "competitors' threatening", and "suppliers' change". The internal motivation usually originated from company development needs, such as "internal development idea". Similarly, the evolution of $WK_{A\text{-}M}$ was revealed from its generation.

Current working requirements ($WK_{A\text{-}Rq}$)

Requirements are the primary means of communication between customers, stakeholders, and developers. Derived from various motivations, $WK_{A\text{-}Rq}$ also included external and internal, representing their different origination. $WK_{A\text{-}Rq}$ was normally documented in "contract", "requirement program", and "verification and validation documents". Moreover, the "system description document" also included requirements descriptions. Overall, the decomposition of requirements from system-level to component-level, and specification of the components that satisfied the requirements revealed its evolution.

The analysis showed that requirements were widely used throughout the design process. It was found that requirements in these document not only acted as requirements defined in Chapter 3, but also as expected function if they were requirements to be addressed, and interpreted function if the requirements were verified requirements. Hence the requirements used in the company had a wider scope than the requirements defined in Chapter 3, in that the requirements also referred to function in some of the analysed documents.

The knowledge elements identified from the content analysis are presented in Figure 5-1 based on the P-FBS model presented in Chapter 3. The seven fundamental current working artefact knowledge elements, the four contextual current working artefact knowledge elements, and domain artefact knowledge are depicted in three blocks in the figure. $WK_{A\text{-}Bis}$ is coloured in grey because it was not identified in the documents. In addition, the black $WK_{A\text{-}Fe}$ and $WK_{A\text{-}Fii}$ (which are located on top of the grey $WK_{A\text{-}Fe}$ and $WK_{A\text{-}Be}$, and $WK_{A\text{-}Fii}$ and $WK_{A\text{-}Bii}$)

indicate that both function and behaviour are often treated as function in industry. The grey arrows represent the causal relationships identified in Chapter 3.

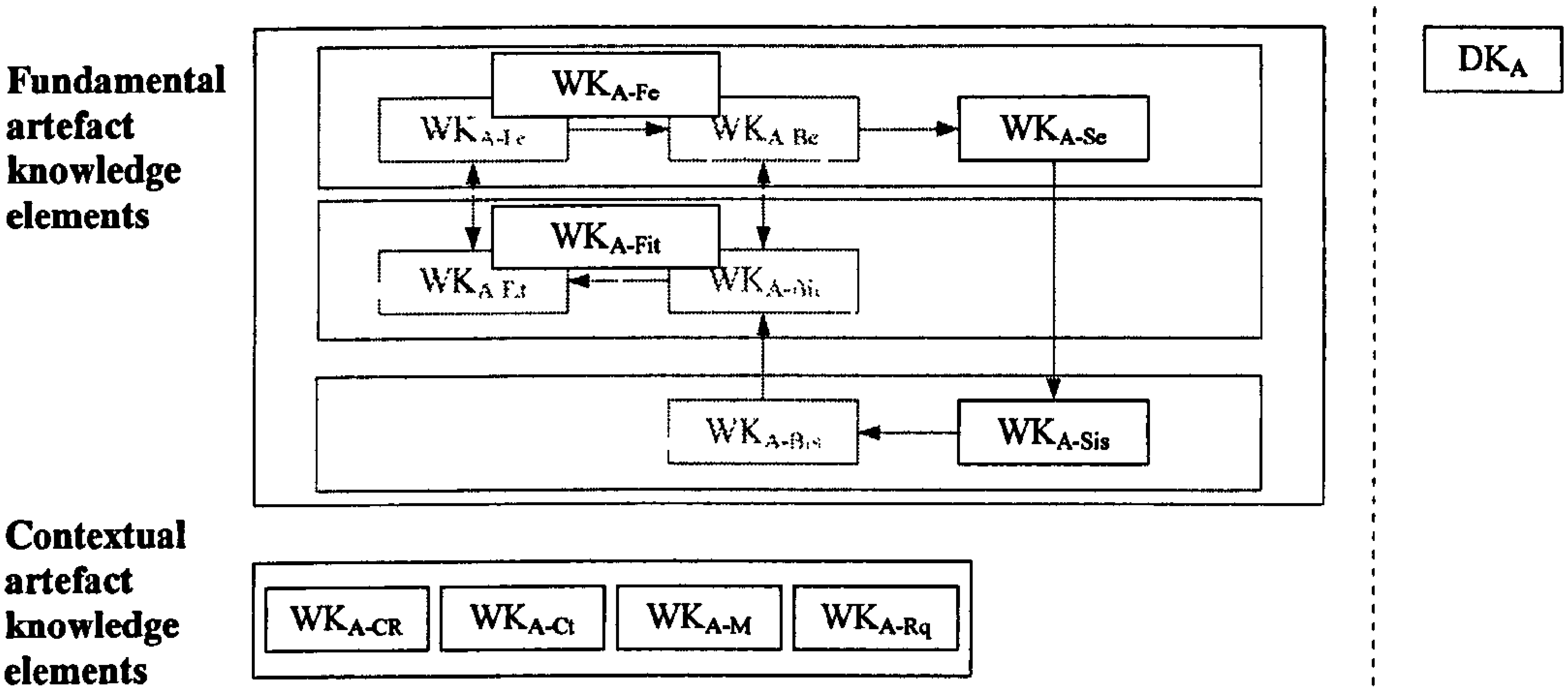


Figure 5-1: Artefact knowledge elements – based on the content analysis

The content analysis showed that through the emergence of new artefact knowledge elements, the current working knowledge of an artefact evolves from motivation (e.g. some ideas or customer requirements), to artefact requirements, artefact system functions, components functions, artefact structure, and finally to a deliverable design. Meanwhile, as a result of modification and specification, the values or properties of these requirements, functions, components, and structures are gradually specified by designers, with the consequence of less ambiguity of the artefact. Therefore, an artefact could be considered evolving in two dimensions during designing. One is qualitative, in which the artefact evolves with more concepts throughout the design process, such as requirements, functions, components, and installation. The other is quantitative, in which the artefact evolves with more detailed description of values or properties of the concepts. Figure 5-2 illustrates such evolution of aircraft knowledge in these two dimensions. The ship in the figure is an example of the artefact.

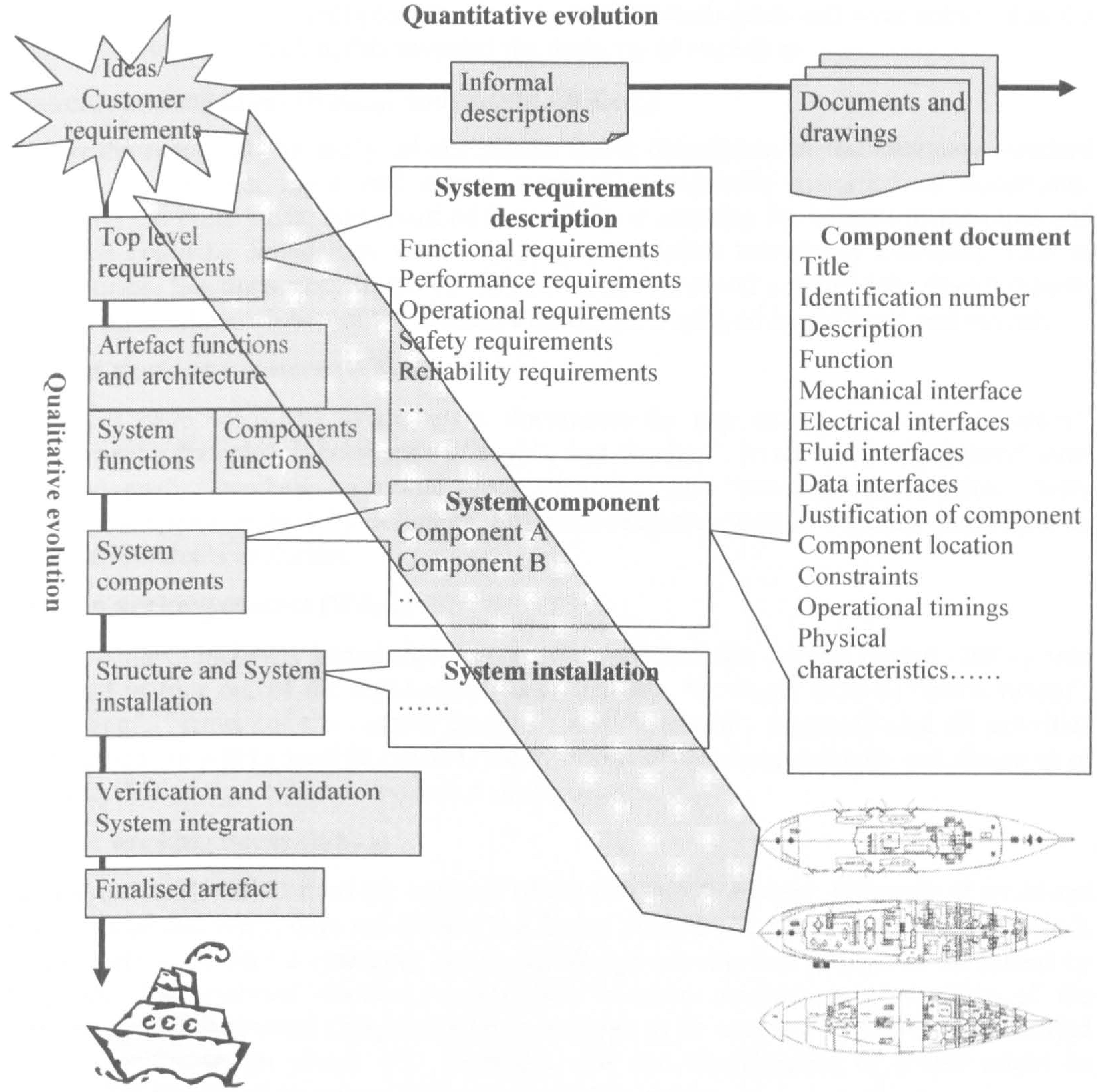


Figure 5-2: Evolutionary artefact knowledge

Design process knowledge

The analysis showed that with the exception of design issues, all the other six design process knowledge elements were identified within the documents.

Current working design activity ($WK_{P\text{-}A}$)

As an essential element of the design process, activity was identified in all the documents. The key words showed the activities included "activities" and "way of working", or some specific activities, such as "analysis", "comparison", "definition", "integration", and "optimisation". With available input and resources, activities were executed concurrently or consecutively during designing. The continuous enactment of new activities revealed the evolution of design activity. While the types of activities could be the same throughout the designing, the activities were different, in a sense that the input, output, goal, and resource related to each activity were different.

Current working goal ($WK_{P\text{-}G}$)

The overall design goal of the design in the company is to convert a set of agreed requirements into realisable product that satisfy the acquirer and other stakeholders' requirements. Goals in the documents were labelled with "aims", "objectives", "targets", or "purposes". While the overall goal was decomposed into sub-goals and were achieved as the result of activities execution, this revealed the design goal evolution.

Current working input ($WK_{P\text{-}In}$) and output ($WK_{P\text{-}Out}$)

Due to the nature of the analysed documents being description of the company standard product and process, input and output were often explicitly specified as documents, specifying the prerequisite and result of the activity. Analysing the content of the input and output, it could be found they were basically the artefact knowledge elements, such as requirements, functions, and structures. Therefore, the input and output of the design process evolved due to the evolution of the artefact knowledge employed by the input and output.

Current working resource ($WK_{P\text{-}R}$)

Resources were identified in the eight documents by key words such as "resources", "department", "people", "techniques", "tools", and "budget". In addition, "literatures" such as "catalogue", "standard functional block diagram", and "standard specification", were information resources used by designers. Different resources used in different design phases revealed resource's evolution.

Current working context ($WK_{P\text{-}C}$)

Design context included knowledge factors that affected the current design. $WK_{P\text{-}C}$ was identified in four out of the eight analysed documents, by words such as "environment", "marketing", "status (of the current design)", and "scenario". Assumed that all activities were carried out within specific context, the evolution of the design activity and changing of an artefact's status revealed the evolution of the context.

Current working issues ($WK_{P\text{-}I}$)

No $WK_{P\text{-}I}$ was identified from the analysis of the documents content. However, it could not be concluded that $WK_{P\text{-}I}$ does not exist in the design process. As it was defined in Chapter 3, issues relate to problems emerging during the design process that needed to be solved by designers. The analysed documents described standard product and procedure of the company, which instructed designers with knowledge to be used and activities to be carried out in specific design phase, etc. Therefore, the non-identification of issues might be explained as a result of the nature of the analysed documents.

Figure 5-3 illustrates the above-mentioned design process knowledge elements based on the process model discussed in Chapter 3. The elements are depicted in two blocks, one representing fundamental and the other showing contextual elements. The grey coloured design issue indicates that the element was not identified from the analysis and the grey arrows represent the relationships between the elements discussed in Chapter 3.

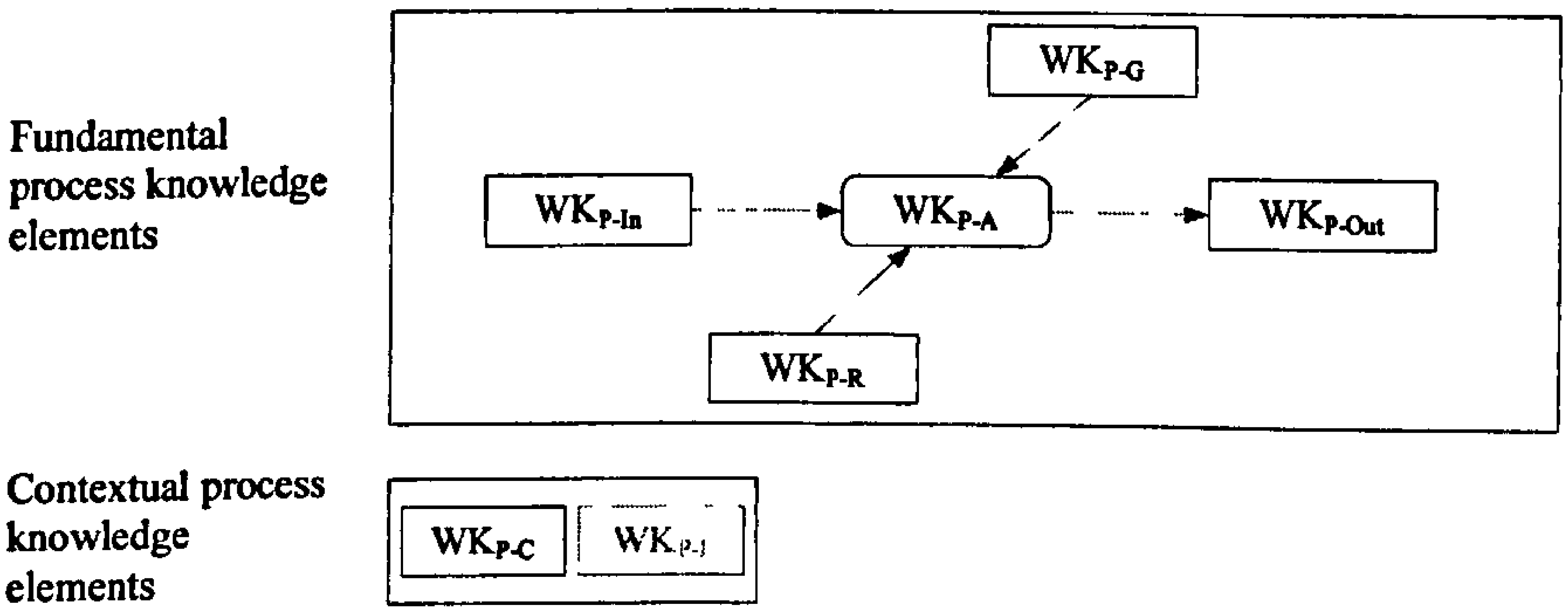


Figure 5-3: Design process knowledge elements – based on the content analysis

Generally, the design process in the company was not developed from scratch. Rather, it is an implementation of certain predefined standard processes and design methods, which specify the main phases or stages that the design should go through. These standards are domain knowledge of the design process (Because it was found through the content analysis that such domain knowledge of the design process did not involve in the coupling of the artefact and design process knowledge, it is therefore not discussed in this thesis). Based on such standards, design process is normally stepwise evolutionary, which introduces new design goals, activities, with inputs, outputs and resources. Hence, similar to artefact, design process evolves both qualitatively and quantitatively. In a qualitative evolution, design process evolves over different design phases following the standard procedure; and in a quantitative evolution, the standard process is endowed with specific activities and goals, which evolve the artefact with new input and output. Figure 5-4 depicts such evolutionary design process knowledge and its two evolution directions.

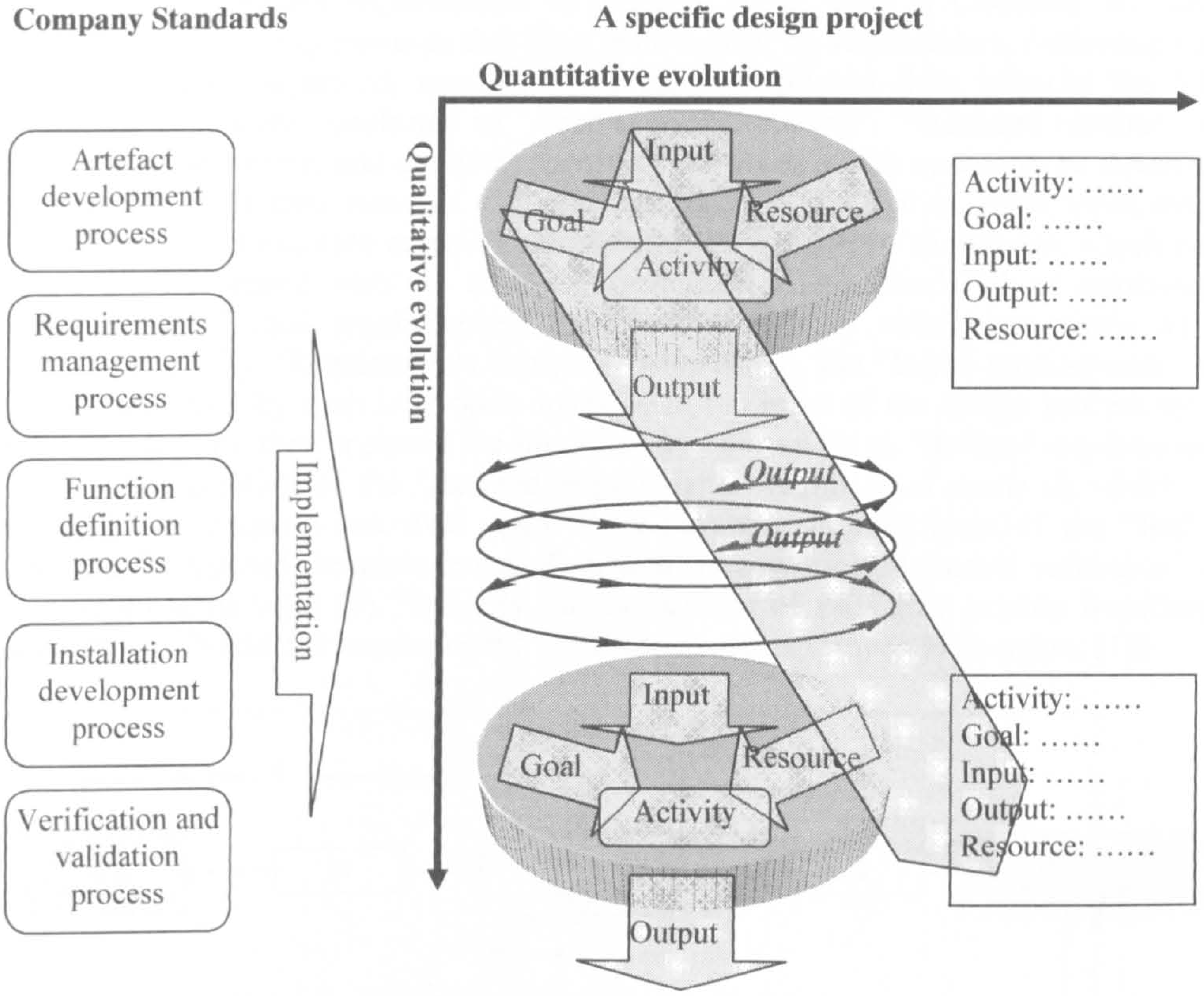


Figure 5-4: Evolutionary design process knowledge

Having presented the evolutionary artefact and design process knowledge elements based on the content analysis, the next section presents the initial findings of the coupling.

5.2.2 Coupling links identified from content analysis

The previous section verified that both the artefact and design process knowledge evolve. The analysis showed that their evolution was not independent. Rather, the artefact knowledge evolution was triggered by the design process, and the enacting of design process was, in turn, triggered by the evolution of the artefact. Hence, it can be argued that their evolution is closely related to links between the artefact and design process knowledge elements. Such links are considered to compose the coupling that is aimed to be presented in this thesis. As mentioned in Section 5.1, the two types of l· :s that closely related to the evolution are *cause-effect link of creation* and *link of emp. yment*. Table 5-5 shows the representation of these two types of links used in this thesis.

Table 5-5: Two types of links identified from the content analysis

Link type	Representation	Explanation
Cause-effect link of creation	A ——> B	Element A triggers the creation or occurrence of element B.
Link of employment	A --------● B	Element A employs element B.

In order to explain how they are related to the design knowledge evolution, 'requirements' are used as an example here. Figure 5-5 depicts the evolution of artefact requirements from "Initial" to "Refined" (indicated by dash dotted open arrow 1) and from "Refined" to "Validated" (arrow 2), and that of the design process through the emergence of two design activities, "Requirements analysis" and "Requirements validation" (arrow 3). The three sets of requirements represent requirements in different status used in Company A. "Initial requirements" are the requirements that have been agreed by stakeholders. Following being removed ambiguity, separated, merged, interpreted, established links between the initial requirements, they were transferred to "Analysed requirements". "Validated requirements" are the correct, consistent, and complete record of the needs of the system to be developed. The emergence of different status of requirements, and design activities, goals, input, output, and resources in this example revealed the evolution of the design knowledge, which could be found closely related with the ***cause-effect link of creation*** and ***link of employment***. Specifically, the "Initial requirements" caused (indicated by solid open arrow 4) the enactment of activity "Requirements analysis". Meanwhile, the "Initial requirements" was employed (indicated by dash oval open arrow 5) in the input of the design process by the activity. The activity then analysed the input and transformed it to "Refined requirements", i.e., caused the creation of the "Refined requirements" (solid open arrow 6), which was employed in its output (dash oval open 7). Meanwhile, the readiness of the "Refined requirements" triggered the occurrence of another activity "Requirements validation" (8), and employed in its input (9). Similarly, the occurrence of validation activity transformed requirements to "Validated requirements" (10), which was employed in its output (11).

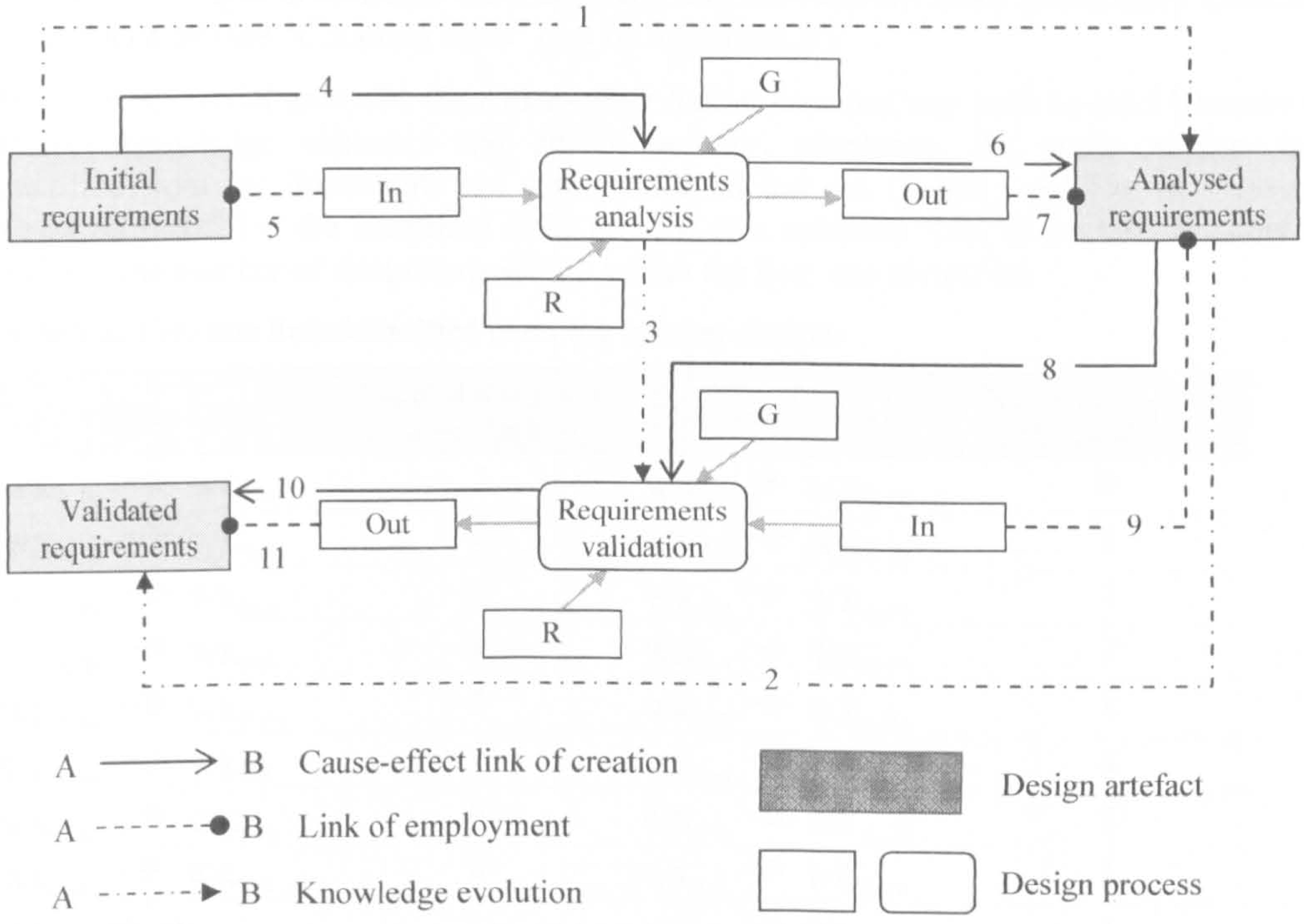


Figure 5-5: Coupling and evolution – requirements example

The above example can be generalised to a model as shown in Figure 5-6. The model shows how the evolution of the artefact and design process knowledge are related to the coupling. As can be seen from Figure 5-6, "Artefact knowledge element 1" causes the creation or occurrence of "Activity A". Meanwhile, it is employed in its input. The activity then causes the creation of another chunk of "Artefact knowledge element 2", which in turn evolves to "Artefact knowledge element 3" by "Activity B". The emergence of the artefact and design process elements forms the evolution of the artefact and design process. The evolution closely related to the links between the artefact and design process knowledge elements, and the links compose the coupling.

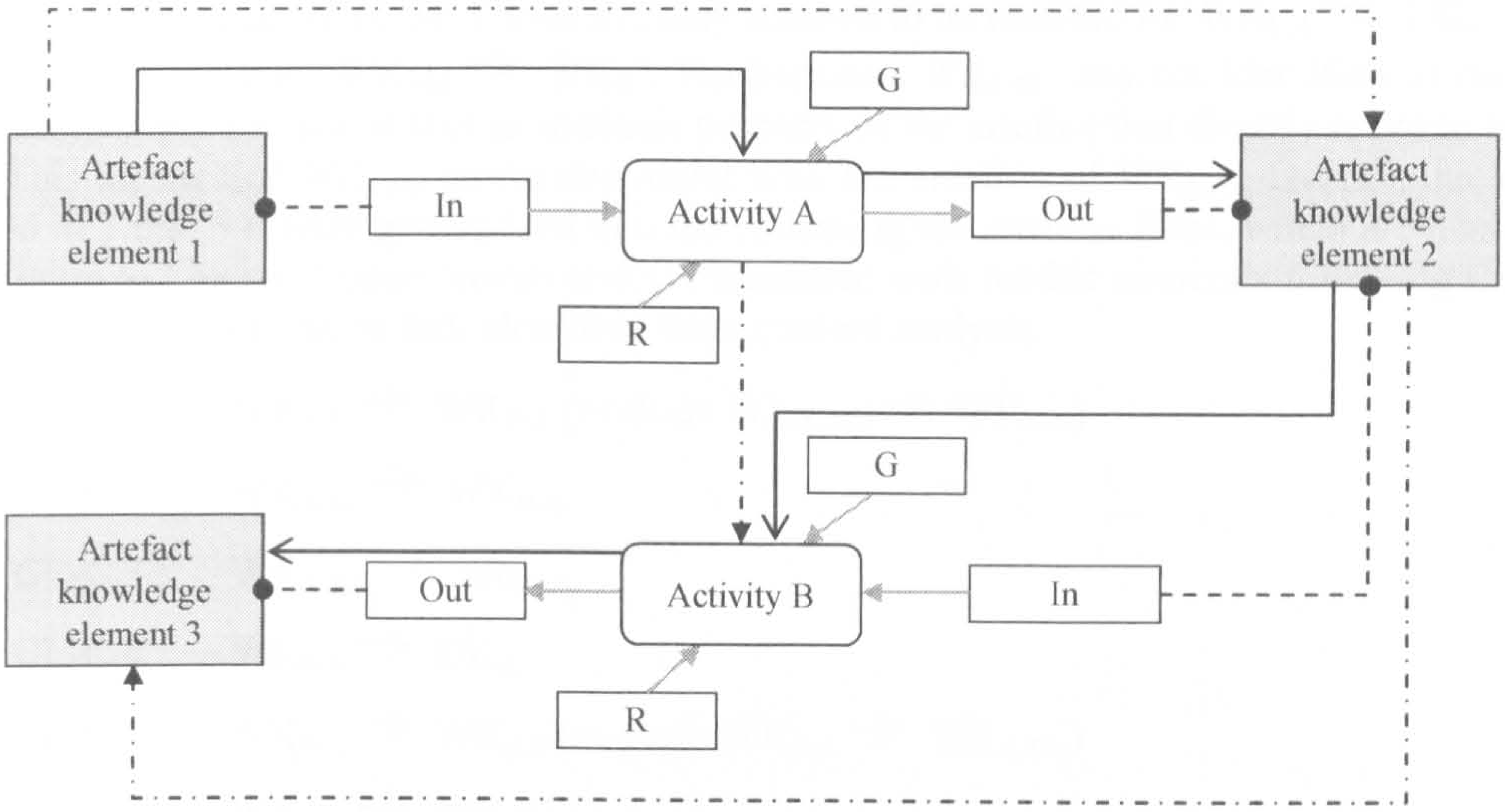


Figure 5-6: Coupling and evolution – general model

In order to identify such coupling, i.e., the two types of links between the knowledge elements, the eight documents were analysed and the relevant links within each document were identified (see "Coupling links" part of Appendix B).

Based on the initial analysis, the *cause-effect link of creation* was seen to exist between the artefact knowledge elements and design activity. Moreover, the main creation links identified from the documents are summarised as follows (Table 5-6). The two columns "Creation links" list the identified links and the two columns "No. of documents show the link" list the number of documents within which the link was identified.

Table 5-6: Creation links identified from the content analysis

Creation links	No. of documents show the link	Creation links	No. of documents show the link
$WK_{A\text{-}Be} \rightarrow WK_{P\text{-}A}$	5	$WK_{P\text{-}A} \rightarrow WK_{A\text{-}Be}$	6
$WK_{A\text{-}Bit} \rightarrow WK_{P\text{-}A}$	5	$WK_{P\text{-}A} \rightarrow WK_{A\text{-}Bit}$	6
$WK_{A\text{-}Fe} \rightarrow WK_{P\text{-}A}$	8	$WK_{P\text{-}A} \rightarrow WK_{A\text{-}Fe}$	7
$WK_{A\text{-}Fit} \rightarrow WK_{P\text{-}A}$	8	$WK_{P\text{-}A} \rightarrow WK_{A\text{-}Fit}$	7
$WK_{A\text{-}Se} \rightarrow WK_{P\text{-}A}$	8	$WK_{P\text{-}A} \rightarrow WK_{A\text{-}Se}$	8
$WK_{A\text{-}Sis} \rightarrow WK_{P\text{-}A}$	7	$WK_{P\text{-}A} \rightarrow WK_{A\text{-}Sis}$	8
$WK_{A\text{-}M} \rightarrow WK_{P\text{-}A}$	6	$WK_{P\text{-}A} \rightarrow WK_{A\text{-}CR}$	2
$WK_{A\text{-}Rq} \rightarrow WK_{P\text{-}A}$	8	$WK_{P\text{-}A} \rightarrow WK_{A\text{-}Ct}$	3
$WK_{P\text{-}A} \rightarrow DK_{A}$	1	$WK_{P\text{-}A} \rightarrow WK_{A\text{-}M}$	4
		$WK_{P\text{-}A} \rightarrow WK_{A\text{-}Rq}$	8

Based on the analysis of the links that cause the creation or occurrence of activity in the first "Creation links" column of Table 5-6, it could be seen that with the exception of the links caused by $WK_{A\text{-}M}$ and $WK_{A\text{-}Rq}$, i.e., '$WK_{A\text{-}M} \rightarrow WK_{P\text{-}A}$' and '$WK_{A\text{-}Rq} \rightarrow WK_{P\text{-}A}$', the other six were caused by the fundamental current working artefact knowledge ($WK_{A/F}$). These six links therefore could be generalised into one link that is caused by $WK_{A/F}$, i.e., '$WK_{A/F} \rightarrow WK_{P\text{-}A}$'. $WK_{A\text{-}Bis}$ was not included in the link as it was not identified from the documents. The links listed in the second "Creation links" column in the table show that the activity caused the creation of domain artefact knowledge and all the identified current working artefact knowledge elements. Therefore, they seemed to be resulted in '$WK_{P\text{-}A} \rightarrow DK_A$' and one generalised link '$WK_{P\text{-}A} \rightarrow WK_A$'. Furthermore, $WK_{A\text{-}Bis}$ was not identified as caused element simply because it was an intrinsic property of the artefact that directly relate to $WK_{A\text{-}Sis}$. This means that $WK_{A\text{-}Bis}$ co-existed along with the creation of $WK_{A\text{-}Sis}$. Overall, the links listed in Table 5-6 were generalised into the following six creation links, which are depicted in Figure 5-7 by solid open arrows and are identified with Arabic numerals following CL-C, which represents creation link identified from content analysis.

CL-C.1 : $WK_{A/F} \rightarrow WK_{P\text{-}A}$ (exclude $WK_{A\text{-}Bis} \rightarrow WK_{P\text{-}A}$)

CL-C.2 : $WK_{A\text{-}M} \rightarrow WK_{P\text{-}A}$

CL-C.3 : $WK_{A\text{-}Rq} \rightarrow WK_{P\text{-}A}$

CL-C.4 : $WK_{P\text{-}A} \rightarrow DK_A$

CL-C.5 : $WK_{P\text{-}A} \rightarrow WK_{A/F}$ (exclude $WK_{P\text{-}A} \rightarrow WK_{A\text{-}Bis}$)

CL-C.6 : $WK_{P\text{-}A} \rightarrow WK_{A/C}$

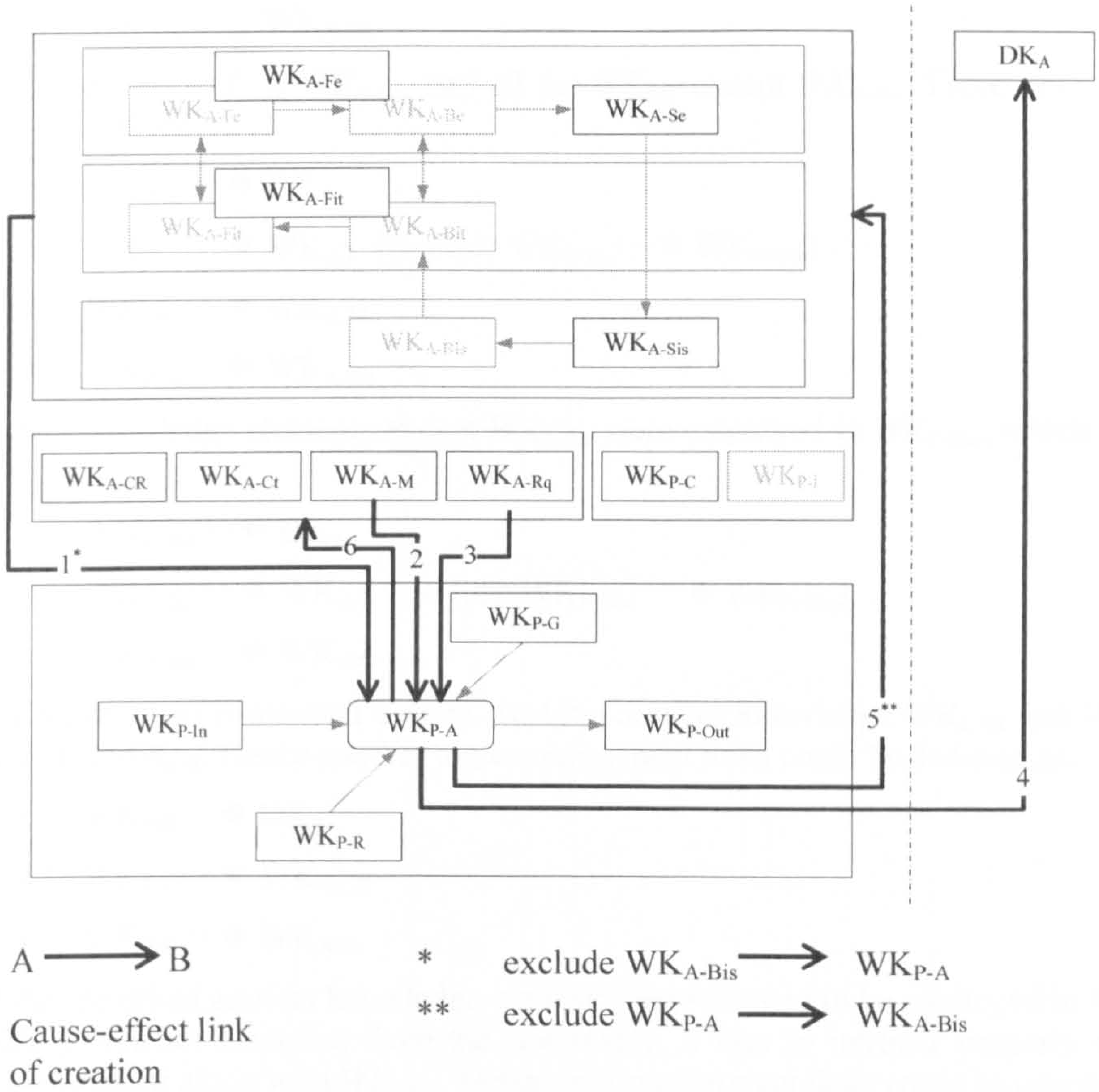


Figure 5-7: Creation links of the coupling – based on the content analysis

In addition to the creation links, Table 5-7 summarises the employment links identified from the content analysis. Instead of listing all the identified links, a matrix as shown in the table is used to indicate the identified links. The second column in the table lists the employing elements and the second row lists the employed elements. The numbers in the table are the number of documents within which the links were identified. The analysis showed that the goal, input, output, resource, and context are the main employing elements, with artefact knowledge elements being the employed elements.

Table 5-7: Employment links identified from the content analysis

Employed element / Employing element		Artefact											
		DK$_A$	WK$_{A-Be}$	WK$_{A-Bit}$	WK$_{A-Bis}$	WK$_{A-Fe}$	WK$_{A-Fit}$	WK$_{A-Se}$	WK$_{A-Sis}$	WK$_{A-CR}$	WK$_{A-Ct}$	WK$_{A-M}$	WK$_{A-Rq}$
Design process	WK$_{P-A}$	0	0	0	0	0	0	0	0	0	0	0	0
	WK$_{P-G}$	0	2	2	0	2	1	3	3	0	0	2	5
	WK$_{P-In}$	2	4	4	0	7	7	8	8	0	0	5	8
	WK$_{P-Out}$	1	4	4	0	8	8	8	8	1	1	3	8
	WK$_{P-R}$	6	0	0	0	0	0	0	0	6	2	0	0
	WK$_{P-C}$	1	1	1	0	2	1	2	2	1	2	1	2
	WK$_{P-I}$	0	0	0	0	0	0	0	0	0	0	0	0

It could be found from the table that WK_{A-M}, WK_{A-Rq}, and all the $WK_{A/F}$ except WK_{A-Bis} were employed in WK_{P-G}. These employment links could be generalised as below. They are identified with Roman numerals following EL-C, which represents employment link identified from content analysis.

EL-C.i : WK$_{P-G}$ --● WK$_{A/F}$ (exclude WK$_{P-G}$ ---● WK$_{A-Bis}$)

EL-C.ii : WK$_{P-G}$ --● WK$_{A-M}$

EL-C.iii : $WK_{P\text{-}G}$ --● $WK_{A\text{-}Rq}$

$WK_{P\text{-}In}$ employed DK_A, $WK_{A\text{-}M}$, $WK_{A\text{-}Rq}$, and all the $WK_{A/F}$ except $WK_{A\text{-}Bis}$. These links could therefore be generalised as:

EL-C.iv : $WK_{P\text{-}In}$ --● DK_A

EL-C.v : $WK_{P\text{-}In}$ --● $WK_{A/F}$ (exclude $WK_{P\text{-}In}$ ---● $WK_{A\text{-}Bis}$)

EL-C.vi : $WK_{P\text{-}In}$ --● $WK_{A\text{-}M}$

EL-C.vii : $WK_{P\text{-}In}$ --● $WK_{A\text{-}Rq}$

All the artefact knowledge elements except $WK_{A\text{-}Bis}$ were employed in $WK_{P\text{-}Out}$, which could be generalised to:

EL-C.viii : $WK_{P\text{-}Out}$ --● DK_A

EL-C.ix : $WK_{P\text{-}Out}$ --● $WK_{A/F}$ (exclude $WK_{P\text{-}Out}$ ---● $WK_{A\text{-}Bis}$)

EL-C.x : $WK_{P\text{-}Out}$ --● $WK_{A/C}$

Moreover, DK_A and two contextual current working artefact knowledge $WK_{A\text{-}CR}$ and $WK_{A\text{-}Ct}$ were employed in $WK_{P\text{-}R}$. Hence another three employment links could be deduced as:

EL-C.xi : $WK_{P\text{-}R}$ --● DK_A

EL-C.xii : $WK_{P\text{-}R}$ --● $WK_{A\text{-}CR}$

EL-C.xiii : $WK_{P\text{-}R}$ --● $WK_{A\text{-}Ct}$

Finally, all the identified artefact knowledge elements were seemed to be employed in $WK_{P\text{-}C}$. Though $WK_{A\text{-}Bis}$ was not identified from the documents, it was an intrinsic property of the artefact and co-existed along with $WK_{A\text{-}Sis}$. Hence two employment links could be generalised as:

EL-C.xiv : $WK_{P\text{-}C}$ --● DK_A

EL-C.xv : $WK_{P\text{-}C}$ --● WK_A

The above generalised 15 employment links of the coupling are depicted in Figure 5-8 by dashed oval arrows.

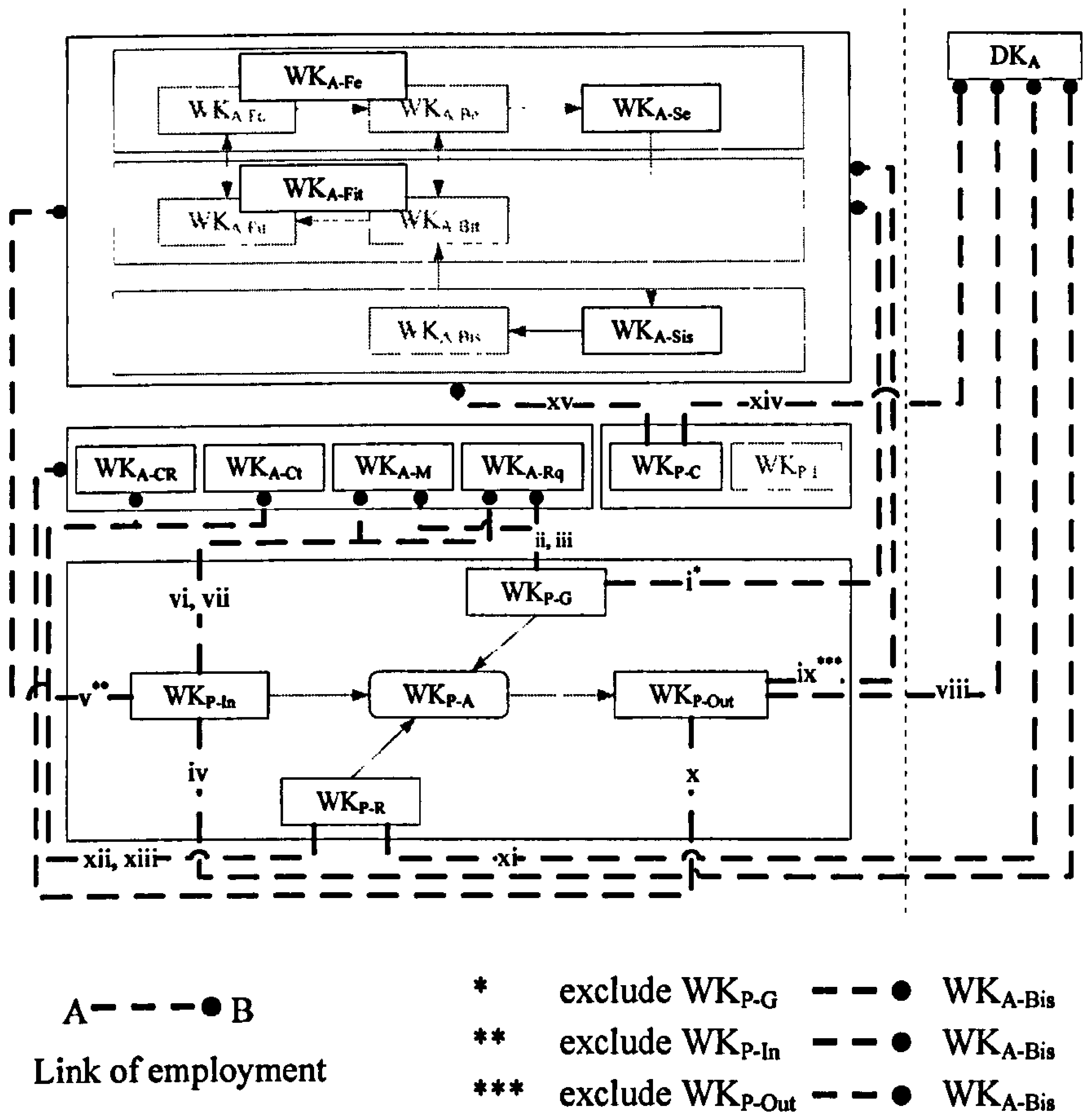


Figure 5-8: Employment links of the coupling – based on the content analysis

In essence, the initial findings of the coupling of the artefact and design process are composed of the six creation links (as shown in Figure 5-7) and 15 employment links (as shown in Figure 5-8). Having identified the links of the coupling based on content analysis, the next two chapters will present a more detailed coupling model based on protocol analysis of a design project.

5.3 SUMMARY

This chapter revealed that the coupling is closely related to knowledge evolution and presented the initial findings of the coupling of evolutionary artefact and design process knowledge based on the content analysis of eight design related documents. The analysis resulted in the following three main points:

- Design artefact knowledge is evolutionary;
- Design process knowledge is evolutionary;
- Two types of links (*cause-effect link of creation* and *link of employment*) compose the coupling of the evolutionary artefact and design process knowledge, which contribute to the knowledge evolution.

The coupling was found to be composed of 6 creation and 15 employment links between the artefact and design process knowledge elements. Such coupling is still a high level one, in that the analysed documents describe standard company artefact knowledge that was accumulated from past designs and processes that describe standard company working procedure. To examine the more detailed knowledge level coupling, the next two chapters will explore the coupling through protocol analysis of a design project.

Chapter 6 COUPLED KNOWLEDGE ELEMENTS

As a result of the content analysis, the previous chapter (Chapter 5) presented initial findings of the coupling. Based on protocol analysis of a design project, chapters 6 and 7 present the coupled elements and coupling model respectively. In this chapter, the process of protocol analysis is explained in Section 6.1, which shows how the protocols were analysed in order to derive the coupled elements and coupling model. Section 6.2 presents the knowledge elements that are involved in the coupling. These elements include behaviour, function, and structure of the artefact; activity, goal, input, output, and resource of the design process, as well as a number of contextual artefact and design process knowledge elements such as design constraints, causal relationships, motivations, requirements, context, and issues. The occurrence trends of these elements over task clarification, conceptual, and embodiment design phases are presented in this section. Finally, Section 6.3 provides concluding remarks about the coupled knowledge elements.

6.1 PROTOCOL ANALYSIS

One frequently used method to understand complex cognitive processes is to explore the subjects' internal states by verbal methods (Adelson 1989; Takeda, Veerkamp et al. 1990), which is termed 'protocol analysis' (Waterman and Newell 1971; Ericsson and Simon 1984). While designing is a complex cognitive endeavour, protocol analysis can be used as an effective method to reveal the thinking of human beings, and therefore has been adopted by a number of researchers to understand various aspects of designing (Gero and McNeill 1998; Gero and Tang 2001), such as design activity (Cross et al. 1996), design artefact function evolution (Takeda et al. 1996), design decision (Akin and Lin 1995), design requirements (Chakrabarti et al. 2004), learning in design (Sim and Duffy 2000), and collective learning in design (Wu and Duffy 2002). Although it seems that issues such as completeness, veridicality, epiphenomenality, objectivity, and soundness undermine the strength of protocol analysis method, existing research (Ericsson and Simon 1993; Wu 2004) shows that these factors can not be regarded as barriers to protocol analysis as an effective way in providing necessary information for examining people's thinking. The advantages of applying the protocol analysis to design research has been summarised by Adelson (1989) as can be used to: (i) examine complex and interactive behaviours; (ii) evaluate cognitive models through testing the predictions that are produced by them; and (iii) study cognitive behaviour in a natural way. In light of these advantages and applications, protocol analysis is adopted in the research presented in this thesis to model the coupling.

Two types of protocol are usually analysed by researchers: concurrent and retrospective (Gero and Tang 2001). In the context of engineering design research, the former is the protocol that is recorded while designers are designing by letting them speak out what they think in their mind, or as Ericsson and Simon (1984) described, *think aloud* protocol. With regard to the latter, the protocol is recorded in retrospect to the design by allowing designers to recollect a design performed earlier. These two types of protocol have both their pros and cons. In comparison to the retrospective protocol, the concurrent protocol can capture real-time information. However, the method may interfere with designing by letting designers utter their thinking while they are designing. On the other hand, retrospective protocol will not interrupt the design process. However, it may lose information that exists only in designers' short-term memory (Ullman 2002).

To take both of their advantages, it was decided to analyse protocols that are semi-concurrent and semi-retrospective. Such mixed adoption of concurrent and retrospective protocols can be collected periodically by recording designers' discussions in a real-time design process. Specifically, protocols of seven undergraduate student design projects were recorded in the

Department of Design, Manufacture and Engineering Management (DMEM), University of Strathclyde. Different from the traditional concurrent and retrospective protocol approach, the collected protocols were the supervision processes between the students and their supervisor, which included both retrospective protocol of the design conducted since the previous supervision session and concurrent protocol of the current supervision session when the meeting was recorded.

The recording process was agreed by all the seven students and the supervisor, and a consent form is attached in Appendix C. In addition, because the study involves 'investigation on human beings', two checklist regarding to "Ethics Committee - Code of Practice on Investigations on Human Beings", and "Department Approved Investigations" were signed by the author and her supervisor to ensure that the recording and analysis abide the rules of such investigation. The checklists are also attached in Appendix C.

The seven students were studying MEng (Master of Engineering) in Product Design Engineering. They took the same module "Product Design Project" and were in either their 4^{th} or 5^{th} year. Throughout the 2005-2006 academic year, each of them was required to conduct one design project. The type of the artefact was chosen individually and the design process had to cover task clarification, conceptual design, embodiment design, detail design, and prototyping. The meetings between the students and supervisor were arranged to be once per week unless they had other commitment. During the meetings, the students reported to the supervisor the activities that had been carried out since the last supervision session, the progress of the designed artefact, as well as the problems they encountered during the design process. The supervisor's responsibility was to supervise and direct students by providing suggestions and information for both the artefact and design process. Both the supervisor and students were regarded as designers of the projects. Therefore, by analysing such supervised design project, one advantage is that it not only provided how the artefact was developed, but also provided insight of how the design process was conducted in order to deliver such artefact. Consequently, the relationships between the artefact and design process knowledge can be observed and the coupling could be better studied compare to a project conducted only by student designers.

The supervision meetings of the seven projects were recorded by using "Absolute MP3 recorder" (TECH logic 2006), a software that run in Microsoft Windows XP. The software can record audio to mp3 files directly stored in a computer. The recording process lasted nine months altogether from September 2005 to May 2006, and it was completed when the students finished building the prototypes of their designs.

Of the seven recorded projects, one was studied through protocol analysis. This was because not all of the students attended the supervision regularly, leaving some sessions incomplete. Further, diction and recording quality meant that six were used for checking the protocol analysis of one specific project, "Roadside furniture" (Crawford 2006). The project was redesign of pedestrian barriers, in which a modular system of barrier with easy replacement was designed for different society environments. A concept of "Locktab mechanism" (Figure 6-1) was developed for the system, in which a circular cross section post could be received into a sustainable ground fixing system and secured with a key (locktab). Following completion of the project, the "Locktab mechanism" had been filed up a British patent POST INSTALLATION (application filing number: 0613906.7).

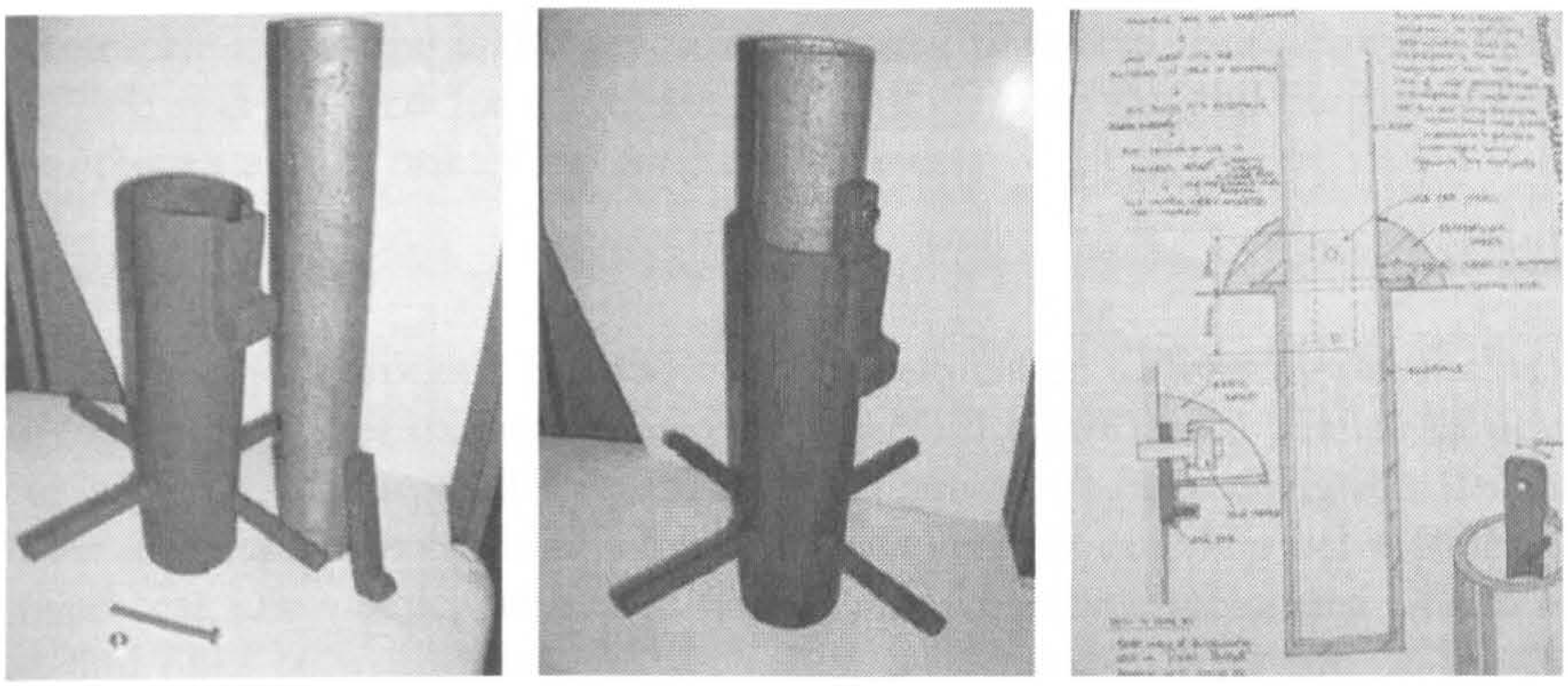


Figure 6-1: Locktab mechanism of the analysed project (Crawford 2006)

Once the project for analysis had been selected, in addition to recording the supervision sessions, two informal interviews were also conducted with the student designer at the end of the project on. The main aim of the interviews was to clarify evolution of design knowledge as well as its relationship with coupling. During the interviews, initial analysis of the knowledge evolution and links between the artefact and design process were explained and displayed to the student designer. Specific questions with regard to the evolution of the artefact and design process knowledge, and relationships between the artefact and design process knowledge were answered by the student. As a result, the interviews not only verified evolution of design knowledge during the project, but also that the evolution was triggered through links between the artefact and design process knowledge. Furthermore, the interviews also provided the author a better understanding of the project for conducting the protocol analysis.

To explore the coupling of the artefact and design process over task clarification, conceptual, and embodiment design, 12 sessions that covered the three phases of the project were analysed. Task clarification lasted the first six sessions from 7th October 2005 to 4th November 2005; conceptual design lasted from Session 7 to Session 9 from 18th November to 2nd December 2005, and finally the last three sessions of embodiment design lasted from 10th March 2006 to 24th March 2006. The recording length of the 12 sessions was 283 mins 54 secs in total. Two project reviews were given at the beginning of Session 2 and Session 9 respectively, within which the design brief was reviewed by the designers. The division of the three design phases was based on the author's interpretation of the transcription, and was confirmed by the student designer. Figure 6-2 illustrates the project sessions, design phase, date, and recording length information.

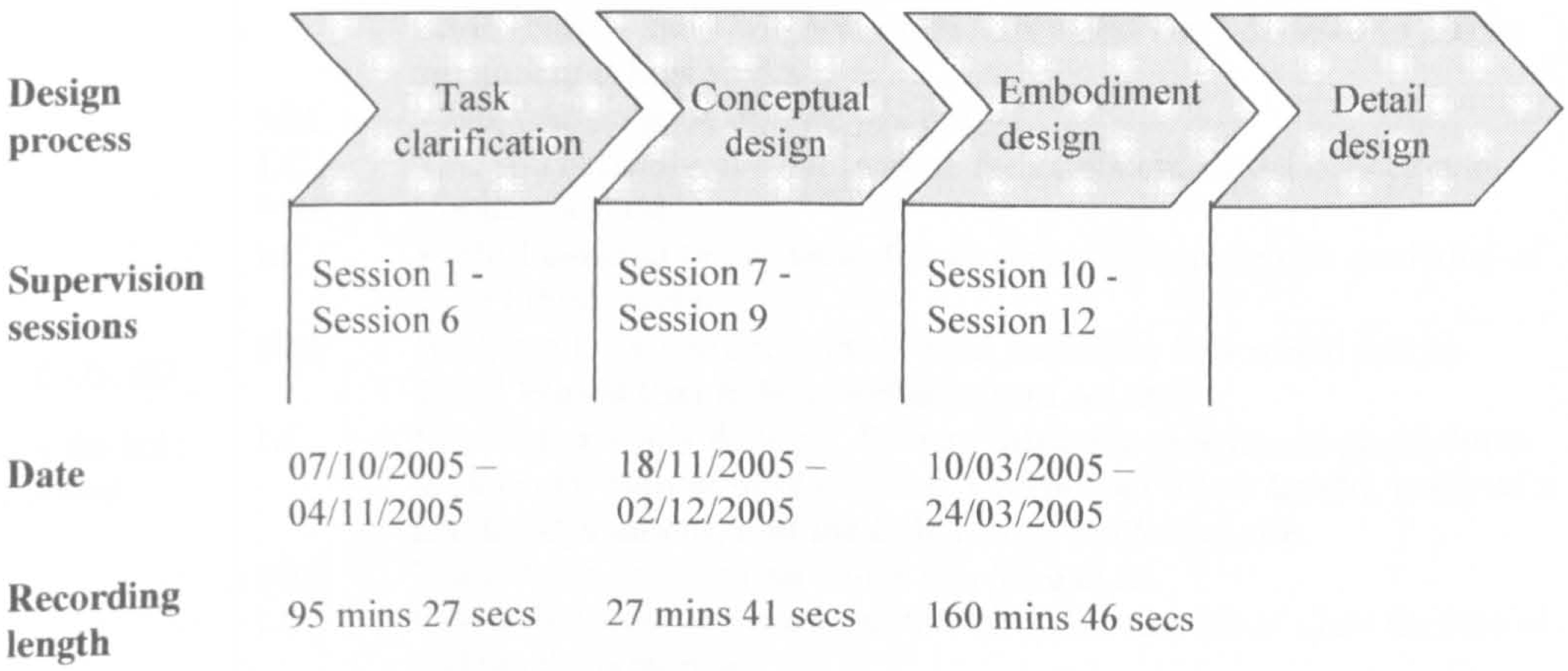


Figure 6-2: Roadside furniture design project sessions

Following transcription of the audio recordings to raw protocols, Gero's protocol analysis approach (1998) was adopted for segmentation, coding, analysis, and interpretation of the data. Each of these stages is briefly explained as follows.

6.1.1 Segmentation

To facilitate the analysis process, protocols can be segmented differently depending on the purpose of the analysis. For example, Gero and McNeill (1998) used change of designer's intention to segment the protocols in their investigation of how designers design. The purpose of the research presented in this thesis is to explore the coupling between the artefact and design process knowledge, with a particular focus on the artefact and design process knowledge, and links between them. As such, it was intended to segment the protocols by the focus of the protocol, which was considered as either artefact or design process knowledge. However, it was found through initial analysis that the artefact and process knowledge occurred concurrently in the protocols. Hence no obvious division could be identified within the protocols, to differentiate whether the discussion was on the artefact or design process. It was therefore decided that the protocols were segmented semantically according to discussion topics. That is, semantic topic was interpreted to produce each segment, and each segment addressed one specific topic, such as clarifying a concept or solving a design problem. As will be discussed later in Chapter 9, segmenting protocols semantically by discussion topics did not affect the analysis result. A short excerpt of segmented protocol is listed in Table 6-1, which shows segments 1 to 3 of Session 11. The first column in the table lists sequence number of each segment within the session, its starting time, and its topic. The second column lists segmented protocols with design knowledge elements highlighted by bold font. NM and LC represent the supervisor and student designer respectively. The detailed protocols and segmentation of sessions 1 to 12 are presented in (Wang 2008c).

Table 6-1: An excerpt of segmented protocol

Seg No. - Time Topic	Protocols	
1 – 00:00:00 Barrier model and using circular	NM	Right, did you get over last week? The supervision last week. I thought I was being a bit bossy.
	LC	Bossy. No, I didn't think you were being bossy. No. It's [last week supervision] kind of made me have wee think.
	NM	Good!
	LC	What I'm actually gonna do. Now as I said, **a model was delivered last week.** So these are kind of pictures of it. I've already had a real one made actually and I will bring it in next week. But I **decided to put on anchoring things** so that...
	NM	Yeah, that's a good casting you did.
	LC	Yes, and basically, it's the same as the cardboard model only circular.
	NM	Circular is good.
	LC	Yeah! **I decided to go circle, it's so secure.** It's made of a steel kind of thing I think. But also...
2 – 00:01:09 How the hole be drilled	NM	Well, can I ask you about this? What would be, how would that be done? **Would that hole be drilled down on site?**
	LC	No, I was actually thinking. **Do you think the pole has to go all down to the very bottom of that?** (No) **'Cause I set it to a height, cause of a height adjustment, and the hole can be drilled on site.**
	NM	Yeah, that's one of those things you have to do.
	LC	It probably wouldn't come out the other side as well. It's just for ease of making the prototype.
	NM	No, you could **drill a hole and put a captive fitting onto it. So that**

		you don't have to slide it in.
3 – 00:01:58 Other types of fitting	LC	Ok. Actually, one of my friends on a PDP project works with a company who makes disabled access ramps, and he was telling me **how to install the ramp thing**, and basically it's such a simple idea that you can't patent it – that's why they've come to the Uni, looking for a more sophisticated way of doing it. But actually, it's a bolt, just a bolt, which is welded onto a circular plate. And a nut is embedded in this top plate here, which is attached to a cylinder. And you set the appropriate height of the ramp by winding it down or up.
	NM	That's a very common fitting.
	LC	Is it?
	NM	You can buy them.
	LC	Actually, I haven't seen anything like that.
	NM	You can buy them.
	LC	But it's not attached.
	NM	I told you. Look at them.
	LC	**Toilet seats. Cubicle holders.** Is that the same principle? All right! Oh well! Yeah, but what intrigued me about it was that it wasn't attached to ground; it was just the sheer weight of the ramp, which held it in position... Ok, so, I'll think.

6.1.2 Coding scheme

Protocol data could provide a deep insight into designing from various viewpoints depending on different research purposes. For researchers, however, it is the knowledge structure of the protocol, rather than the protocol and the transcripts themselves, which is of paramount importance. Therefore, the purpose of the protocol analysis is to detect this knowledge structure through some coding schemes.

Within the context of this research, to analyse the protocols in order to identify the knowledge structure, a suitable coding scheme that can elicit the coupling of the artefact and design process knowledge is necessary. As mentioned earlier, the analysis should focus on the artefact, process knowledge elements and their links. Based on the review presented in Chapter 3 and initial study of the protocols, it was found that there were a number of particular design artefact and process knowledge elements related to the coupling. Specifically, four types of domain knowledge of design artefact ($DK_{A\text{-}G}$, $DK_{A\text{-}Bit}$, $DK_{A\text{-}Fit}$, and $DK_{A\text{-}Sis}$), seven types of current working knowledge of design artefact ($WK_{A\text{-}Be}$, $WK_{A\text{-}Bis}$, $WK_{A\text{-}Bit}$, $WK_{A\text{-}Fe}$, $WK_{A\text{-}Fit}$, $WK_{A\text{-}Se}$, and $WK_{A\text{-}Sis}$), four types of current working artefact contextual knowledge ($WK_{A\text{-}CR}$, $WK_{A\text{-}Ct}$, $WK_{A\text{-}M}$, and $WK_{A\text{-}Rq}$), five types of current working knowledge of design process ($WK_{P\text{-}A}$, $WK_{P\text{-}G}$, $WK_{P\text{-}In}$, $WK_{P\text{-}Out}$, and $WK_{P\text{-}R}$), and two types of current working design process contextual knowledge ($WK_{P\text{-}C}$ and $WK_{P\text{-}I}$) were considered to be the elements that might be involved in the coupling. These 22 elements and their associated codes are listed in Table 6-2.

Table 6-2: The coding scheme of coupled knowledge elements

Knowledge category	Coding	Knowledge element
Domain Knowledge of Design Artefact (DK_A)	$DK_{A\text{-}G}$	General design artefact (A-G)
	$DK_{A\text{-}Bit}$	Interpreted artefact behaviour (Bit)
	$DK_{A\text{-}Fit}$	Interpreted artefact function (Fit)
	$DK_{A\text{-}Sis}$	Instantiated artefact structure (Sis)
Fundamental Current Working Artefact	$WK_{A\text{-}Be}$	Expected artefact behaviour (Be)
	$WK_{A\text{-}Bis}$	Instantiated artefact behaviour (Bis)

Knowledge category	Coding	Knowledge element
Knowledge ($WK_{A/F}$)	WK_{A-Bit}	Interpreted artefact behaviour (Bit)
	WK_{A-Fe}	Expected artefact function (Fe)
	WK_{A-Fit}	Interpreted artefact function (Fit)
	WK_{A-Se}	Expected artefact structure (Se)
	WK_{A-Sis}	Instantiated artefact structure (Sis)
Contextual Current Working Artefact Knowledge ($WK_{A/C}$)	WK_{A-CR}	Causal relationship (CR)
	WK_{A-Ct}	Artefact constraint (Ct)
	WK_{A-M}	Design motivation (M)
	WK_{A-Rq}	Artefact requirement (Rq)
Fundamental Current Working Design Process Knowledge ($WK_{P/F}$)	WK_{P-A}	Design activity (A)
	WK_{P-G}	Design goal (G)
	WK_{P-In}	Activity input (In)
	WK_{P-Out}	Activity output (Out)
	WK_{P-R}	Design resource (R)
Contextual Current Working Design Process Knowledge ($WK_{P/C}$)	WK_{P-C}	Design context (C)
	WK_{P-I}	Design issue (I)

Among the above-mentioned elements, there exist different types of links that signify different relationships between them. The *cause-effect link of creation* has already been identified in Chapter 5 through content analysis. Through protocol analysis, another three types were identified between these elements, which were *cause-effect link of referral, link of usage* and *link of containment.* Table 6-3 gives further explanations and representations of the four types of links used in the protocol analysis. Though link of employment identified in Chapter 5 was not used in the protocol analysis, it was found that it has close affinity with these four basic types of links, and some employment links can be deduced from these four types. The detailed links analyses will be presented in Chapter 7.

Table 6-3: Four types of links identified from the protocol analysis

Link type	Representation	Explanation
Cause-effect link of creation	A ⟶ B	Element A causes creation or occurrence of element B.
Cause-effect link of referral	A —◆ B	Element A causes occurrence of element B in the protocol (B is an existing element that has been created earlier).
Link of usage	A ◆—● B	Element A uses element B.
Link of containment	A ⟵—● B	Element A contains element B.

For each of the 12 sessions, the raw protocols were encoded using the above coding scheme, which identified the main artefact and design process knowledge elements involved in the coupling. Meanwhile, the four types of links between these knowledge elements were identified and marked with the representations listed in Table 6-3. Table 6-4 shows encoded protocols of segments 1 to 3 in Session 11. The first column lists the segment sequence number, its start time and topic. The second and third columns contain the encoded design process and artefact knowledge elements respectively, which are numbered within each segment. The links are shown in the last three columns. The fifth column shows the links that link adjacent knowledge elements within the same segment ("Segment link"). The fourth and sixth columns contain the links that link elements prior to and after the current segment ("Prior segment link" and "Post segment link"). The elements in other segments are identified with three numbers: session, segment, and elements. For example, the element identified with 10.16.3 means that it is the third element in the Session 10, segment 16. The full version of encoded knowledge elements and their associated links can be found in a report (Wang 2008b).

Table 6-4: An excerpt of encoded knowledge elements and links

Seg No. – Time Topic	Design process knowledge coupling elements	Design artefact knowledge coupling elements	Prior segment links	Segment links	Post segment links
1 – 00:00:00 Artefact model and using circular	**1 WK_{P-A}** = delivered [modelling the artefact, embodiment] **3 WK_{P-A}** = to put on…[Generating] **5 WK_{P-A}** = [Decision making] I decided to **7 WK_{P-A}** = [Evaluating]	**2 WK_{A-Sis}** = a model **4 WK_{A-Sis}** = anchoring things **6 WK_{A-Sis}** = circle	10.16.3 WK_{A-Sis} →	1 WK_{P-A} → 2 WK_{A-Sis} 2 WK_{P-A} → 4 WK_{A-Sis} 5 WK_{P-A} → 6 WK_{A-Sis} 6 WK_{A-Sis} → 7 WK_{P-A}	
2 – 00:01:09 How the hole be drilled	**1 WK_{P-I}** = Would that hole be drilled down on site? **2 WK_{P-A}** = [Analysing] **4 WK_{P-A}** = [Generating] **6 WK_{P-R}** = So that you don't have to slide it in	**3 WK_{A-Sis}** = set it to a height, cause of a height adjustment, and the hole can be drilled on site **5 WK_{A-Se}** = drill a hole and put a captive fitting onto it		1 WK_{P-I} ↓ 2 WK_{P-A} 2 WK_{P-A} —◆ 3 WK_{A-Sis} 3 WK_{A-Sis} → 4 WK_{P-A} 4 WK_{P-A} → 5 WK_{A-Se} 4 WK_{P-A} ◆—● 6 WK_{P-R}	

6.1.3 Analysis and interpretation

As previously mentioned, one of the objectives of the research presented in this thesis was to explore the occurrence trend of design knowledge elements over task clarification, conceptual, and embodiment design phases. In this regard, it was found that neither the occurrence times of the elements over the 12 sessions could reflect their trend, in that the durations of the 12 sessions varied from 7 to 60 minutes (longer session resulted in more occurrence), nor could the chronological method, which analyses elements' occurrence frequency over a period of time. This was mainly because the 12 sessions were conducted irregularly over six months, i.e., there was no supervision session in some months, and in contrast there were up to three supervision sessions in other months. Consequently, to enhance the reliability of the analysis and normalise the data by eliminating the impact of the duration variation and session irregularity, it was decided to use session-based percentage method to analyse the occurrence trend of coupling knowledge elements over the three design phases, i.e., the occurrence percentage of each element within each session was calculated to indicate the occurrence trend. In view of this, the occurrence trend does not indicate the change of occurrence times of different elements. Rather, it shows change in their percentages or ratios. Furthermore, to identify the coupling of the artefact and design process, which is composed of different links between knowledge elements, occurrences of links over the 12 sessions were used to identify those main links that constituted the coupling.

The analyses were conducted in Microsoft Excel 2003. Following identification and encoding of the knowledge elements and their relevant links for all of the 12 sessions, the occurrence times of each element within each segment were counted, and their total occurrences within each session were calculated. In addition, the occurrences of each of the aforementioned four types of links were counted within each session. The occurrences of the elements and links within each session were then input into Excel for further analysis. These descriptive data can be found in (Wang 2008a).

The analyses and interpretations of the data were conducted in two main steps: (i) knowledge elements occurrence trends analysis and (ii) coupling analysis. In respect of the former, the knowledge elements occurrences over the 12 sessions was analysed in order to derive the occurrence trend of each specific knowledge element over the three design phases. With regard to the latter, the occurrences of the links over the 12 sessions were analysed in order to reveal the coupling model of artefact and design process knowledge.

The coupling analysis will be presented in Chapter 7, this chapter focuses on the knowledge elements analysis. Table 6-5 lists the occurrence times of each knowledge element (Second row) over the 12 sessions, and Table 6-6 lists the percentage of each knowledge element within each session over the 12 sessions. The analysis results, occurrence trends of the artefact and design process knowledge elements, are presented in Section 6.2.

Table 6-5: Occurrence times of design knowledge elements

	Design artefact knowledge elements															Design process knowledge elements							
	$DK_{A\text{-}G}$	$DK_{A\text{-}Bit}$	$DK_{A\text{-}Fit}$	$DK_{A\text{-}Sis}$	$WK_{A\text{-}Be}$	$WK_{A\text{-}Bis}$	$WK_{A\text{-}Bit}$	$WK_{A\text{-}Fe}$	$WK_{A\text{-}Fit}$	$WK_{A\text{-}Se}$	$WK_{A\text{-}Sis}$	$WK_{A\text{-}CR}$	$WK_{A\text{-}Ct}$	$WK_{A\text{-}M}$	$WK_{A\text{-}Rq}$	$WK_{P\text{-}A}$	$WK_{P\text{-}G}$	$WK_{P\text{-}In}$	$WK_{P\text{-}Out}$	$WK_{P\text{-}R}$	$WK_{P\text{-}C}$	$WK_{P\text{-}I}$	Sum
Session 1	7		2	1	1			2		4				1	2	16	4		2	1	6	7	56
Session 2	5									5						11	1		1	2	3	1	29
Session 3	16		8	3												29	2			2	2	6	68
Session 4	17	2	12	13									1			36	3			1		3	88
Session 5	18							1								20					3	8	50
Session 6	9	2	1					1		3			1			16					2	4	39
Session 7	2		1	2	4			4		12						26	1				4	2	58
Session 8	5		2	1	3					8						15	4					1	39
Session 9	3		1	1	2		1	2	2	5	1		2	2	2	16	8				3	2	53
Session 10	8	3		4	11		5	6	3	40	12		9			67	15			3	5	13	204
Session 11				7	3		3	3	4	51	22		1		1	71	14			4	1	28	213
Session 12	7	1	1	2	10		7	1	2	37	30		6			73	11		2	2		32	224

Table 6-6: Occurrence percentage of design knowledge elements

	Design artefact knowledge elements															Design process knowledge elements						
	$DK_{A\text{-}G}$	$DK_{A\text{-}Bit}$	$DK_{A\text{-}Fit}$	$DK_{A\text{-}Sis}$	$WK_{A\text{-}Be}$	$WK_{A\text{-}Bis}$	$WK_{A\text{-}Bit}$	$WK_{A\text{-}Fe}$	$WK_{A\text{-}Fit}$	$WK_{A\text{-}Se}$	$WK_{A\text{-}Sis}$	$WK_{A\text{-}CR}$	$WK_{A\text{-}Ct}$	$WK_{A\text{-}M}$	$WK_{A\text{-}Rq}$	$WK_{P\text{-}A}$	$WK_{P\text{-}G}$	$WK_{P\text{-}In}$	$WK_{P\text{-}Out}$	$WK_{P\text{-}R}$	$WK_{P\text{-}C}$	$WK_{P\text{-}I}$
Session 1	12.50%	0.00%	3.57%	1.79%	1.79%	0.00%	0.00%	3.57%	0.00%	7.14%	0.00%	0.00%	0.00%	1.79%	3.57%	28.57%	7.14%	0.00%	3.57%	1.79%	10.71%	12.50%
Session 2	17.24%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	17.24%	0.00%	0.00%	0.00%	0.00%	0.00%	37.93%	3.45%	0.00%	3.45%	6.90%	10.34%	3.45%
Session 3	23.53%	0.00%	11.76%	4.41%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	42.65%	2.94%	0.00%	0.00%	2.94%	2.94%	8.82%
Session 4	19.32%	2.27%	13.64%	14.77%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.14%	0.00%	0.00%	40.91%	3.41%	0.00%	0.00%	1.14%	0.00%	3.41%
Session 5	36.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	2.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	40.00%	0.00%	0.00%	0.00%	0.00%	6.00%	16.00%
Session 6	23.08%	5.13%	2.56%	0.00%	0.00%	0.00%	0.00%	2.56%	0.00%	7.69%	0.00%	0.00%	2.56%	0.00%	0.00%	41.03%	0.00%	0.00%	0.00%	0.00%	5.13%	10.26%
Session 7	3.45%	0.00%	1.72%	3.45%	6.90%	0.00%	0.00%	6.90%	0.00%	20.69%	0.00%	0.00%	0.00%	0.00%	0.00%	44.83%	1.72%	0.00%	0.00%	0.00%	6.90%	3.45%
Session 8	12.82%	0.00%	5.13%	2.56%	7.69%	0.00%	0.00%	0.00%	0.00%	20.51%	0.00%	0.00%	0.00%	0.00%	0.00%	38.46%	10.26%	0.00%	0.00%	0.00%	0.00%	2.56%
Session 9	5.66%	0.00%	1.89%	1.89%	3.77%	0.00%	1.89%	3.77%	3.77%	9.43%	1.89%	0.00%	3.77%	3.77%	3.77%	30.19%	15.09%	0.00%	0.00%	0.00%	5.66%	3.77%
Session 10	3.92%	1.47%	0.00%	1.96%	5.39%	0.00%	2.45%	2.94%	1.47%	19.61%	5.88%	0.00%	4.41%	0.00%	0.00%	32.84%	7.35%	0.00%	0.00%	1.47%	2.45%	6.37%
Session 11	0.00%	0.00%	0.00%	3.29%	1.41%	0.00%	1.41%	1.41%	1.88%	23.94%	10.33%	0.00%	0.47%	0.00%	0.47%	33.33%	6.57%	0.00%	0.00%	1.88%	0.47%	13.15%
Session 12	3.13%	0.45%	0.45%	0.89%	4.46%	0.00%	3.13%	0.45%	0.89%	16.52%	13.39%	0.00%	2.68%	0.00%	0.00%	32.59%	4.91%	0.00%	0.89%	0.89%	0.00%	14.29%
Average	13.39%	0.78%	3.39%	2.92%	2.62%	0.00%	0.74%	1.97%	0.67%	11.90%	2.62%	0.00%	1.25%	0.46%	0.65%	36.94%	5.24%	0.00%	0.66%	1.42%	4.22%	8.17%

6.2 RESULTS

Following calculation of occurrence percentages of the design knowledge elements over the 12 sessions, the occurrence trends of the knowledge elements were analysed through viewing their trend charts created in the Excel. The identified artefact and design process elements as well as their occurrence trends are explained in the following two sub-sections.

In addition to the session-based percentage analysis presented in this section, a time-based analysis of occurrence trend of three elements (DK_{A-G}, WK_{A-Se}, and WK_{P-A}) is presented in Appendix E. Each element represents one main group of knowledge elements: domain artefact knowledge, current working artefact knowledge, and process knowledge. The analysis showed the time-based and session-based methods resulted in the similar trend for the three groups of design knowledge elements, which verified that the session-based analysis does not affect the analysing result.

6.2.1 Design artefact knowledge elements

Both domain knowledge and current working knowledge of the artefact were found closely coupled with the design process. In this regard, four main types of domain artefact knowledge (DK_{A-G}, DK_{A-Bit}, DK_{A-Fit}, and DK_{A-Sis}), seven types of fundamental current working artefact knowledge (WK_{A-Be}, WK_{A-Bis}, WK_{A-Bit}, WK_{A-Fe}, WK_{A-Fit}, WK_{A-Se}, and WK_{A-Sis}), and four types of contextual current working artefact knowledge (WK_{A-CR}, WK_{A-Ct}, WK_{A-Rq}, and WK_{A-M}) are discussed in this section.

Domain artefact knowledge (DK_A)

As a result of encoding, it was found that the domain artefact knowledge discussed by the designers (supervisor and student) in this project was primarily related to their understanding, or interpretation of the existing knowledge in the roadside furniture domain. Four main types of domain artefact knowledge were identified from the protocols. They were general domain artefact knowledge (DK_{A-G}), interpreted behaviour (DK_{A-Bit}), interpreted function (DK_{A-Fit}), and instantiated structure (DK_{A-Sis}) of the artefact (see Chapter 3 for further details on their definitions). DK_{A-G}, such as conceptual understanding of roadside furniture, categorisation of roadside furniture, is the domain knowledge other than that related to specific function, behaviour or structure. The designers did not seem to create 'expected domain knowledge' in this project. Hence there were no references to *expected domain artefact functional, behavioural and structural knowledge.* Figure 6-3 illustrates the occurrence trends of the four design domain artefact knowledge elements and the total domain artefact knowledge, which is the sum of the four domain knowledge elements.

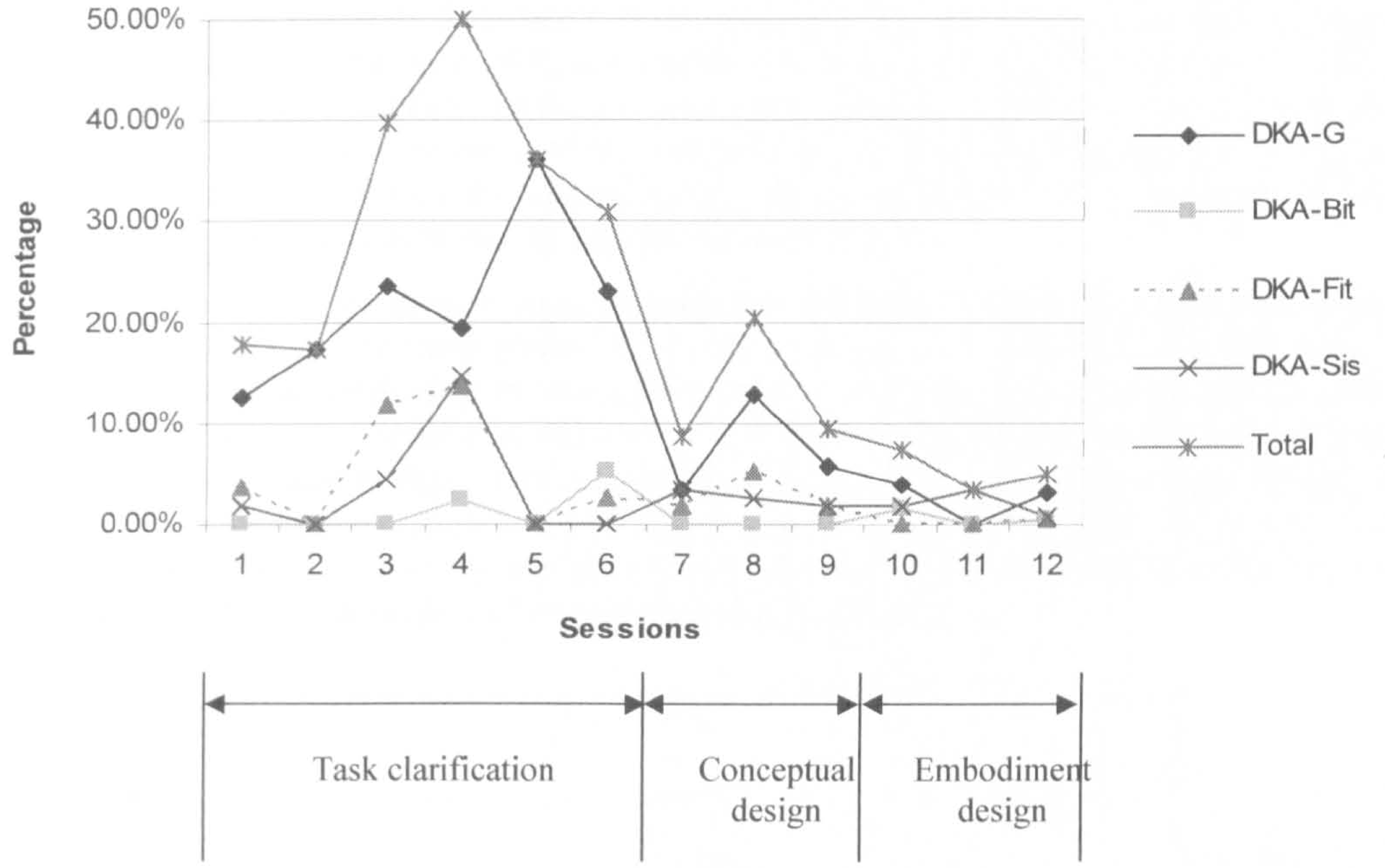


Figure 6-3: DK_A occurrence trend

The chart shows an overall decreasing trend of the domain artefact knowledge over the three design phases, with a trough in Session 7. Specifically, the occurrence percentage of the domain artefact knowledge increased to reach its highest peak in Session 4 (50%) during task clarification. It then decreased gradually through conceptual and embodiment design when designers were concentrating on the current design. This implied that designers worked with the domain artefact knowledge in task clarification phase to understand design problem. With increasing understanding of the problem, designers use less proportion of domain knowledge in the following stages. The trough in Session 7 was because 10 design concepts were presented at the beginning of this session, within which domain artefact knowledge was comparatively less discussed.

The observation of the domain artefact knowledge trends can be summarised as follows:

- Four types of domain artefact knowledge (DK_{A-G}, DK_{A-Bit}, DK_{A-Fit}, and DK_{A-Sis}) were identified involving coupling.
- No *expected domain artefact knowledge* occurred during the design process.
- DK_A exhibited an overall decreasing occurrence trend over task clarification, conceptual, and embodiment design phases, with its highest peak during task clarification.

The deductions from analysing domain artefact knowledge can be described as follows:

- Artefact, rather than process knowledge, is the main domain knowledge involved in the coupling of artefact and design process.
- Designers of the analysed project work in the *interpreted* and *instantiated*, rather than *expected* knowledge space of domain artefact knowledge.
- Designers work with higher proportion of domain knowledge in task clarification phase while understanding design problem, than in conceptual and embodiment design phases while concentrating on their current design.

Fundamental current working artefact knowledge ($WK_{A/F}$)

As mentioned in the discussion of P-FBS model (Chapter 3), there are seven fundamental artefact knowledge elements distributed in three knowledge spaces, i.e. expected behaviour ($WK_{A\text{-}Be}$), instantiated behaviour ($WK_{A\text{-}Bis}$), interpreted behaviour ($WK_{A\text{-}Bit}$), expected function ($WK_{A\text{-}Fe}$), interpreted function ($WK_{A\text{-}Fit}$), expected structure ($WK_{A\text{-}Se}$), and instantiated structure ($WK_{A\text{-}Sis}$). Based on the protocol analysis of the design project presented in this thesis, it was found that with the exception of $WK_{A\text{-}Bis}$, all the other fundamental artefact knowledge elements were analysed to exist in the three phases.

Figure 6-4 shows the occurrence trend of **expected current working artefact knowledge elements ($WK_{A/E}$)** over the three phases. From the chart, it can be observed that following a peak (17.24%) in the beginning of task clarification, the proportion of $WK_{A/E}$ decreased to zero and then began to increase at the end of this phase before it arrived its highest peak (34.48%) in conceptual design. Then following a trough at the end of conceptual design, it recovered in embodiment design and continued towards the end of embodiment design. The trough in session 9 was caused by a project review conducted at the beginning of this session, which resulted in less proportion of *expected* artefact knowledge.

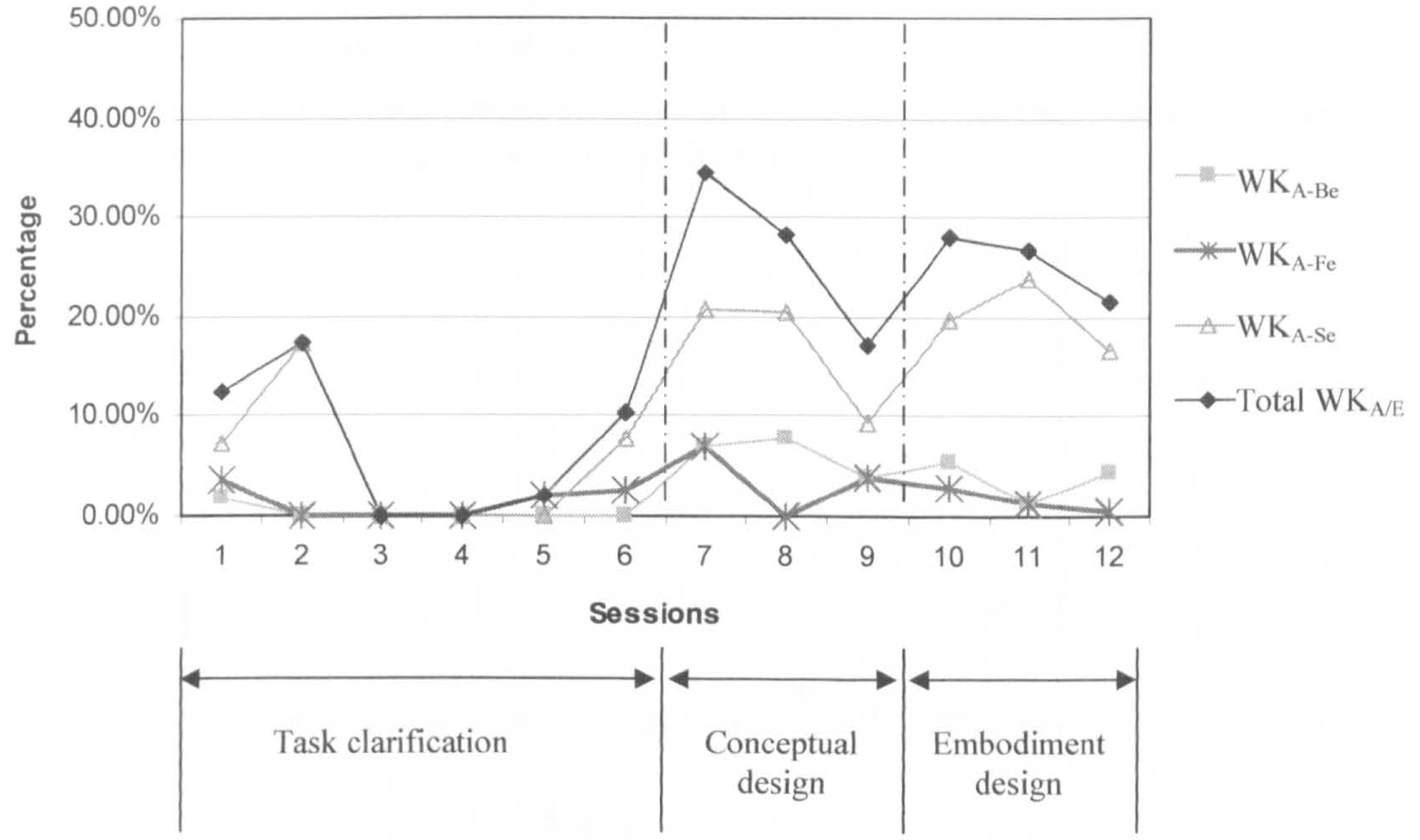


Figure 6-4: $WK_{A/E}$ occurrence trend

With regard to each expected element, $WK_{A\text{-}Se}$ had a similar trend to total $WK_{A/E}$. Following a peak (17.24%) at the beginning of task clarification, its occurrence percentage decreased to zero. It was not discussed by designers until the end of task clarification and then reached its highest peak (20.69%) in conceptual design. Following a trough in Session 9, it recovered and reached its peak before it began to slightly decrease in embodiment design. Meanwhile, in conceptual and embodiment design, it kept a higher ratio compared to $WK_{A\text{-}Be}$ and $WK_{A\text{-}Fe}$. The observed occurrence trend implies that designers had expectations towards the artefact structure at the beginning of task clarification, even before they concentrated on understanding the design problem. Upon clarification of the design problem, $WK_{A\text{-}Se}$ was then created in conceptual design for deriving the desired concepts. The higher proportion of $WK_{A\text{-}Se}$ in embodiment design (compared to that in task clarification) indicates that designers still created or/and changed $WK_{A\text{-}Se}$ while refining the design concepts.

$WK_{A\text{-}Be}$ and $WK_{A\text{-}Fe}$ had a similar trend to that of $WK_{A\text{-}Se}$. Both of them began to occur gradually at the beginning of the design. Following a period of non-occurrence, they started to occur and increase from the end of task clarification, followed with reaching their peak in conceptual design. Similarly, their occurrences in embodiment design indicate that artefact concepts were still under revision during embodiment design.

The observation of the trends of $WK_{A/E}$ can be summarised as follows:

- The overall occurrence proportion of $WK_{A/E}$ decreased in task clarification phase and then increased to its highest peak in conceptual design, which is followed with a slight decrease in embodiment design.
- WK_{A-Be}, WK_{A-Fe}, and WK_{A-Se} exhibited similar trend to that of total $WK_{A/E}$.

The deductions from the analysis of the expected current working artefact knowledge are as follows:

- Prior to clarification of the design problem, i.e. at the beginning of the design, designers have expectations towards the artefact structure.
- Once the design problem has been clarified, expected artefact structure is then created by designers for deriving the desired concepts.
- Designers still create/change the expected artefact structure while refining design concepts in embodiment design.

The occurrence trend of **interpreted ($WK_{A/It}$)** and **instantiated current working artefact knowledge elements ($WK_{A/Is}$)** are depicted in Figure 6-5.

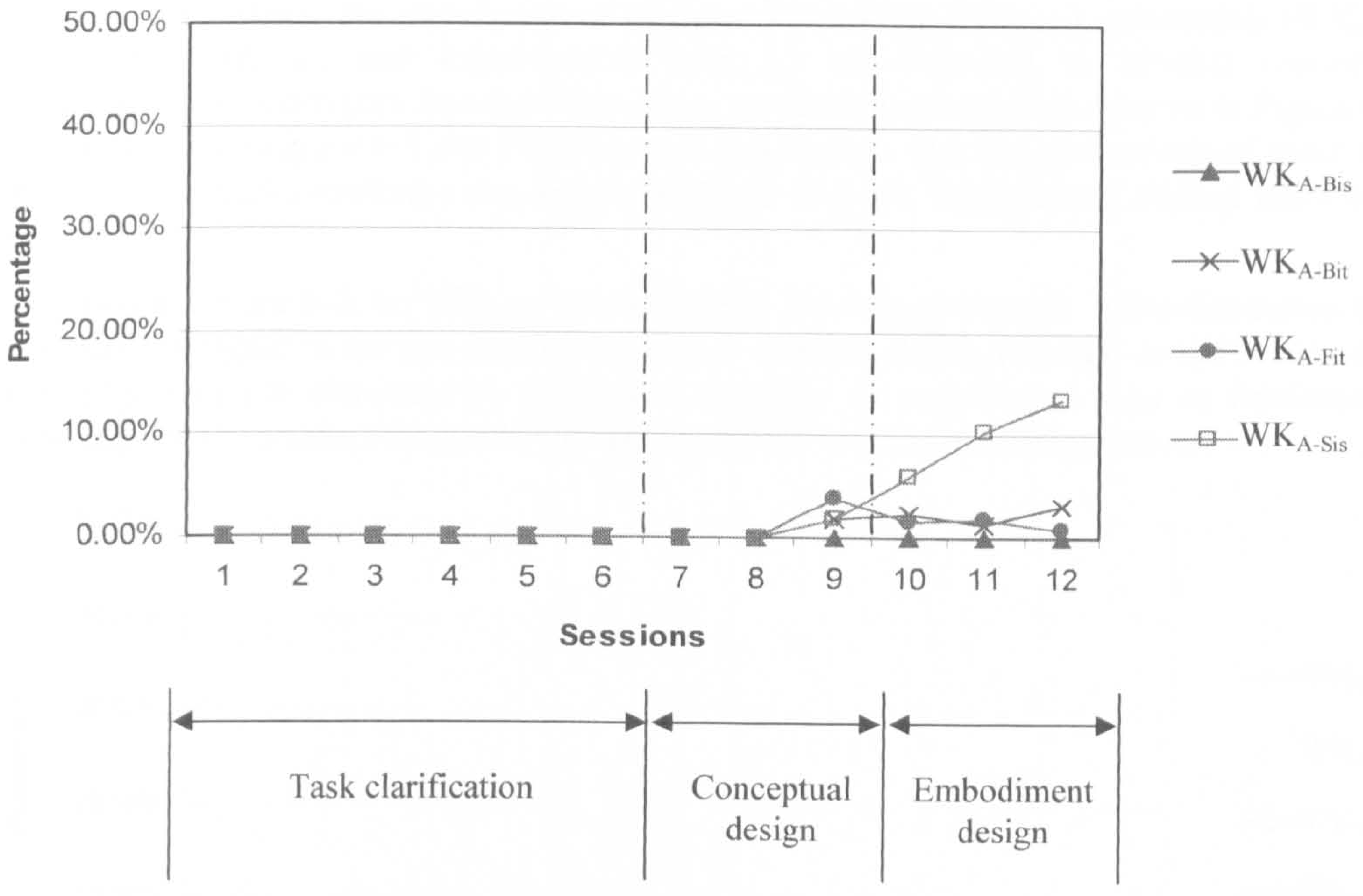


Figure 6-5: $WK_{A/It}$ and $WK_{A/Is}$ occurrence trend

No WK_{A-Bis} was identified from the protocols. One explanation for this is that all the analysed protocols were spoken by designers. Hence based on the definition of the WK_{A-Bis} and WK_{A-Bit} (see Chapter 3), all the identified artefact behavioural knowledge was encoded as *interpreted*, though they are also WK_{A-Bis}.

As seen in Figure 6-5, WK_{A-Sis} appeared from the end of conceptual design (Session 9), and reached its highest peak (15.42%) in Session 11 of embodiment design. This indicates that designers began to instantiate and specify artefact structure at the end of conceptual design. The design was then specified with more structural parameters being finalised in embodiment design before being finalised at the end of this phase.

Similar to $WK_{A\text{-}Sis}$, both $\boldsymbol{WK_{A\text{-}Bit}}$ and $\boldsymbol{WK_{A\text{-}Fit}}$ did not occur until Session 9, the end of conceptual design. The occurrence of these two elements then continued towards the end of embodiment design though not so much as $WK_{A\text{-}Sis}$ in this phase. This implies that $WK_{A\text{-}Bit}$, and $WK_{A\text{-}Fit}$ were mainly used by designers in conceptual and embodiment design and they might be used to refine the designed artefact.

The observation of the trends of $WK_{A/Is}$ and $WK_{A/It}$ can be summarised as follows:

- No $WK_{A\text{-}Bis}$ was identified from the protocols.
- $WK_{A\text{-}Sis}$ appeared from the end of conceptual design and reached its highest peak in the embodiment design.
- $WK_{A\text{-}Bit}$ and $WK_{A\text{-}Fit}$ had a similar trend to $WK_{A\text{-}Sis}$, with less proportion.

The deduction from the analysis of the ***instantiated*** and ***interpreted*** current working knowledge of artefact are also as follows:

- While $WK_{A\text{-}Bis}$ exists as all possible behaviours that an artefact can exhibit, all the behavioural knowledge discussed by designers are interpreted behavioural knowledge.
- Designers instantiate the artefact mainly in embodiment design.
- Designers use $WK_{A\text{-}Bit}$ and $WK_{A\text{-}Fit}$ in embodiment design to refine artefact.

Contextual current working artefact knowledge ($WK_{A/C}$)

As mentioned earlier, the knowledge of causal relationships ($WK_{A\text{-}CR}$), constraints ($WK_{A\text{-}Ct}$), motivations ($WK_{A\text{-}M}$), and requirements ($WK_{A\text{-}Rq}$) are regarded as artefact contextual knowledge. The occurrence trends of these four contextual elements are shown in Figure 6-6. In comparison to Figure 6-4 and Figure 6-5, it can be seen that the proportions of these four types of contextual knowledge elements were lower than the fundamental artefact knowledge elements.

As shown in Figure 6-6, no $\boldsymbol{WK_{A\text{-}CR}}$ was identified from the protocols. After discussion with the student designer in the two interviews, it was confirmed that although causal relationship knowledge was not discussed by designers explicitly to transfer one type of fundamental knowledge of the artefact to another; it was implicitly used in the design process.

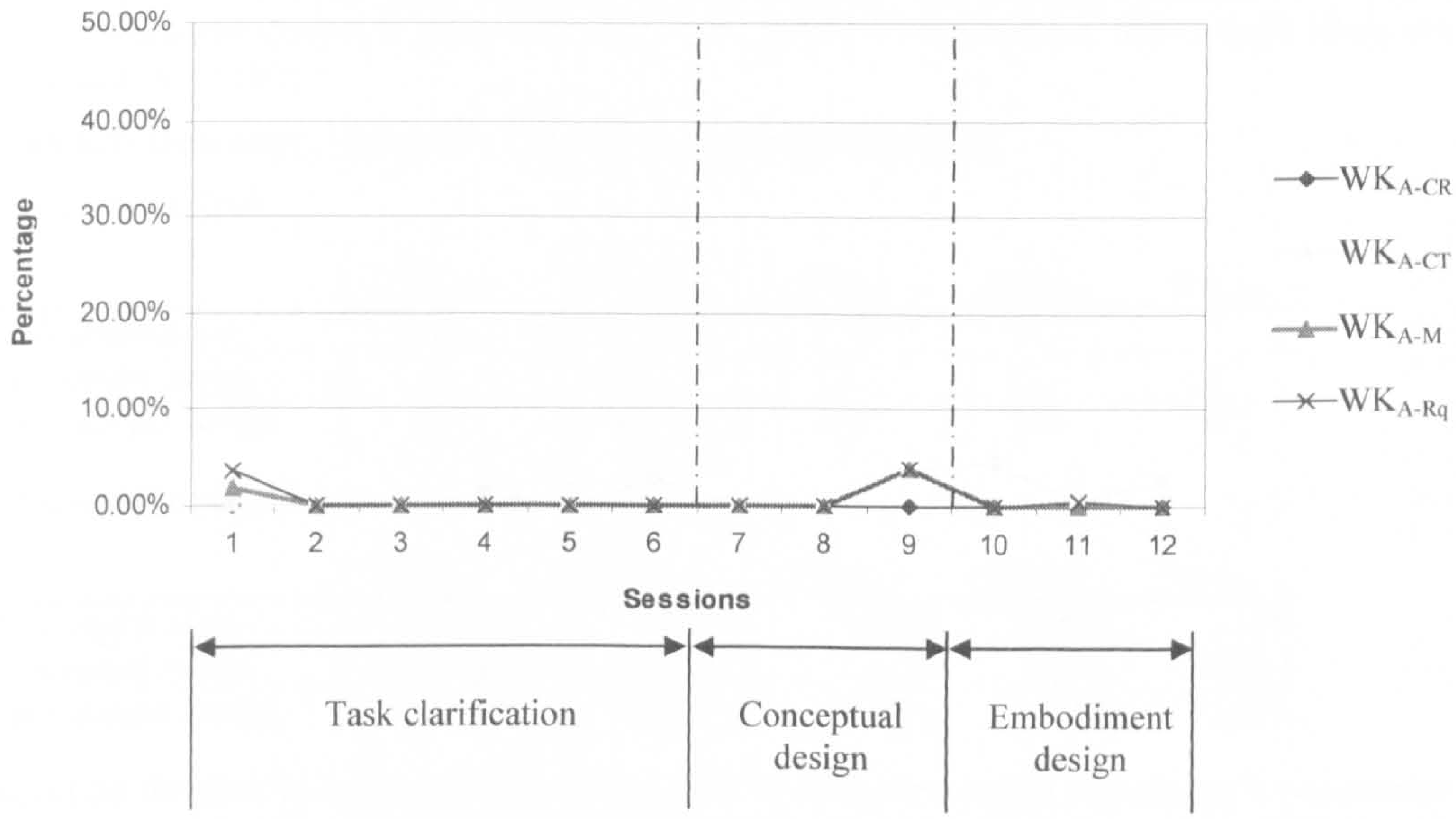


Figure 6-6: $WK_{A/C}$ occurrence trend

The analysis showed that $WK_{A\text{-}Ct}$ occurred from the end of task clarification through all the three phases. In comparison to the fundamental knowledge elements, however, its occurrence did not seem to have an obvious pattern, and its percentage was seen to be lower. Through interviews with the student designer, it was found that its low occurrence in this project might because: i), the roadside furniture design itself was a comparatively less constrained design; and ii), the design project was a student design project rather than an industrial commercial one.

The chart shows that $WK_{A\text{-}M}$ and $WK_{A\text{-}Rq}$ occurred at the beginning of task clarification and the end of conceptual design. The occurrence $WK_{A\text{-}Rq}$ at the very beginning of the design revealed that the design originated from motivations and requirements. It was found that their occurrence at the end of conceptual design was because a project review was held in session 9, during which a project brief was given by the student that include some description of motivations and requirements. In addition, the interviews with the student designer showed that the requirements were considered in conceptual and embodiment design.

The observation of the trends of $WK_{A/C}$ can be summarised as follows:

- $WK_{A/C}$ was observed less during the design process than $WK_{A/F}$.
- $WK_{A\text{-}CR}$ was not identified in the protocols.
- $WK_{A\text{-}Ct}$ occurred from the end of task clarification through all the three phases with low proportion owing to the project nature.
- $WK_{A\text{-}M}$ and $WK_{A\text{-}Rq}$ occurred from the beginning of task clarification.

The deductions from the analysis of the trends of $WK_{A/C}$ are as follows:

- $WK_{A\text{-}CR}$ is probably used implicitly rather than explicitly uttered by designers.
- Design originates from $WK_{A\text{-}M}$ and $WK_{A\text{-}Rq}$, which are considered by designers over the three phases.

A comparison of artefact knowledge

In order to compare the artefact knowledge, which includes domain artefact knowledge (DK_A), current working expected ($WK_{A/E}$), instantiated ($WK_{A/Is}$), and interpreted ($WK_{A/It}$) knowledge, and artefact contextual knowledge ($WK_{A/C}$) over task clarification, conceptual, and embodiment design, their occurrence times and their percentages within each phase are presented in Table 6-7.

Table 6-7: Occurrence of artefact knowledge over the three phases

a) Occurrence times

	DK_A	$WK_{A/E}$	$WK_{A/Is}$	$WK_{A/It}$	$WK_{A/C}$
Task clarification	116	17	0	0	5
Conceptual design	18	40	1	3	6
Embodiment design	33	162	64	24	17

b) Occurrence percentage

	DK_A	$WK_{A/E}$	$WK_{A/Is}$	$WK_{A/It}$	$WK_{A/C}$
Task clarification	35.15%	5.15%	0.00%	0.00%	1.52%
Conceptual design	12.00%	26.67%	0.67%	2.00%	4.00%
Embodiment design	5.15%	25.27%	9.98%	3.74%	2.65%

Based on the data in Table 6-7, Figure 6-7 illustrates these artefact knowledge's occurrence trends. It can be seen that the trend of DK_A was decreasing with its peak (31.10%) in task clarification; $WK_{A/E}$ increased along task clarification and conceptual design and slightly decreased in embodiment design, with its peak (27.52%) in conceptual design; $WK_{A/Is}$ and $WK_{A/It}$ had an increasing trend with their peaks (11.68% and 3.43%) in embodiment design; $WK_{A/C}$ appeared to have a relatively stable occurrence percentage over the three phases. Table 6-8 summarises the comparison of these artefact knowledge occurrence trend.

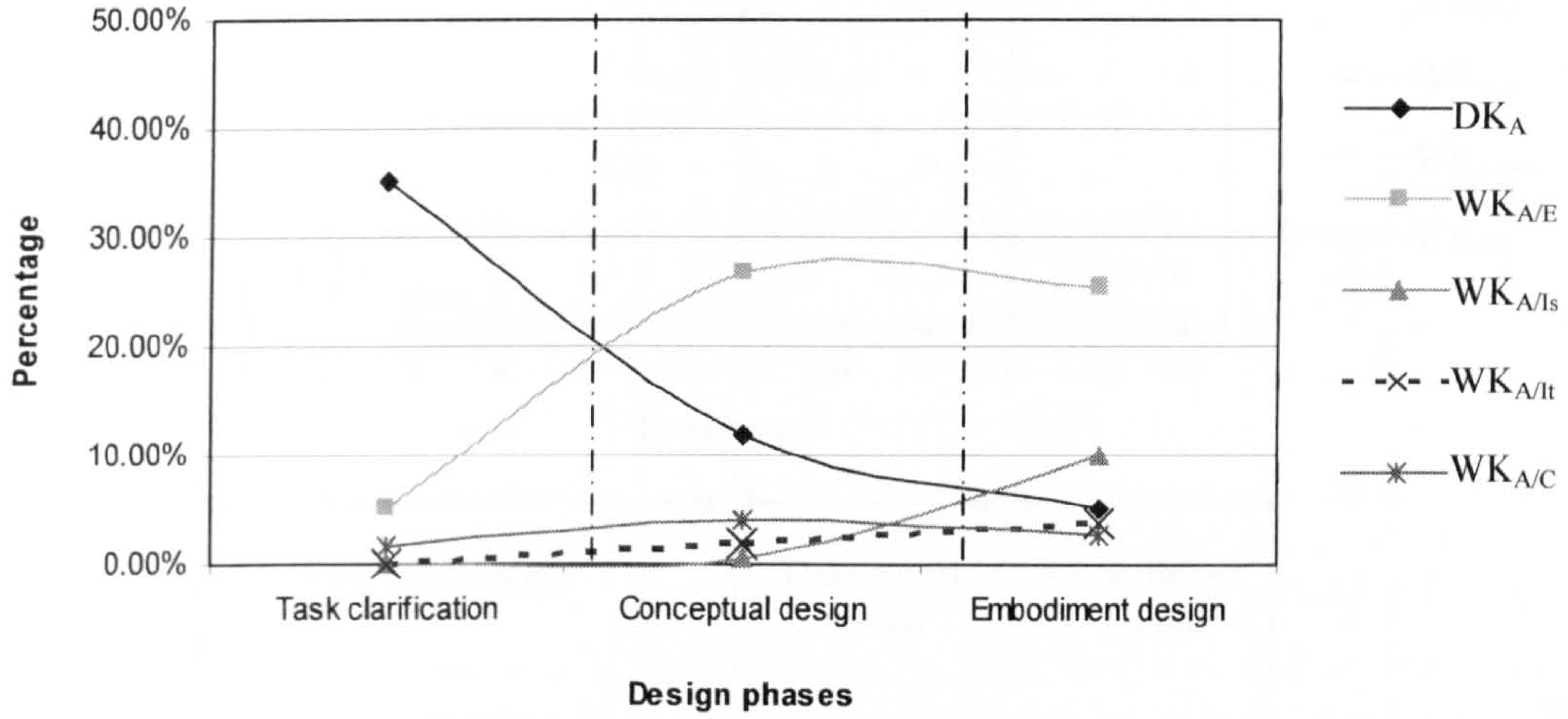


Figure 6-7: Comparison of artefact knowledge occurrence trends

Table 6-8: Comparison of artefact knowledge occurrence trend

	DK	$WK_{A/E}$	$WK_{A/Is}$	$WK_{A/It}$	$WK_{A/C}$
Occurrence trend	Decrease	Increase and stable	Slight increase	Slight increase	Relatively stable
Peak phase	Task clarification	Conceptual design	Embodiment design	Embodiment design	N/A

6.2.2 Design process knowledge elements

Similar to artefact, design process knowledge contains both domain and current working knowledge. Although a little domain design process knowledge was found in the initial protocol analysis, it was mainly related to design management knowledge. Due to the focus of the research being the coupling of the artefact and design process knowledge, only current working design process knowledge is discussed in this thesis as process knowledge elements coupling with the artefact knowledge. In this respect, five fundamental current working design process knowledge elements ($WK_{P\text{-}A}$, $WK_{P\text{-}G}$, $WK_{P\text{-}In}$, $WK_{P\text{-}Out}$, and $WK_{P\text{-}R}$) and two contextual design process knowledge elements ($WK_{P\text{-}C}$ and $WK_{P\text{-}I}$) are analysed and discussed in this section.

Fundamental current working design process knowledge ($WK_{P/F}$)

Figure 6-8 illustrates the occurrence trend of the $WK_{P/F}$ elements that were identified from the protocol analysis over the three phases.

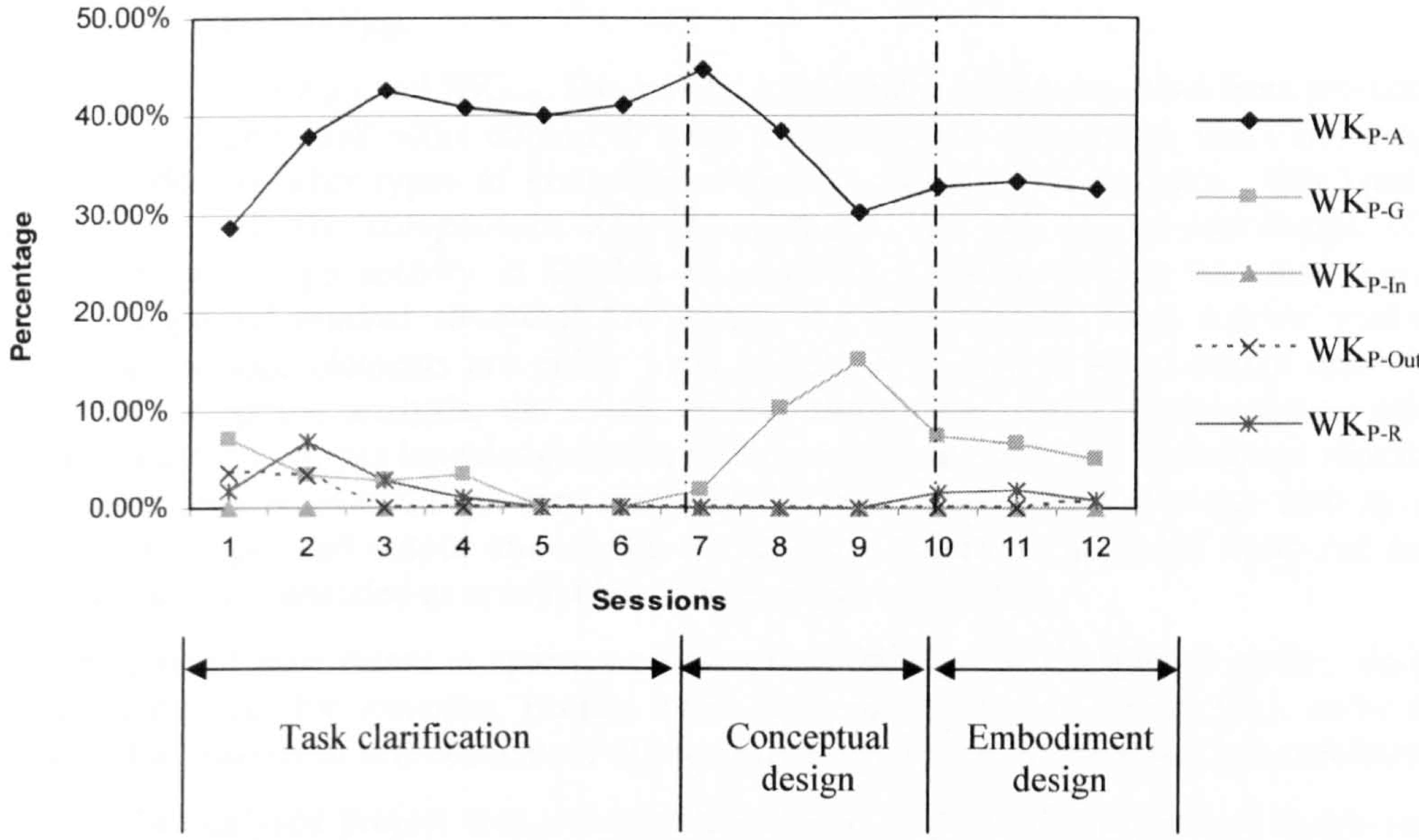


Figure 6-8: $WK_{P/F}$ occurrence trend

As can be seen from the chart, activity ($WK_{P\text{-}A}$) and goal ($WK_{P\text{-}G}$) were identified as the two main occurred elements of the design process. The occurrences of input ($WK_{P\text{-}In}$), output ($WK_{P\text{-}Out}$), and resource ($WK_{P\text{-}R}$) elements were rather low compare to design activity.

As one the fundamental knowledge element of design process, $WK_{P\text{-}A}$, such as generating, evaluating, modifying, and documenting, gradually evolved the design artefact knowledge. It is therefore the operating element that couples the artefact and design process knowledge. As can be seen from Figure 6-8, design activity occurred prevalently throughout the three phases, with approximately 15% fluctuation. More specifically, it constituted around 40% of the total elements during task clarification and the beginning of conceptual design, and 35% during the following conceptual and embodiment design. Moreover, its highest peak percentage was 44.83% in Session 7, the first session of conceptual design. This was because 10 proposed concepts were presented in this session. The trough (30.19%) in Session 9 was due to the project review, which went through the project from task clarification, resulted in higher percentage of $WK_{P\text{-}G}$ and lower percentage of $WK_{P\text{-}A}$.

During the analysis, it was found that quite often one piece of knowledge in the protocols could be encoded as different types of knowledge elements. Design activity and goal fall in this scope. As a result, if a chunk of knowledge could be encoded as either a goal or an activity, it was encoded with higher priority as a design activity in this thesis. For example, "I think you should do installation, as well as repairing it" was encoded as a "generating" activity that generated expected structural knowledge ("installation" and "repairing"), though it was also used as a design goal (do both installation and repairing) in the design.

$WK_{P\text{-}G}$ is the teleology element that couples the artefact and design process knowledge because it reveals designers' objectives intended to be achieved during the design process. In the protocols, design goals were generally characterised by words such as "in order to" and "need to". Its occurrence trend in Figure 6-8 indicates that $WK_{P\text{-}G}$ had a relatively higher occurrence percentage in conceptual design than the other two phases. However, as mentioned earlier, some knowledge elements that could be encoded as $WK_{P\text{-}G}$ were encoded as $WK_{P\text{-}A}$ with higher priority. In addition, the project review in Session 9 also contributed to the higher occurrence proportion of $WK_{P\text{-}G}$ in conceptual design because a number of design goals were presented during the review. As a result, the trend chart might not reveal the occurrence trend of $WK_{P\text{-}G}$.

In comparison to $WK_{P\text{-}A}$ and $WK_{P\text{-}G}$, fewer $WK_{P\text{-}In}$ and $WK_{P\text{-}Out}$ were encoded from protocols. One main reason is that some chunks of knowledge could be encoded as input and output were encoded as other types of knowledge elements already. For example, "this kind of infrastructure, all the components will be modular" was the output knowledge of a "Synthesising" design activity in Session 10, segment 6. Meanwhile, it was also current working expected artefact structural knowledge. To some extent, most current working artefact knowledge elements are either input or output of one or more design activities. However, during the analysis, the chunk of knowledge that could be encoded as either artefact or design process knowledge elements, was encoded as artefact knowledge elements with higher priority, even though they could also be the input or output of design activity. As a result, the input and output knowledge are sparsely shown in the trend chart not least because they were encoded as artefact knowledge elements already.

The trend chart also shows a sparse occurrence of $WK_{P\text{-}R}$. As mentioned earlier, design resources can be, for example, people, hardware, techniques, or information. After the analysis, the reasons of low occurrence of the design resource could be identified as follows:

- The analysed project was an individual design project with supervised instruction. This means that in comparison to collaborative design, the resource allocation, such as expertise and hardware was, therefore, relatively inessential and, hence was rarely discussed during the design process.
- While some information resources were used as design resources by the designers, they were encoded as elements of either DK_A or WK_A already.

Overall, the observation of the occurrence trend of $WK_{P/F}$ can be summarised as follows:

- $WK_{P\text{-}A}$ occurred prevalently throughout the three phases.
- $WK_{P\text{-}G}$ showed its peaks at the beginning of task clarification and conceptual design.
- $WK_{P\text{-}In}$, $WK_{P\text{-}Out}$, and $WK_{P\text{-}R}$ were sparsely identified in the trend analysis.

Based on the above discussion, the deductions of $WK_{P/F}$ can be summarised as follows:

- $WK_{P\text{-}A}$, as the operating element that couples artefact and design process, seems to dominate the design process elements.
- Since some chunks of knowledge that could be encoded as $WK_{P\text{-}G}$ were encoded with higher priority as $WK_{P\text{-}A}$, and that the highest peak of $WK_{P\text{-}G}$ in conceptual design was caused by a project review, Figure 6-8 might not reflect the real trend of $WK_{P\text{-}G}$.
- Most $WK_{P\text{-}In}$ and $WK_{P\text{-}Out}$ are artefact knowledge.
- Resource allocation, such as expertise and hardware, is relatively inessential to individual design project.
- Most information resources are artefact knowledge.
- Since some chunks of knowledge that could be encoded as $WK_{P\text{-}In}$, $WK_{P\text{-}Out}$, and $WK_{P\text{-}R}$ were encoded with higher priority as artefact knowledge, Figure 6-8 might not reflect their occurrence trend.

Contextual current working design process knowledge ($WK_{P/C}$)

Two types of $WK_{P/C}$ were analysed, i.e., design context ($WK_{P\text{-}C}$) and design issue ($WK_{P\text{-}I}$). Figure 6-9 depicts their occurrence trend over the three design phases.

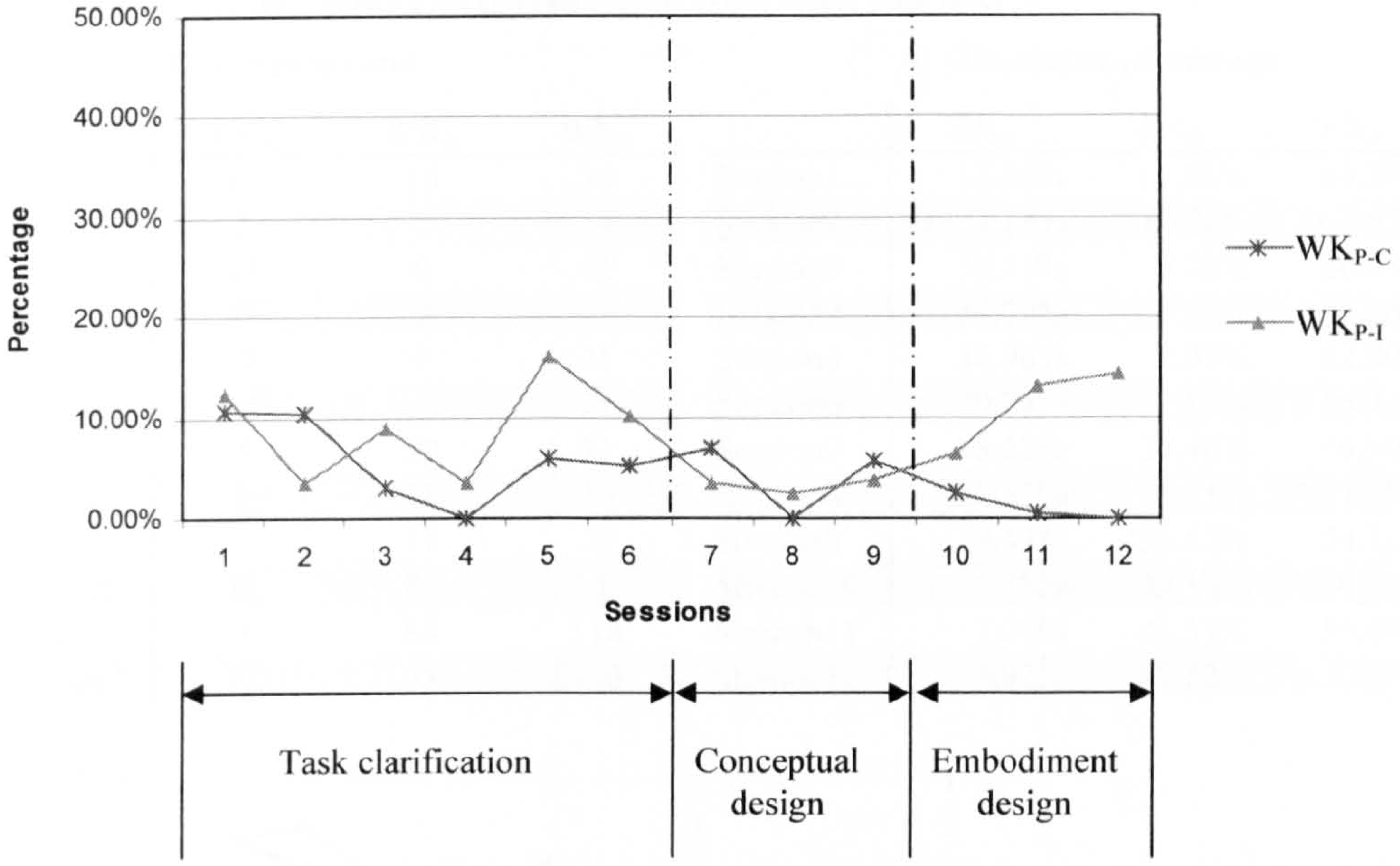


Figure 6-9: $WK_{P/C}$ occurrence trend

As mentioned earlier, WK_{P-C} includes knowledge factors that affect the design, in a sense that any design activity occurs within a specific context. Figure 6-9 does not show an obvious occurrence pattern for WK_{P-C} as it fluctuated through the three phases with occurrence percentage less than 11%. Such occurrence might be explained as i) WK_{P-C} does not possess a particular pattern, and ii) designers seldom discussed WK_{P-C} explicitly during the design.

WK_{P-I} implies the problem needs to be solved by designers. The occurrence trend shows that the issue occurred with relatively higher occurrence percentage in task clarification and embodiment design, than conceptual design. This implies that issues arise more frequently during clarifying design problem and refining design concepts, than during creating the design concepts.

The observation of the trend of $WK_{P/C}$ can be summarised as follows:

- WK_{P-C} occurred over the three phases.
- WK_{P-C} did not show an obvious occurrence pattern.
- The occurrence proportion of WK_{P-I} was higher in task clarification and embodiment design, than that in conceptual design.

The deductions from the analysis of the trend of $WK_{P/C}$ are follows:

- Designers do not discuss all design contexts explicitly during the design process.
- WK_{P-I} arises more frequently when designers clarify design problem, and subsequently refine the design concept in embodiment design, than when designers create the design concepts.

A comparison of artefact and design process knowledge

Having presented the occurrence trends of artefact and design process knowledge elements, this part compares the occurrence between the artefact and design pocess over the three phases. Table 6-9 lists the occurrence times (a) and percentages (b) of domain artefact knowledge, current working artefact, and design process knowledge over the 12 sessions, and Figure 6-10 depicts their occurrence over the three phases. Their trends are shown by their logarithmic trendlines in order to have a clear view of the overall trend.

Table 6-9: Occurrence times and percentage of DK_A, WK_A, and WK_P

a. Occurrence times

	DK_A	WK_A	WK_P
Session1	10	10	36
Session2	5	5	19
Session3	27	0	41
Session4	44	1	43
Session5	18	1	31
Session6	12	5	22
Session7	5	20	33
Session8	8	11	20
Session9	5	19	29
Session10	15	86	103
Session11	7	88	118
Session12	11	93	120

b. Occurrence percentage

	DK_A	WK_A	WK_P
Session1	17.86%	17.86%	64.29%
Session2	17.24%	17.24%	65.52%
Session3	39.71%	0.00%	60.29%
Session4	50.00%	1.14%	48.86%
Session5	36.00%	2.00%	62.00%
Session6	30.77%	12.82%	56.41%
Session7	8.62%	34.48%	56.90%
Session8	20.51%	28.21%	51.28%
Session9	9.43%	35.85%	54.72%
Session10	7.35%	42.16%	50.49%
Session11	3.29%	41.31%	55.40%
Session12	4.91%	41.52%	53.57%

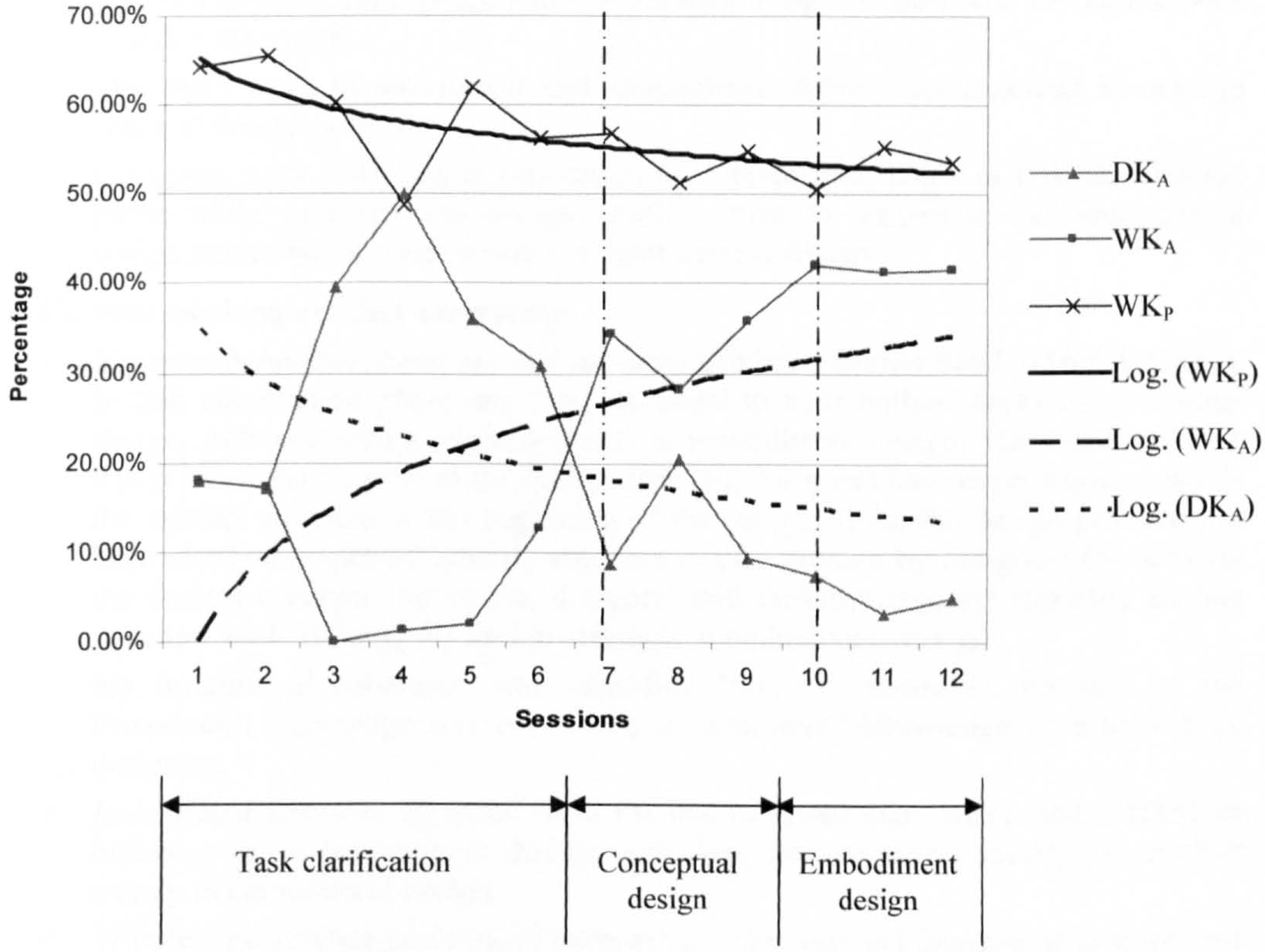


Figure 6-10: Comparison of artefact and design process knowledge occurrence trends

As can be seen, WK_P occurred at a slightly decreasing from around 60% to 55% over the three phases. DK_A and WK_A showed an overall increasing and decreasing trend over the three phases respectively. As two main types of the artefact knowledge, they formed a complementary pair, while one's occurrence percentage increased, the other's decreased.

6.3 CONCLUSION

This chapter presented the protocol analysis method and analysis results of occurrence trend of knowledge elements involved in the coupling. Within the protocol analysis method, protocol segmentation, a coding scheme, and the analysis process were described in order to give a view of how the work was conducted. Artefact knowledge elements (domain, current working fundamental, and current working contextual) and design process knowledge elements (current working fundamental and contextual knowledge) were analysed in terms of their occurrence trends over task clarification, conceptual, and embodiment design phases, Such analysis revealed that some design knowledge elements exhibited particular patterns, and some did not. The main observations and deductions from the protocol analysis are summarised as follows:

- **Domain artefact knowledge**
  - ✓ Domain artefact, rather than process knowledge is the main domain knowledge involved in the coupling.
  - ✓ Four types of domain artefact knowledge (*general*, *interpreted behaviour*, *interpreted function*, and *instantiated structure* of domain artefact knowledge) were identified to involve in the coupling.
  - ✓ No *expected domain artefact knowledge* occurred during the design process.
  - ✓ Domain artefact knowledge exhibited an overall decreasing occurrence trend over task clarification, conceptual, and embodiment design phases, with its highest peak in task clarification.
  - ✓ Designers work in *interpreted* and *instantiated*, rather than *expected* knowledge space of domain artefact.
  - ✓ Designers work with higher proportion of domain knowledge in task clarification phase while understanding design problem, than in conceptual and embodiment design phases while concentrating on their current design.
- **Current working artefact knowledge**
  - ✓ *Expected behaviour*, *function*, and *structure* exhibited similar trend, which decreased in task clarification phase and then increased to their highest peaks in conceptual design, followed with a slight decrease in embodiment design. The trend indicates that prior to clarification of the design problem, designers have expectations towards the artefact structure at the beginning of the design. Once the design problem has been clarified, expected artefact structure is then created by designers for deriving the desired concepts. Moreover, designers still create/change the expected artefact structure while refining the design concepts in embodiment design.
  - ✓ No *instantiated behaviour* was identified from the protocols, because all the behavioural knowledge was considered as interpreted knowledge once uttered by designers.
  - ✓ *Instantiated structure* appeared from the end of conceptual design and reached its highest peak in embodiment design, indicating that designers specify the artefact mainly in embodiment design.
  - ✓ With less occurrence percentage, *interpreted behaviour* and *interpreted function* had a similar trend with *instantiated structure*, indicating that designers use *interpreted behaviour* and *interpreted function* in embodiment design to refine artefact.
  - ✓ *Contextual current working artefact knowledge* was observed to have a lower ratio during the design process than the *fundamental artefact knowledge* elements.
  - ✓ *Causal relationships* were not identified in the protocols. However, they were probably used implicitly rather than explicitly uttered by designers.
  - ✓ *Constraints* occurred from the end of task clarification through all the three phases with low occurrence proportion owing to the project nature.

- ✓ *Motivations* and *requirements* occurred from the beginning of task clarification, indicating that design originates from them, and that they are considered by designers over the three phases.

- **Current working design process knowledge**
  - ✓ *Activity*, as the operating element that couples artefact and design process, seemed to dominate the design process elements.
  - ✓ Since some chunks of knowledge that could be encoded as *goal* were encoded with higher priority as *activity*, and that the highest peak of *goal* in conceptual design was caused by a project review, its trend chart might not reflect the real trend of *goal*.
  - ✓ *Input*, *output*, and *resource* were sparsely identified in the trend analysis. Because some chunks of knowledge that could be encoded as *input*, *output*, and *resource* were encoded with higher priority as artefact knowledge, their trend charts might not reflect their occurrence trend.
  - ✓ Most *input*, *output*, and information *resources* are artefact knowledge.
  - ✓ Resource allocation, such as expertise and hardware, is relatively inessential for individual design project.
  - ✓ *Context* did not show an obvious occurrence pattern, probably because designers did not discuss all design contexts during the design process.

The occurrence percentage of *issue* was higher in task clarification and embodiment design than that in conceptual design, indicating that *issue* arose more frequently when designers clarified design problem and refined the design concept, than when designers created design concepts.

Chapter 7 COUPLING OF ARTEFACT AND DESIGN PROCESS KNOWLEDGE

In the previous chapter, knowledge elements involved in the coupling and their occurrence trend over task clarification, conceptual, and embodiment design phases were discussed. This chapter presents the evolved coupling by combining the coupling links identified from both the content analysis presented in Chapter 5 and those identified from protocol analysis identified in this chapter. This chapter is organised as follows. Section 7.1 introduces the coupling analysis approach. The analysis of the coupling links based on protocol analysis is presented in Section 7.2. Section 7.3 presents the evolved coupling model based on the results obtained from both content and protocol analysis. Finally Section 7.4 concludes this chapter.

7.1 COUPLING ANALYSIS APPROACH

Different from the analysis conducted in Chapter 6, which included both the coupling elements and their occurrence trends, the analysis conducted in this chapter focused only on identifying those main links that compose the coupling. Further analysis of the links' trends, which can be found in Appendix F, showed that the links with sufficient occurrences exhibit trends that are similar to the artefact elements of the links. However, the links with fewer occurrences did not seem to have an obvious trend.

As previously mentioned in Section 6.1.2, four types of links between knowledge elements of the artefact and design process, i.e., *cause-effect link of creation, link of referral, link of usage*, and *link of containment*, were identified through the protocol analysis, which are considered as the basis for the coupling. They represent different relationships between the artefact and design process. As a result of the protocol analysis, 86 links were identified. Their occurrence times over the 12 design sessions were then incorporated into Excel for further analysis.

It was found that the occurrence times of these links varied from 1 to 141. In this thesis, it was hypothesised that the higher occurrences the link had, the more significant it was. Though 86 **links** were identified, not all of them were considered to be the links included in the coupling, because some occurred only once or twice over the 12 sessions. In comparison to those links that occurred tens of times, the effect of low occurrence links on the design could be considered insignificant. It was therefore decided to include only **main links** in the coupling. However, it seemed rather difficult to decide whether a link was a main one, as there was no clear guideline on what the main link's occurrence times should be. In addition, it seemed that their occurrences did not fit in with a known distribution pattern that could be analysed by a traditional statistical method. Therefore, following an initial analysis of the data, it was decided to consider a link as a main one only if its total occurrence times over the 12 sessions fell into the higher 95% range of the overall occurrences of all the same type of links. That is, for each type of link, all the identified links were initially listed by their occurrence percentages in descending order. Then, those links that fell into the higher 95% range were identified as the main links and were therefore considered in the coupling. The remaining links fell into the lower 5% were identified as minor links, bearing less effect on design than the main ones. However, the higher range might not be exactly 95% because several links could also have same occurrence percentage, and were at the cutting edge of this 95% range. Whether these links were identified as main ones, it was subject to whichever' percentage was closer to 95%.

Moreover, because the protocols included 12 sessions, there were two methods to judge whether a link's occurrence fell into the higher 95% range of the overall occurrence. It can be judged by either the overall percentage (the link's occurrence times over 12 sessions/total occurrence numbers of all links over 12 sessions*100%) or average percentage (average of the link's occurrence percentage of all occurred sessions). To eliminate the risk of losing some main links, it was then decided to judge the links based on both methods. Although there appeared to exist some links that were mistakenly identified, the risk was considered minimal and therefore acceptable for the analysis of the coupling model by using the 95% range and the two methods.

Having identified the main links of the four types from the protocol analysis, it was then found that the referral, usage, and containment links could be deduced to *link of employment*. Moreover, some of employment links could also be deduced from some of the main creation links. Hence the main creation links were analysed, which resulted in **creation links of the coupling from protocol analysis (CL-P)** and some main employment links EL-P(Cr). The main referral, usage, and containment links were also analysed and resulted in some main employment links deduced from each type (EL-P(R), EL-P(U), and EL-P(C)). **Employment links of the coupling from protocol analysis (EL-P)** were then generalised from the employment links deduced from each type of links. Combining with the **creation (CL-C)** and **employment links of the coupling (EL-C)** identified **from the content analysis** presented in Chapter 5, the evolved **coupling model** was then derived, which is composed of the **creation (CL)** and **employment links of the coupling (EL)**. Figure 7-1 shows this analysis approach of the coupling model. Detailed analysis of the main links and links of the coupling are presented in Section 7.2.

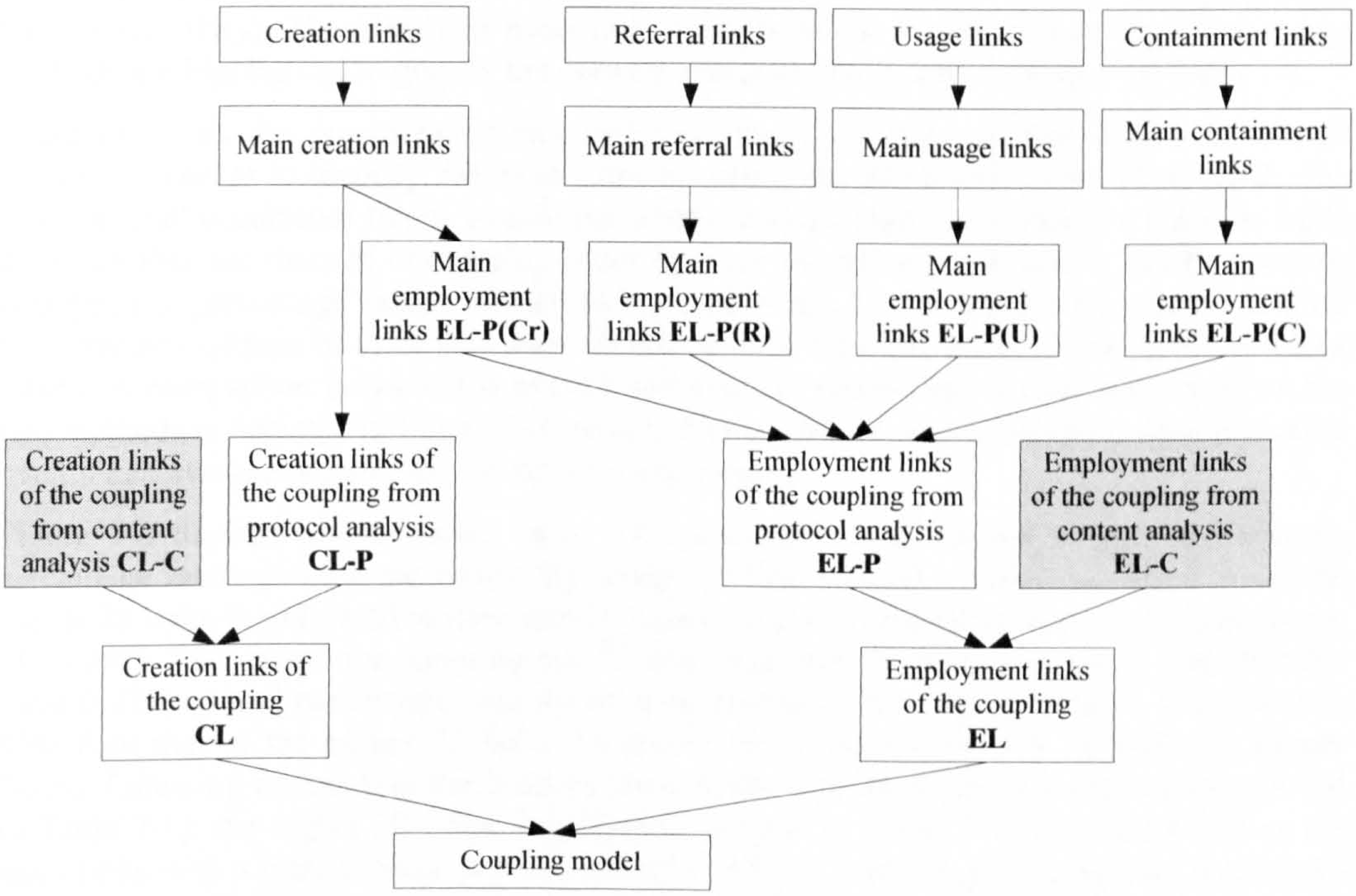


Figure 7-1: Coupling analysis approach

7.2 COUPLING LINKS IDENTIFIED FROM PROTOCOL ANALYSIS

In this section, further explanation of the four types of links, their main links, as well as the links of the coupling that were identified from the main links are presented.

7.2.1 Cause-effect link of creation

Cause-effect link of creation[8] exists between two elements, if one causes or triggers the creation of the other. For example, "So, then I proposed that two (rings attach the panel to the post) would be bolted, and two would be welded loops." includes two knowledge elements, a "Detailing" design activity ($WK_{P\text{-}A}$), "proposed...", and an expected artefact structure element ($WK_{A\text{-}Se}$), "two would be bolted, and two would be welded loops". The detailing activity caused the creation of the expected structure, which implies a creation link that exists between them, i.e., '$WK_{P\text{-}A} \rightarrow WK_{A\text{-}Se}$'.

Among the four types of links, *link of creation* was seen to have the highest frequency over the 12 sessions both in terms of the number of links (51) and the number of occurrences (731). The occurrence times and percentage of all the identified 51 creation links over the 12 sessions are shown in Table D-1, Appendix D. The upper half of the table shows the links' occurrence times over the 12 sessions (from row "Session 1" to row "Session 12"), their total occurrence times over the 12 sessions (in the row "Sum"), and their overall percentages among all the 51 links (in the row "Overall %"). The lower half of the table shows the links' occurrence percentages within each session (from row "Session 1" to row "Session 12") and their average percentages over the 12 sessions (in the row "Average %"). If element 'A' causes the creation of 'B', it is represented as 'A $\rightarrow$ B' in the second row of the table. The 51 links were grouped into three main groups based on the types of causing elements that are listed in the first row of the table ("Causing element"), i.e., domain artefact knowledge (DK_A), current working artefact knowledge (WK_A), and current working design process knowledge (WK_P). The identified main links from both the overall and average percentage methods are highlighted in grey in the corresponding columns, and explained in Table 7-1.

Table D-1 lists the occurrence times and percentage of each creation link over the 12 sessions. In order to identify the main links by using the aforementioned two methods, the links' overall occurrence times, overall percentage and average percentage are listed in Table 2, which lists the links in descending order by their overall percentages. It can be seen the two types of percentage values of each link are different. The difference was mainly caused by different numbers of links that were identified over different sessions due to their variant length. A comparison between the overall and average percentage of each link based on the two methods is depicted in Figure 7-2, which shows that the two methods resulted in similar overall and average percentages of most creation links.

Figure 7-3 depicts how the main links were analysed based on the overall and average percentage methods with pie charts. By using the first method, as seen in Figure 7-3.a, the higher 28 links (highlighted in dark grey in Table 7-1) were identified with a total percentage of 94.94%. The reason for choosing the 28 links was that the subsequent four links had the same 0.41% overall percentage, and the total percentage of the higher 28 links was closer to 95% than that of the higher 32 links. Moreover, by using the second method (see Figure 7-3.b), following descending the links by their average percentages (not the sequence listed in Table 7-1), the higher 29 links (highlighted in grey in Table 7-1) were identified as the main links with a total average percentages of 95.01%. Combining the identified main links by both methods, 31 links were subsequently pinpointed as the main creation links. It can be seen that most of the main links (26) were identified by both methods. There were, however, two links ($WK_{A\text{-}Sis} \rightarrow WK_{P\text{-}G}$ and $WK_{A\text{-}Bit} \rightarrow WK_{P\text{-}A}$) that were identified only by the overall percentage method and three links ($WK_{A\text{-}Fe} \rightarrow WK_{P\text{-}A}$, $WK_{P\text{-}A} \rightarrow WK_{A\text{-}Rq}$, and $WK_{P\text{-}A} \rightarrow DK_{A\text{-}G}$) were identified only by the average percentage method.

[8] Unless explicitly stated, *link of creation* will be used throughout this thesis to represent *cause-effect link of creation*.

Table 7-1: Analysis of main creation links based on the protocol analysis

Creation links	$WK_{P-A} \rightarrow WK_{A-Se}$	$WK_{P-I} \rightarrow WK_{P-A}$	$WK_{A-Se} \rightarrow WK_{P-A}$	$WK_{P-G} \rightarrow WK_{P-A}$	$DK_{A-G} \rightarrow WK_{P-A}$	$WK_{A-Sis} \rightarrow WK_{P-I}$	$WK_{P-A} \rightarrow DK_{A-Fit}$	$WK_{A-Se} \rightarrow WK_{P-I}$	$WK_{A-Sis} \rightarrow WK_{P-A}$	$WK_{P-A} \rightarrow WK_{A-Bit}$
Sum	141	100	63	57	52	30	27	27	25	18
Overall percentage	19.29%	13.68%	8.62%	7.80%	7.11%	4.10%	3.69%	3.69%	3.42%	2.46%
Average percentage	13.57%	13.76%	6.81%	5.90%	14.43%	1.64%	5.58%	1.64%	1.54%	1.70%

Creation links	$WK_{P-A} \rightarrow WK_{A-Sis}$	$WK_{P-C} \rightarrow WK_{P-I}$	$DK_{A-G} \rightarrow WK_{P-I}$	$WK_{P-C} \rightarrow WK_{P-A}$	$WK_{A-Se} \rightarrow WK_{P-G}$	$WK_{P-A} \rightarrow WK_{A-Fit}$	$DK_{A-Sis} \rightarrow WK_{P-A}$	$WK_{P-I} \rightarrow WK_{P-G}$	$WK_{P-A} \rightarrow WK_{A-Fe}$	$WK_{P-A} \rightarrow DK_{A-Bit}$
Sum	17	16	14	12	11	11	10	9	7	7
Overall percentage	2.33%	2.19%	1.92%	1.64%	1.50%	1.50%	1.37%	1.23%	0.96%	0.96%
Average percentage	0.98%	4.69%	3.56%	2.47%	2.24%	1.02%	1.88%	0.83%	1.62%	1.23%

Creation links	$WK_{A-Sis} \rightarrow WK_{P-G}$	$WK_{P-A} \rightarrow WK_{P-G}$	$DK_{A-G} \rightarrow WK_{P-G}$	$WK_{P-A} \rightarrow WK_{P-Out}$	$WK_{A-Bit} \rightarrow WK_{P-A}$	$WK_{A-Rq} \rightarrow WK_{P-G}$	$DK_{A-Fit} \rightarrow WK_{P-A}$	$WK_{P-G} \rightarrow WK_{P-G}$	$WK_{A-Fe} \rightarrow WK_{P-A}$	$WK_{P-A} \rightarrow WK_{A-Rq}$
Sum	7	6	5	5	5	4	4	4	3	3
Overall percentage	0.96%	0.82%	0.68%	0.68%	0.68%	0.55%	0.55%	0.55%	0.41%	0.41%
Average percentage	0.37%	1.05%	1.10%	1.09%	0.29%	1.15%	0.74%	0.62%	0.78%	0.77%

Creation links	$WK_{P-A} \rightarrow DK_{A-G}$	$WK_{A-Be} \rightarrow WK_{P-A}$	$WK_{P-G} \rightarrow WK_{P-I}$	$WK_{A-Fit} \rightarrow WK_{P-A}$	$WK_{P-C} \rightarrow WK_{P-G}$	$WK_{P-A} \rightarrow WK_{A-Ct}$	$WK_{A-Bit} \rightarrow WK_{P-I}$	$WK_{P-I} \rightarrow WK_{P-I}$	$DK_{A-Sis} \rightarrow WK_{P-G}$	$WK_{A-Fe} \rightarrow WK_{P-I}$
Sum	3	3	2	2	2	2	2	2	1	1
Overall percentage	0.41%	0.41%	0.27%	0.27%	0.27%	0.27%	0.27%	0.27%	0.14%	0.14%
Average percentage	0.62%	0.45%	0.41%	0.31%	0.26%	0.13%	0.11%	0.11%	0.35%	0.33%

Creation links	$WK_{A-M} \rightarrow WK_{P-A}$	$WK_{A-Rq} \rightarrow WK_{P-I}$	$WK_{P-A} \rightarrow WK_{A-Be}$	$WK_{A-M} \rightarrow WK_{P-G}$	$WK_{A-Ct} \rightarrow WK_{P-A}$	$DK_{A-Fit} \rightarrow WK_{P-G}$	$DK_{A-Fit} \rightarrow WK_{P-I}$	$DK_{A-Bit} \rightarrow WK_{P-A}$	$WK_{P-A} \rightarrow WK_{P-A}$	$WK_{A-Fit} \rightarrow WK_{P-I}$	$WK_{A-Ct} \rightarrow WK_{P-I}$
Sum	1	1	1	1	1	1	1	1	1	1	1
Overall percentage	0.14%	0.14%	0.14%	0.14%	0.14%	0.14%	0.14%	0.14%	0.14%	0.14%	0.14%
Average percentage	0.26%	0.26%	0.26%	0.25%	0.25%	0.19%	0.19%	0.05%	0.05%	0.05%	0.05%

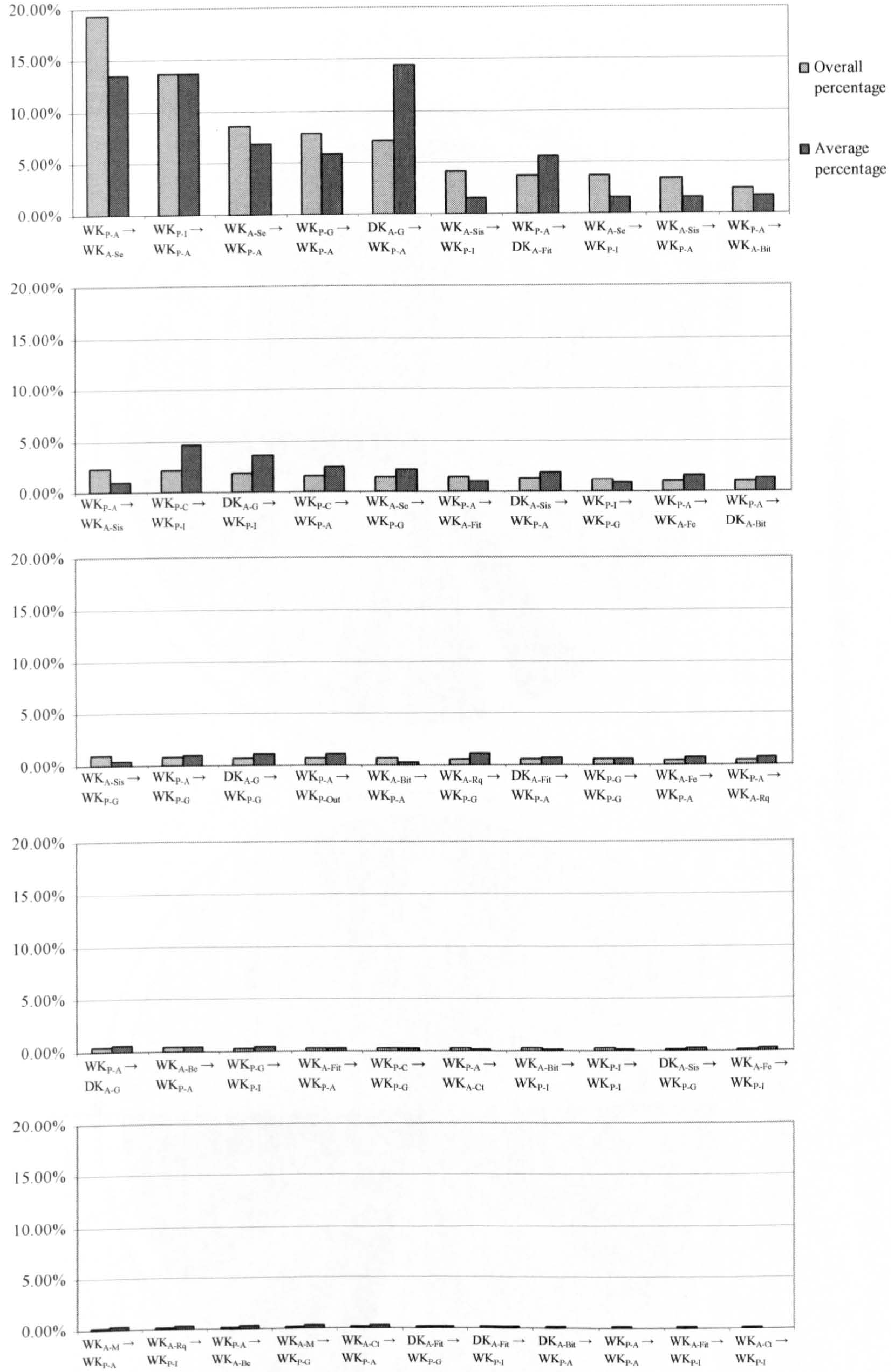


Figure 7-2: Comparison of overall and average percentage of creation links

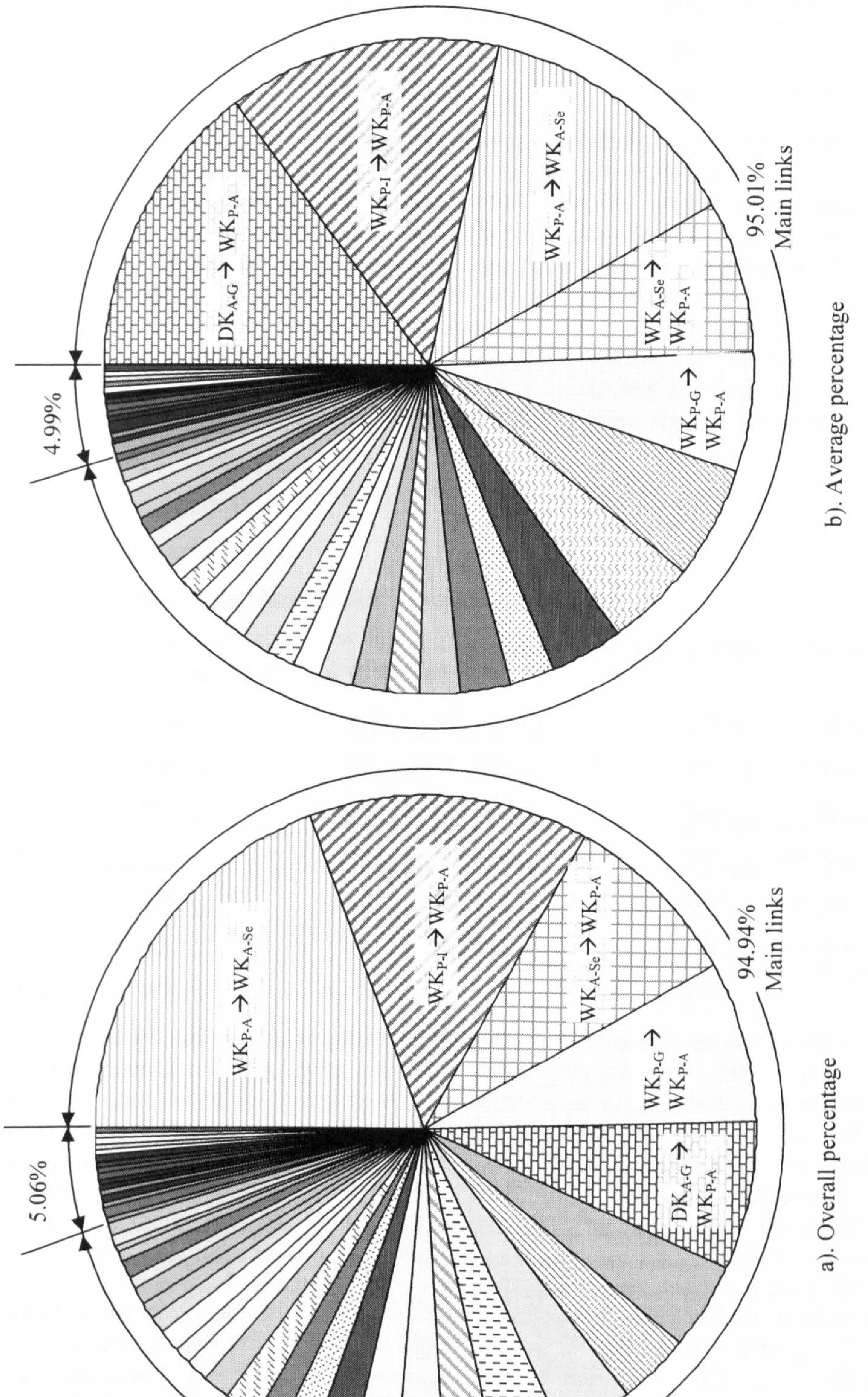


Figure 7-3: Overall and average percentage pie of creation links

Domain artefact knowledge as causing element

As shown in Table D-1 in Appendix D, nine creation links were identified with domain artefact knowledge as their causing elements. These are:

$\underline{DK_{A-G} \rightarrow WK_{P-A}}$	$\underline{DK_{A-G} \rightarrow WK_{P-G}}$	$\underline{DK_{A-G} \rightarrow WK_{P-I}}$
$DK_{A-Bit} \rightarrow WK_{P-A}$	$\underline{DK_{A-Fit} \rightarrow WK_{P-A}}$	$DK_{A-Fit} \rightarrow WK_{P-G}$
$DK_{A-Fit} \rightarrow WK_{P-I}$	$\underline{DK_{A-Sis} \rightarrow WK_{P-A}}$	$DK_{A-Sis} \rightarrow WK_{P-G}$

The analysis showed that five of them (underlined in the above list) were main links. Of these five links, three triggered the creation of design activity (WK_{P-A}), with the domain artefact general knowledge (DK_{A-G}), interpreted function (DK_{A-Fit}), and instantiated structure (DK_{A-Sis}) as their causing elements. Considering a minor link '$DK_{A-Bit} \rightarrow WK_{P-A}$' with interpreted behaviour as its causing element, these four links can be generalised into '$DK_A \rightarrow WK_{P-A}$', because their causing elements cover the four domain artefact knowledge elements discussed in this thesis. This generalised link and the other two main links, therefore, are considered as creation links of the coupling with domain artefact knowledge as their causing element. These three links are listed below and are identified with Arabic numerals follow CL-P, which represents creation link identified from protocol analysis.

CL-P.1 : $DK_A \rightarrow WK_{P-A}$

CL-P.2 : $DK_{A-G} \rightarrow WK_{P-G}$

CL-P.3 : $DK_{A-G} \rightarrow WK_{P-I}$

Current working artefact knowledge as causing element

As can be seen in Table D-1, 19 links were recognised with current working artefact knowledge as their causing element. They are:

$WK_{A-Be} \rightarrow WK_{P-A}$	$\underline{WK_{A-Bit} \rightarrow WK_{P-A}}$	$WK_{A-Bit} \rightarrow WK_{P-I}$
$\underline{WK_{A-Fe} \rightarrow WK_{P-A}}$	$WK_{A-Fe} \rightarrow WK_{P-I}$	$WK_{A-Fit} \rightarrow WK_{P-A}$
$WK_{A-Fit} \rightarrow WK_{P-I}$	$\underline{WK_{A-Se} \rightarrow WK_{P-A}}$	$\underline{WK_{A-Se} \rightarrow WK_{P-G}}$
$\underline{WK_{A-Se} \rightarrow WK_{P-I}}$	$\underline{WK_{A-Sis} \rightarrow WK_{P-A}}$	$\underline{WK_{A-Sis} \rightarrow WK_{P-G}}$
$\underline{WK_{A-Sis} \rightarrow WK_{P-I}}$	$WK_{A-Ct} \rightarrow WK_{P-A}$	$WK_{A-Ct} \rightarrow WK_{P-I}$
$WK_{A-M} \rightarrow WK_{P-A}$	$WK_{A-M} \rightarrow WK_{P-G}$	$\underline{WK_{A-Rq} \rightarrow WK_{P-G}}$
$WK_{A-Rq} \rightarrow WK_{P-I}$		

Having been measured against the aforementioned two methods, 9 out of the above 19 links (which are underlined in the above list) were seen to be the main links. Further analysis revealed that four out of these nine links caused the occurrence of WK_{P-A}, with the causing elements WK_{A-Bit}, WK_{A-Fe}, WK_{A-Se}, and WK_{A-Sis}. Considering two minor links '$WK_{A-Be} \rightarrow WK_{P-A}$' and '$WK_{A-Fit} \rightarrow WK_{P-A}$', which also caused the creation of WK_{P-A}, it would seem reasonable to generalise these six links into '$WK_{A/F} \rightarrow WK_{P-A}$', because their causing elements cover six out of seven fundamental current working knowledge elements of artefact. The generalised link indicates that fundamental WK_A causes design activity. It should be noted that instantiated behaviour (WK_{A-Bis}) is not included in this link because no WK_{A-Bis} was identified in the protocols. In addition, if the structural knowledge of the current working artefact is represented as WK_{A-S}, the two links '$WK_{A-Se} \rightarrow WK_{P-G}$' and '$WK_{A-Sis} \rightarrow WK_{P-G}$' can be generalised into '$WK_{A-S} \rightarrow WK_{P-G}$', and the other two '$WK_{A-Se} \rightarrow WK_{P-I}$' and '$WK_{A-Sis} \rightarrow WK_{P-I}$' can be generalised into '$WK_{A-S} \rightarrow WK_{P-I}$'. Overall, the following four links are considered to be another four creation links of the coupling, with current working artefact knowledge as their causing elements.

CL-P.4 : $WK_{A/F} \rightarrow WK_{P\text{-}A}$ (exclude $WK_{A\text{-}Bis} \rightarrow WK_{P\text{-}A}$)

CL-P.5 : $WK_{A\text{-}S} \rightarrow WK_{P\text{-}G}$

CL-P.6 : $WK_{A\text{-}S} \rightarrow WK_{P\text{-}I}$

CL-P.7 : $WK_{A\text{-}Rq} \rightarrow WK_{P\text{-}G}$

Current working design process knowledge as causing element

23 links were identified in this group, with activity ($WK_{P\text{-}A}$), goal ($WK_{P\text{-}G}$), context ($WK_{P\text{-}C}$), and issues ($WK_{P\text{-}I}$) as their causing elements (see Table D-1), which include:

$\underline{WK_{P\text{-}A} \rightarrow DK_{A\text{-}G}}$	$\underline{WK_{P\text{-}A} \rightarrow DK_{A\text{-}Bit}}$	$\underline{WK_{P\text{-}A} \rightarrow DK_{A\text{-}Fit}}$
$WK_{P\text{-}A} \rightarrow WK_{A\text{-}Be}$	$\underline{WK_{P\text{-}A} \rightarrow WK_{A\text{-}Bit}}$	$\underline{WK_{P\text{-}A} \rightarrow WK_{A\text{-}Fe}}$
$\underline{WK_{P\text{-}A} \rightarrow WK_{A\text{-}Fit}}$	$\underline{WK_{P\text{-}A} \rightarrow WK_{A\text{-}Se}}$	$\underline{WK_{P\text{-}A} \rightarrow WK_{A\text{-}Sis}}$
$WK_{P\text{-}A} \rightarrow WK_{A\text{-}Ct}$	$\underline{WK_{P\text{-}A} \rightarrow WK_{A\text{-}Rq}}$	$WK_{P\text{-}A} \rightarrow WK_{P\text{-}A}$
$\underline{WK_{P\text{-}A} \rightarrow WK_{P\text{-}G}}$	$\underline{WK_{P\text{-}A} \rightarrow WK_{P\text{-}Out}}$	$\underline{WK_{P\text{-}G} \rightarrow WK_{P\text{-}A}}$
$\underline{WK_{P\text{-}G} \rightarrow WK_{P\text{-}G}}$	$WK_{P\text{-}G} \rightarrow WK_{P\text{-}I}$	$\underline{WK_{P\text{-}C} \rightarrow WK_{P\text{-}A}}$
$WK_{P\text{-}C} \rightarrow WK_{P\text{-}G}$	$\underline{WK_{P\text{-}C} \rightarrow WK_{P\text{-}I}}$	$\underline{WK_{P\text{-}I} \rightarrow WK_{P\text{-}A}}$
$\underline{WK_{P\text{-}I} \rightarrow WK_{P\text{-}G}}$	$WK_{P\text{-}I} \rightarrow WK_{P\text{-}I}$	

Of the above 23 links, 17 (underlined in the above list) were identified as the main links. Further analysis showed that if interpreted domain artefact behaviour and function were represented as $DK_{A/It}$, '$WK_{P\text{-}A} \rightarrow DK_{A\text{-}Bit}$' and '$WK_{P\text{-}A} \rightarrow DK_{A\text{-}Fit}$' could be generalised as '$WK_{P\text{-}A} \rightarrow DK_{A/It}$'. The above list also shows that five main links share $WK_{P\text{-}A}$ as their causing element, with five fundamental current working knowledge elements of artefact being their caused elements, i.e., $WK_{A\text{-}Bit}$, $WK_{A\text{-}Fe}$, $WK_{A\text{-}Fit}$, $WK_{A\text{-}Se}$, and $WK_{A\text{-}Sis}$. Considering a minor link '$WK_{P\text{-}A} \rightarrow WK_{A\text{-}Be}$' listed above, these six links can be generalised into '$WK_{P\text{-}A} \rightarrow WK_{A/F}$'. It should be noted that $WK_{A\text{-}Bis}$ is not included in this link because no $WK_{A\text{-}Bis}$ was identified in the protocol analysis. In addition, if two types of contextual design process knowledge elements, $WK_{P\text{-}C}$ and $WK_{P\text{-}I}$, are represented as $WK_{P/C}$, '$WK_{P\text{-}C} \rightarrow WK_{P\text{-}A}$', '$WK_{P\text{-}I} \rightarrow WK_{P\text{-}A}$' can then be generalised as '$WK_{P/C} \rightarrow WK_{P\text{-}A}$'. The remaining eight main links could not be generalised and will be considered as the creation links of the coupling. Thus, the following 11 creation links of the coupling could be deduced from this group of creation links.

CL-P.8 : $WK_{P\text{-}A} \rightarrow DK_{A\text{-}G}$

CL-P.9 : $WK_{P\text{-}A} \rightarrow DK_{A/It}$

CL-P.10 : $WK_{P\text{-}A} \rightarrow WK_{A/F}$ (exclude $WK_{P\text{-}A} \rightarrow WK_{A\text{-}Bis}$)

CL-P.11 : $WK_{P\text{-}A} \rightarrow WK_{A\text{-}Rq}$

CL-P.12 : $WK_{P\text{-}A} \rightarrow WK_{P\text{-}G}$

CL-P.13 : $WK_{P\text{-}A} \rightarrow WK_{P\text{-}Out}$

CL-P.14 : $WK_{P\text{-}G} \rightarrow WK_{P\text{-}A}$

CL-P.15 : $WK_{P\text{-}G} \rightarrow WK_{P\text{-}G}$

CL-P.16 : $WK_{P/C} \rightarrow WK_{P\text{-}A}$

CL-P.17 : $WK_{P\text{-}C} \rightarrow WK_{P\text{-}I}$

CL-P.18 : $WK_{P\text{-}I} \rightarrow WK_{P\text{-}G}$

Employment links deduced from link of creation

As discussed in Chapter 6, in comparison to design activity, very few input and output were identified in the protocols, because most of them were encoded as artefact knowledge elements with higher priority. However, further analysis of the creation links between design activity and artefact knowledge elements identified in this section revealed that some of these artefact knowledge elements were employed as either the input or output of the design process. Hence a *link of employment* (a type of link that represents an employing relationship between two knowledge elements) could be deduced from some of the creation links. Knowledge element A employs B means B is used as A and is represented with 'A --● B' in this thesis. For example, in Session 11, segment 2, $WK_{A\text{-}Sis}$ "I set it to a height, cause of a height adjustment, and the hole can be drilled on site." caused a "Generating" activity, which caused the creation of $WK_{A\text{-}Se}$ "you could drill a hole and put a captive fitting onto it". It can be said that the $WK_{A\text{-}Sis}$ was employed as the input of the activity and the $WK_{A\text{-}Se}$ was employed as the output of the activity. Thus, two employment links '$WK_{P\text{-}In}$ --● $WK_{A\text{-}Se}$' and '$WK_{P\text{-}Out}$ --● $WK_{A\text{-}Sis}$' could be deduced. The discussions in the next three sections will show that the other three basic types of links could be deduced into employment links, in that the artefact knowledge elements were employed by or incorporated into design process knowledge elements.

Analysing the aforementioned creation links of the coupling between the activity and artefact knowledge, it was found that 'CL-P.1: $DK_{A} \rightarrow WK_{P\text{-}A}$' and 'CL-P.4: $WK_{A/F} \rightarrow WK_{P\text{-}A}$' could be deduced to two employment links: 'EL(Cr)-P.1: $WK_{P\text{-}In}$ ---● DK_{A}' and 'EL(Cr)-P.2: $WK_{P\text{-}In}$ ---● $WK_{A/F}$'. While EL represents link of employment and Cr (inside the bracket) means that this employment link was deduced from a creation link. In the same vein, 'CL-P.8: $WK_{P\text{-}A} \rightarrow DK_{A\text{-}G}$', 'CL-P.9: $WK_{P\text{-}A} \rightarrow DK_{A/It}$', 'CL-P.10: $WK_{P\text{-}A} \rightarrow WK_{A/F}$', and 'CL-P.11: $WK_{P\text{-}A} \rightarrow WK_{A\text{-}Rq}$' could be deduced into 'EL(Cr)-P.3: $WK_{P\text{-}Out}$ ---● $DK_{A\text{-}G}$', 'EL(Cr)-P.4: $WK_{P\text{-}Out}$ ---● $DK_{A/It}$', 'EL(Cr)-P.5: $WK_{P\text{-}Out}$ ---● $WK_{A/F}$', and 'EL(Cr)-P.6: $WK_{P\text{-}Out}$ ---● $WK_{A\text{-}Rq}$'. Similar to the $WK_{A/F}$ in links CL-P.4 and CL-P.10, the $WK_{A/F}$ does not include $WK_{A\text{-}Bis}$ in EL(Cr)-P.2 and EL(Cr)-P.5.

It was also discussed in Chapter 6 that causal relationships ($WK_{A\text{-}CR}$) were not uttered explicitly by designers in the analysed project. However, during the two interviews with the student designer, it was confirmed that $WK_{A\text{-}CR}$ was implicitly used as information resource in order to perform the activities that transformed artefact knowledge elements, such as requirements, function, behaviour, and structure. For example, while designers were trying to define a family of roadside furniture, including one that could remind road users of school nearby in Session 1, segment 7, the protocol "Their heights, their sizes, and things. They might be more physical. They might be more obvious, and that might turn signals to any road users" was encoded as including $WK_{A\text{-}Se}$ - "Their heights, their sizes and things, more physical", $WK_{A\text{-}Be}$ - "they might be more obvious", and $WK_{A\text{-}Fe}$ - "that might turn signals to any road users". In the meantime, one creation link was encoded to represent the transformation from expected behaviour and function to structure: '$WK_{P\text{-}A} \rightarrow WK_{A\text{-}Se}$'. Therefore, the dependency between expected function "turn signals to any road users" and expected behaviour of the furniture "(looks) more obvious" was the causal relationship used by designer during the creation of the expected structure. In this regard, the causal relationship was employed as the resource for the design activity. Hence an employment link 'EL(Cr)-P.7 $WK_{P\text{-}R}$ ---● $WK_{A\text{-}CR}$' could be deduced based on transformations among the artefact knowledge elements. Overall, seven employment links listed below were deduced from link of creation. These employment links will be discussed in Section 7.2.5 along with other employment links that were deduced from other three basic types of links presented in sections 7.2.2, 7.2.3, and 7.2.4.

EL(Cr)-P.1 : $WK_{P\text{-}In}$ ---● DK_A

EL(Cr)-P.2 : $WK_{P\text{-}In}$ ---● $WK_{A/F}$ (exclude $WK_{P\text{-}In}$ ---● $WK_{A\text{-}Bis}$)

EL(Cr)-P.3 : $WK_{P\text{-}Out}$ ---● $DK_{A\text{-}G}$

EL(Cr)-P.4 : $WK_{P\text{-}Out}$ ---● $DK_{A/It}$

EL(Cr)-P.5 : $WK_{P\text{-}Out}$ ---● $WK_{A/F}$ (exclude $WK_{P\text{-}Out}$ ---● $WK_{A\text{-}Bis}$)

EL(Cr)-P.6 : $WK_{P\text{-}Out}$ ---● $WK_{A\text{-}Rq}$

EL(Cr)-P.7 : $WK_{P\text{-}R}$ ---● $WK_{A\text{-}CR}$

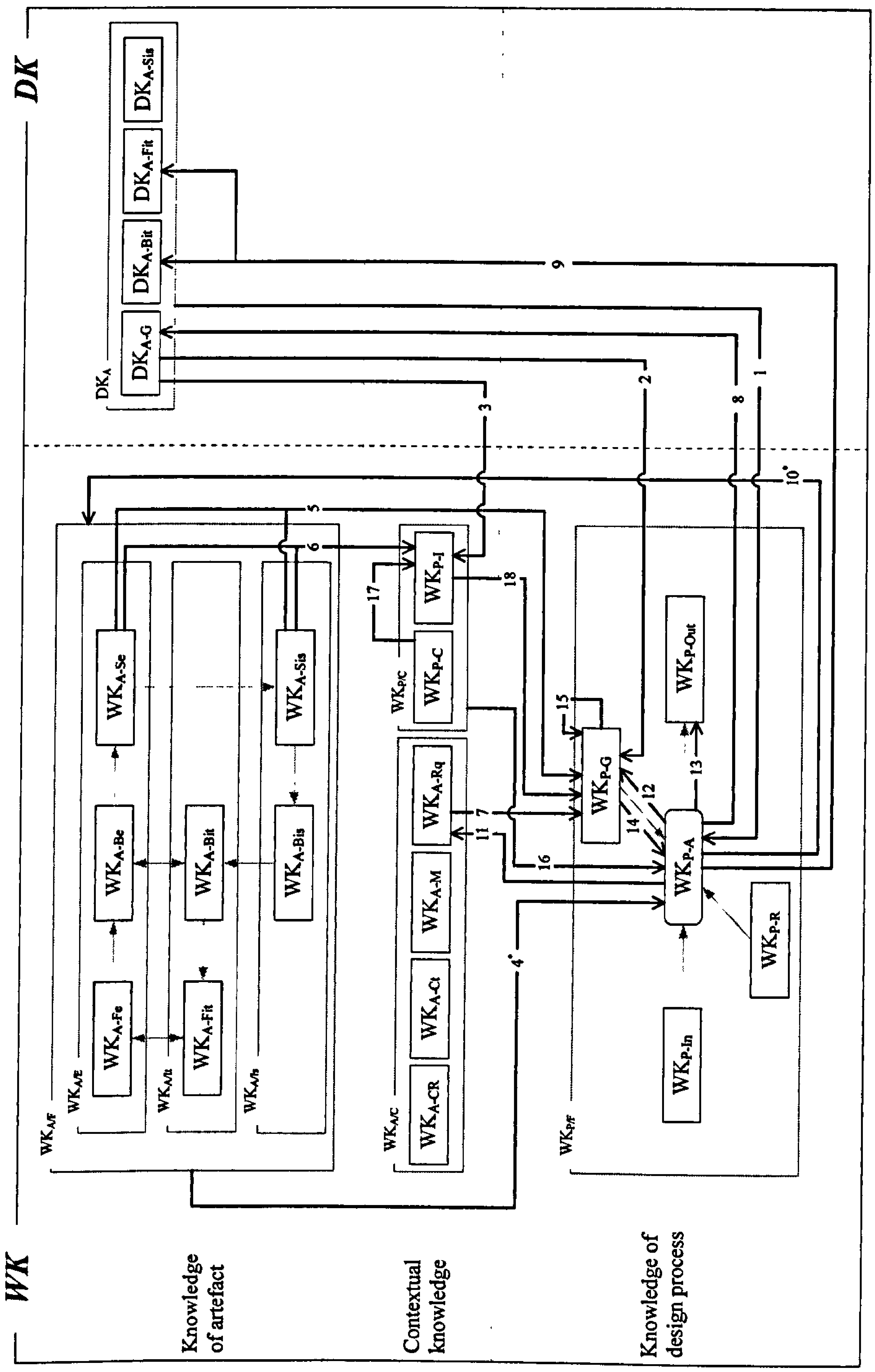
Creation links of the coupling deduced from link of creation: the key findings

Having identified the creation links of the coupling from the three groups of creation links, Table 7-2 summarises the numbers of links, main links, and links of the coupling identified within each group. It can be seen that of all the 51 identified creation links, 32 links were analysed and subsequently regarded as the main links. Following generalisation, 18 coupling links were deduced and considered as the creation links of the coupling. These links compose a main part of the coupling of the artefact and design process on the knowledge level.

Table 7-2: A summary of the links, main links, and links of the coupling identified across the three groups of creation links

Causing element of the group	Links	Main links	Links of the coupling
DK_A (Table D-1)	9	5	3 (CL-P.1–CL-P.3)
WK_A (Table D-1)	19	9	4 (CL-P.4–CL-P.7)
WK_P (Table D-1)	23	17	11 (CL-P.8–CL-P.18)
Total	**51**	**31**	**18**

These 18 creation links of the coupling are depicted in Figure 7-4 by using black open arrows. The links are marked by their sequence number without CL such as 1 and 2. As can be seen from the figure, the knowledge elements are categorised into five groups: fundamental current working knowledge of the artefact (*$WK_{A/F}$*) and design process (*$WK_{P/F}$*), contextual current working knowledge of the artefact (*$WK_{A/C}$*) and design process (*$WK_{P/C}$*), and domain knowledge of the artefact (*DK_A*). The light grey arrows in Figure 7-4 are the causal relationships of the artefact and the links of the design process discussed in Chapter 3.



* Links 4 and 10 do not include $WK_{A\text{-}Bis}$

Figure 7-4: Creation links of the coupling - based on the protocol analysis

7.2.2 Link of referral

During the protocol analysis, it was found that frequently, one knowledge element referred to another, though the latter was already created. For example, in the protocol "Would you like to include the tactile road studs, are they barriers? Yeah, they are. They are another sort of barriers for people who are visually impaired", an "Identifying" design activity referred domain artefact knowledge "tactile road studs is a barrier for the visually impaired", and this chunk of knowledge had already existed by the time the designer mentioned it. This type of relationship is termed ***link of referral*** in this thesis and is represented with diamond arrow. Thus, the referral link in the above example can be represented as '$WK_{P\text{-}A}$ —◆ $DK_{A\text{-}G}$'.

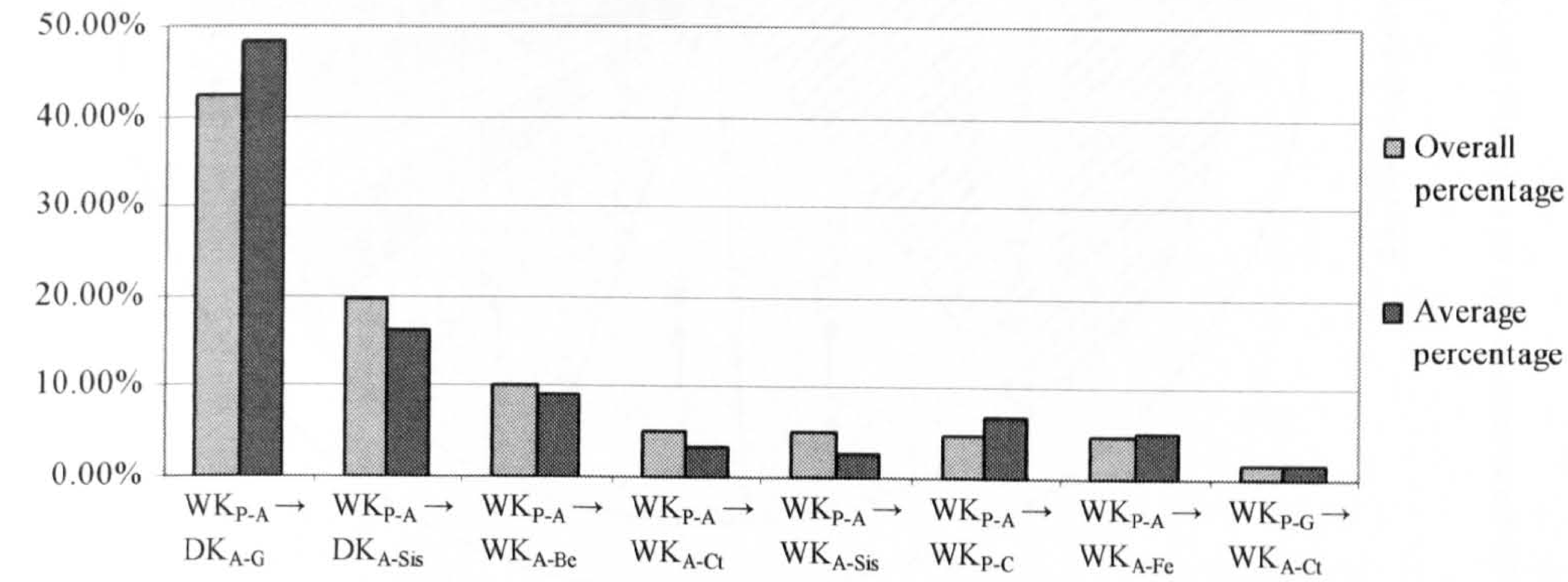
Table D-2 in Appendix D shows that as a result of the protocols analysis, 17 referral links were identified with a total of 175 occurrences. The upper half of the table shows the links' occurrence times over the 12 sessions (from row "Session 1" to "Session 12"), their total occurrence times during the 12 sessions (in the row "Sum"), and the overall percentages of the 17 links (in the row 'Overall %'). The lower half of the table shows the links' occurrence percentages within each session (from row "Session 1" to "Session 12") and their average percentages over the 12 sessions (in the row "Average %"). Due to the limitation of representing arrows in Excel, this type of link is represented with open arrow in Table D-2. However, except in this table and Table 7-3, this link has been represented with diamond arrow '—◆' during the protocol analysis (Wang 2008b) and throughout this thesis. In Table D-2, if element 'A' refers to 'B', the referral link between them is represented as 'A → B' in the second row of the table. The 11 grey columns marked main link analysis as seen in the next paragraph showed that 11 of them were identified as the main links (indicated by grey columns in Table D-2).

In order to identify the main links by using the aforementioned two methods, each link's overall occurrence times, as well as overall and average percentages over the 12 sessions are listed in Table 7-3, which lists the links in descending order by their overall percentages. A comparison between each link's overall and average percentages is depicted in Figure 7-5, which shows that the two methods resulted in similar percentage values of each link. Figure 7-6 depicts how the main links were identified by using the two methods. By using the overall percentage method, as can be seen in Figure 7-6.a, the higher nine links (highlighted in dark grey in Table 7-3) were identified as the main links because their total occurrence was 94.86% of the overall occurrence. Moreover, by using the average percentage method, as seen in Figure 7-6.b, the links were initially sorted in descending order by their average percentages (not the sequence listed in Table 7-3), and the higher nine links (highlighted in grey in Table 7-3) were then identified as the main links with a total of 94.86 % average percentage. Combining the main links identified through the two methods, 10 links were identified as the main creation links. Among them, eight were identified by using both methods. There was one link ('$WK_{P\text{-}I}$ —◆ $WK_{A\text{-}Sis}$') that was identified only by the overall percentage method and another link ('$WK_{P\text{-}A}$ —◆ $WK_{P\text{-}A}$') that was identified only by the average percentage method.

Table 7-3: Analysis of main referral links based on the protocol analysis

Referral links	$WK_{P-A} \rightarrow DK_{A-G}$	$WK_{P-A} \rightarrow DK_{A-Sis}$	$WK_{P-A} \rightarrow WK_{A-Be}$	$WK_{P-A} \rightarrow WK_{A-Ct}$	$WK_{P-A} \rightarrow WK_{A-Sis}$	$WK_{P-A} \rightarrow WK_{P-C}$	$WK_{P-A} \rightarrow WK_{A-Fe}$	$WK_{P-G} \rightarrow WK_{A-Ct}$	$WK_{P-I} \rightarrow WK_{A-Sis}$
Sum	74	34	18	9	9	8	8	3	3
Overall percentage	42.29%	19.43%	10.29%	5.14%	5.14%	4.57%	4.57%	1.71%	1.71%
Average percentage	48.39%	16.23%	9.15%	3.48%	2.86%	6.61%	5.20%	1.74%	1.10%

Referral links	$WK_{P-I} \rightarrow WK_{A-Ct}$	$WK_{P-A} \rightarrow WK_{A-Se}$	$WK_{P-G} \rightarrow WK_{A-M}$	$WK_{A-Se} \rightarrow WK_{P-C}$	$WK_{P-A} \rightarrow WK_{A-Rq}$	$WK_{P-I} \rightarrow WK_{A-Se}$	$WK_{P-I} \rightarrow WK_{P-R}$	$WK_{A-Se} \rightarrow WK_{P-G}$
Sum	2	1	1	1	1	1	1	1
Overall percentage	1.14%	0.57%	0.57%	0.57%	0.57%	0.57%	0.57%	0.57%
Average percentage	0.67%	1.19%	0.93%	0.93%	0.42%	0.42%	0.42%	0.27%



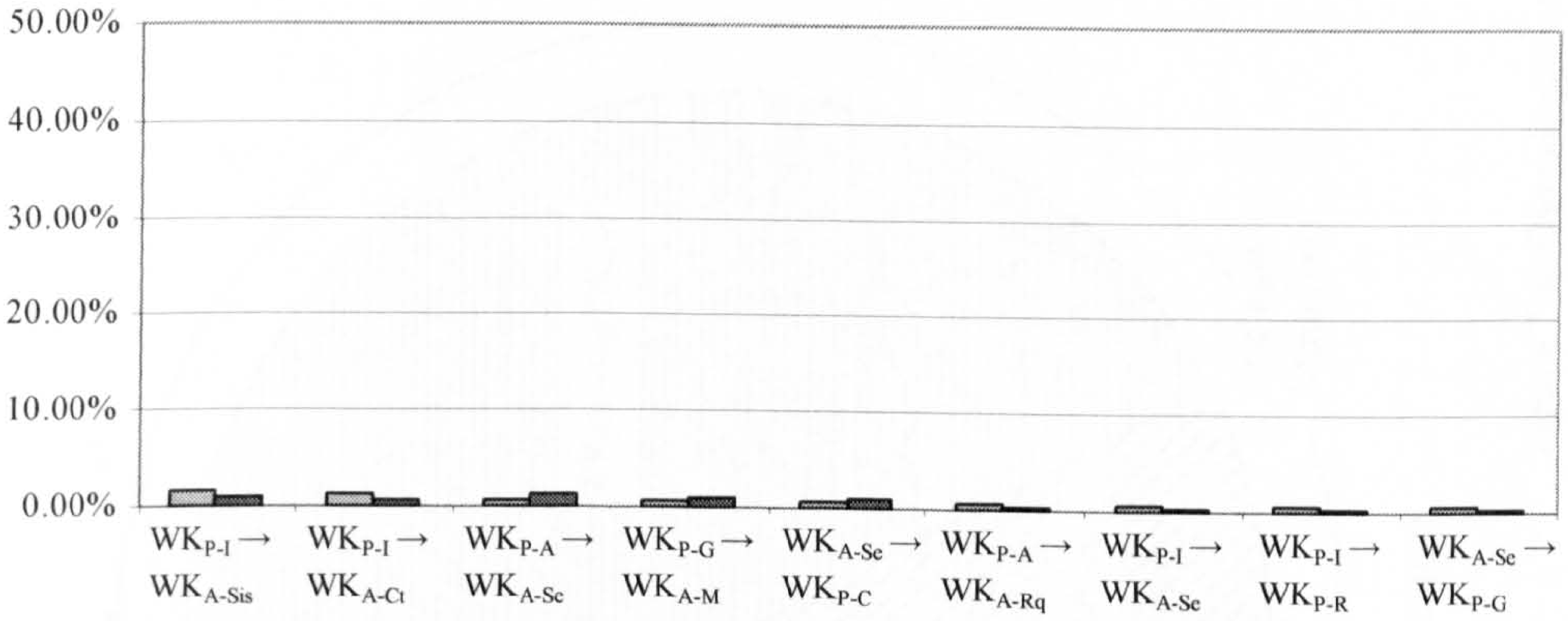


Figure 7-5: Comparison of overall and average percentage of referral links

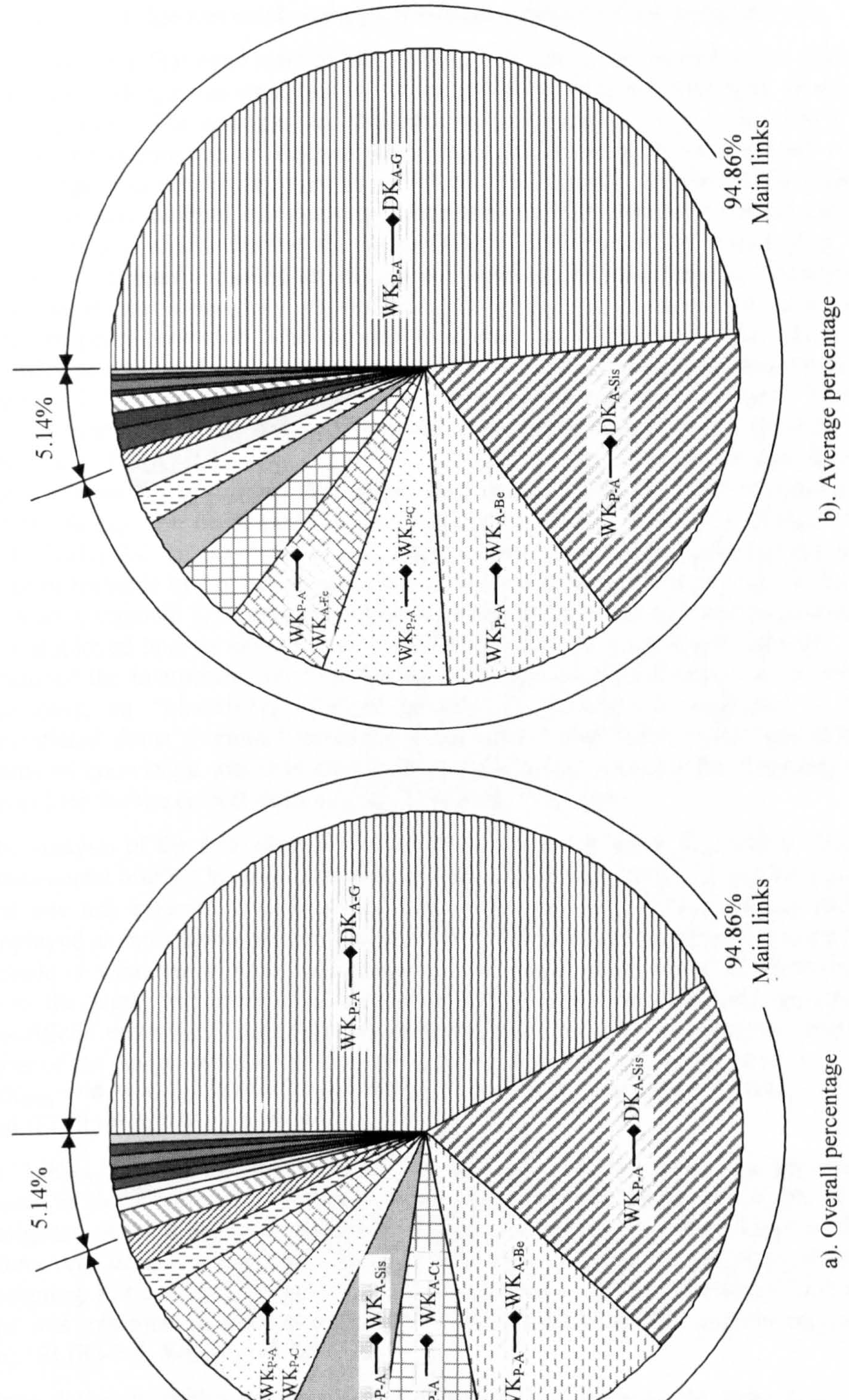


Figure 7-6: Overall and average percentage pie of referral links

As can be seen from Table 7-3, all the referring elements of the identified 10 main links were design process knowledge elements and their referred elements were all design artefact knowledge elements. Further analysis of the protocols (as will be explained in detail below) revealed that these 10 links could be deduced to ***link of employment***, in that the referred artefact knowledge was employed by knowledge elements of the design process.

Analysis of the first main referral link 'WK_{P-A} —◆ DK_{A-G}' revealed that the referred domain artefact knowledge was employed in the follow-up protocol as either input or resource of the design process. For example, an "Information gathering" activity in Session 3, segment 4 caused the occurrence of domain knowledge "Different sorts of barriers". The domain knowledge was employed as an ***input*** for an "Identifying" activity in the same segment, which, in turn, resulted in producing interpreted function "Barriers can actually stop. Like those you get, which absolve the impact (crash)". Moreover, an "Identifying" activity in Session 1, segment 2 caused the occurrence of the domain knowledge, "Roadside furniture describes at least somewhere, eh, bollards, pedestrian, crash barriers, etc. Roadside furniture includes permanent road furniture and temporary road furniture". This chunk of domain knowledge was used later as the ***resource*** for a "Decision making" activity in Session 2, segment 2, that decided the design to be "permanent roadside furniture". Therefore, two employment links can be deduced from these two referral links, i.e. 'EL(R)-P.1: WK_{P-In} --● DK_{A}' and 'EL(R)-P.2: WK_{P-R} --● DK_{A-G}'. EL(R)-P here means the ***link of employment*** deduced from ***link of referral*** through protocol analysis. In a similar vein, referral link 'WK_{P-A} —◆ DK_{A-Sis}' can be deduced to two employment links 'EL(R)-P.3: WK_{P-In} --● DK_{A-Sis}' and 'EL(R)-P.4: WK_{P-R} --● DK_{A-Sis}' because the referred DK_{A-Sis} was employed as either input or resource in the follow-up protocol. For example, an "Identifying" design activity in Session 3, segment 7, referred to domain knowledge "painted lines on the pavement", which was employed later as ***input*** for an "Identifying" activity in the same segment. The activity produced the interpreted function "do not step beyond the red line, you go wrong there". Moreover, an "Identifying" design activity, in Session 11, segment 11, referred to instantiated domain artefact structural knowledge "smart kerb, which has slots in". This chunk of knowledge was then employed as information ***resource*** for designing one type of smart kerb for the current design in the consecutive segment.

The analysis of the following four main referral links in Table 7-3, which referred to four fundamental artefact knowledge elements, WK_{A-Be}, WK_{A-Fe}, WK_{A-Se}, and WK_{A-Sis} by WK_{P-A}, and one link referred to WK_{A-Sis} by WK_{P-I}, showed that the four artefact elements were employed as input knowledge in the protocols. For example, expected behaviour "if a car or vehicle or whatever hits the actual barrier,... it would break, shear or whatever the barrier from the legs" was mentioned following the activity that generated expected structure "sacrificial material". This chunk of expected behavioural knowledge was employed as an ***input*** of the design process. Hence, four employment links can be deduced, i.e., 'EL(R)-P.5: WK_{P-In} --● WK_{A-Be}', 'EL(R)-P.6: WK_{P-In} --● WK_{A-Fe}', 'EL(R)-P.7: WK_{P-In} --● WK_{A-Se}', and 'EL(R)-P.8: WK_{P-In} --● WK_{A-Sis}'.

In 'WK_{P-A} —◆ WK_{A-Ct}' and 'WK_{P-G} —◆ WK_{A-Ct}', design activity and goal were seen to result in the occurrence of design constraints. As mentioned in the previous chapter, designers did not seem to explicitly discuss constraints so frequently in this project. Moreover, design constraints were mainly employed as information resource during designing. For example, "poles have to be inserted in a specific orientation" was a constraint that was subsequently used as a resource. This in turn resulted in another employment link, i.e., 'EL(R)-P.9: WK_{P-R} --● WK_{A-Ct}'.

Since design activities are carried out within design context, the main link 'WK_{P-A} —◆ WK_{P-C}', representing a referral to context by activity, could imply that designers mentioned the context during designing. This was represented by the design process model discussed in Chapter 3, hence no employment link was deduced from this link.

Overall, the 18 referral links referred by the design process knowledge elements can be deduced to the following nine employment links:

EL(R)-P.1 : $WK_{P\text{-}In}$ --● $DK_{A\text{-}G}$

EL(R)-P.2 : $WK_{P\text{-}R}$ --● $DK_{A\text{-}G}$

EL(R)-P.3 : $WK_{P\text{-}In}$ --● $DK_{A\text{-}Sis}$

EL(R)-P.4 : $WK_{P\text{-}R}$ --● $DK_{A\text{-}Sis}$

EL(R)-P.5 : $WK_{P\text{-}In}$ --● $WK_{A\text{-}Be}$

EL(R)-P.6 : $WK_{P\text{-}In}$ --● $WK_{A\text{-}Fe}$

EL(R)-P.7 : $WK_{P\text{-}In}$ --● $WK_{A\text{-}Se}$

EL(R)-P.8 : $WK_{P\text{-}In}$ --● $WK_{A\text{-}Sis}$

EL(R)-P.9 : $WK_{P\text{-}R}$ --● $WK_{A\text{-}Ct}$

7.2.3 Link of usage

When a knowledge element uses another element, it implies that a *link of usage* exists between them. For example, within the following protocol "I brainstormed the concept of roadside furniture by exploring what is in the world to separate the different areas of space. ... I concluded that there are six main functions of barrier to either detect, control, contain, protect, inform or warn.", domain artefact knowledge ($DK_{A\text{-}G}$) "concept of roadside furniture" was used by an "Analysing/interpreting" activity ($WK_{P\text{-}A}$) that deduced domain artefact interpreted function "there are six main functions of barrier". Thus, it can be said that the usage link '$WK_{P\text{-}A}$ ◆—● $DK_{A\text{-}G}$' existed between the two elements.

As a result of protocol analysis, 11 usage links were identified with 70 occurrences. Their occurrence times and percentage within each session are listed in Table D-3, Appendix D. The upper half of the table shows the links' occurrence times over the 12 sessions (from row "Session 1" to "Session 12"), their total occurrence times over the 12 sessions (in the row 'Sum'), and their overall percentages of all the 11 links (in the row "Overall %"). The lower half of the table shows the links' occurrence percentages within each session (from row "Session 1" to "Session 12") and their average percentages of the 12 sessions (in the row "Average %"). Due to the limitation of representing arrows in Excel, this type of link is represented with open arrow in the table. With the exception of Table D-3 and Table 7-4, this link, however, is represented with oval and diamond arrow '◆—●' throughout this thesis as well as in the protocol analysis (Wang 2008b). In Table D-3 and Table 7-4, if element 'A' uses 'B', the link of usage between them is represented as 'A → B'.

By using the overall and average percentage methods (explained in the next paragraph), 10 links were identified as the main links, which are highlighted in grey in Table D-3. To identify the main usage links, Table 7-4 lists all the usage links in descending order by their overall percentages. A comparison between the overall and average percentages of each link is depicted in Figure 7-7. In comparison to the creation and referral links, it was found that, the difference between the overall and the average percentage of some usage links is more obvious. For example, based on the average percentage method, the link with lowest overall percentage (1.52%) takes the fourth place with average percentage of 5.00%. This was mainly due to the low occurrence of this type of link, which could cause a link to have a high percentage but with very few links in a session.

In order to show how the main links were identified, Figure 7-8 illustrates the overall and average percentage pies of the usage links. By using the overall percentage method, as can be seen in Figure 7-8.a, the higher eight links (highlighted in dark grey in Table 7-4) were identified as the main links because their total occurrence was 94.29% of the overall occurrence. Moreover, by using the average percentage method as seen in Figure 7-8.b, following descending the links by their average percentages (not the sequence listed in Table 7-4), the higher seven links (highlighted in grey in Table 7-4) were identified as the main links with the sum of 94.72 % average percentages. Combining the main links identified from both methods, nine links were identified as the main usage links. It can be seen from Table 7-4 that there were six main links were identified by using both methods. In addition, there were two (WK_{P-A} ♦—● WK_{A-Sis} and WK_{P-A} ♦—● WK_{A-Ct}) links were identified only by the overall percentage method, and one (WK_{P-A} ♦—● DK_{A-Fit}) was identified only by the average percentage method.

Table 7-4: Analysis of main usage links based on the protocol analysis

Using links	WK_{P-A} → DK_{A-G}	WK_{P-A} → WK_{P-R}	WK_{P-A} → WK_{A-Be}	WK_{P-A} → DK_{A-Sis}	WK_{P-A} → WK_{A-Fe}	WK_{P-A} → WK_{A-Sis}	WK_{P-A} → WK_{A-Se}	WK_{P-A} → WK_{A-Ct}	WK_{P-A} → WK_{A-Bit}	WK_{P-A} → DK_{A-Fit}	WK_{P-A} → DK_{A-Bit}
Sum	18	14	9	8	6	5	3	3	2	1	1
Overall percentage	25.71%	20.00%	12.86%	11.43%	8.57%	7.14%	4.29%	4.29%	2.86%	1.43%	1.43%
Average percentage	38.56%	28.67%	5.56%	6.39%	6.94%	1.39%	3.61%	0.83%	0.56%	5.00%	2.50%

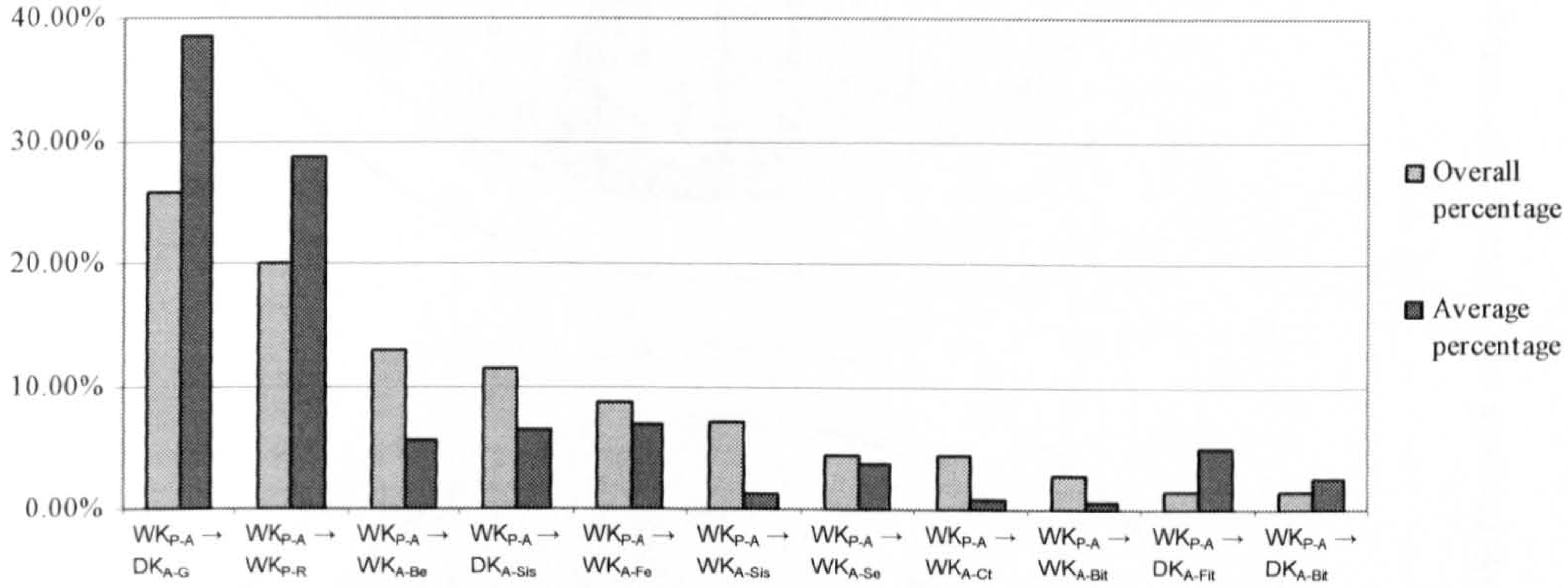


Figure 7-7: Comparison of overall and average percentage of usage links

a). Overall percentage

b). Average percentage

Figure 7-8: Overall and average percentage pie of usage links

As can be seen from Table 7-4, all the 10 main usage links have design activity as their using elements, and DK_A, WK_A, and WK_{P-R} as their used elements. Further analysis revealed that these usage links could also be deduced to employment links, in that the artefact knowledge was employed as either input or resource of the design process.

Specifically, the analysis of the links that used domain artefact general knowledge by activity (WK_{P-A} ◆—● DK_{A-G}) showed that DK_{A-G} was employed as either input or resource of the design process. For example, when domain knowledge "different types of barriers" was used by an "Identifying" activity, "The things that are aesthetic, eye, hearing, sight, touch. That might be to do with the wind. They protect you from something, barriers are protective", in Session 3, segment 6, it can be explained that, first, the activity produced an interpreted function of barriers, and second, to produce the interpreted function, the domain knowledge was employed as an *input* for the activity. Therefore, an employment link 'EL(U)-P.1: WK_{P-In} --● DK_{A-G}' can be deduced. EL(U)-P refers to the *link of employment* deduced from *link of usage* through protocol analysis. In addition, when domain knowledge "a range of physical divisions: barriers, bollards, higher kerbs" was used by a "Decision making" activity in Session 2, segment 1, "to look at it in a wider context first before I focused on barriers", two points can be concluded: first, design artefact was decided to be a barrier, and second, the domain knowledge was employed as a *resource* by this activity. Hence another employment link 'EL(U)-P.2: WK_{P-R} --● DK_{A-G}' can be deduced from this usage link. Moreover the following two usage links 'WK_{P-A} ◆—● DK_{A-Bit}' and 'WK_{P-A} ◆—● DK_{A-Fit}' can be deduced to 'EL(U)-P.3: WK_{P-In} --● DK_{A-Bit}' and 'EL(U)-P.4: WK_{P-In} --● DK_{A-Fit}', as the analysis shows that the interpreted behaviour and function were employed as an input of the activity. For example, in the protocol "Children can, would actually climb and sit on it and go through it. So, it's a kind of advisory or reminder thing that cars want out and children the other.", DK_{A-Bit} "Children can, would actually climb and sit on it and go through it" was used by an "Interpreting" activity, which produced an interpreted function "it's a kind of advisory or reminder thing" in Session 6, segment 2. This usage link could therefore be deduced to 'WK_{P-In} --● DK_{A-Bit}' because the interpreted behaviour was employed as the input of the activity. Similarly, the usage link 'WK_{P-A} ◆—● DK_{A-Sis}' can be deduced to 'EL(U)-P.5: WK_{P-In} --● DK_{A-Sis}', because analysis of the seven instances of this link (in sessions 10 and 12) revealed that DK_{A-Sis} was employed as input of each design activity. For example, structural knowledge "...emergency barriers. They've got a hook on one side and eye on the other" was employed as an input for an "Interpreting" activity producing interpreted function, "that allows them to have huge flexibility" in Session 12, segment 7.

There are four main links in Table 7-4 show that four fundamental artefact current working knowledge elements (WK_{A-Be}, WK_{A-Fe}, WK_{A-Se}, and WK_{A-Sis}) were used by design activity. It was also found that the four elements were employed as inputs of design activities. For instance, WK_{A-Be} - "move it around" was employed as an *input* by a "Generating" activity producing an expected structure "a slot at the bottom, a bolt going across it, a rawl bolt underneath, slide the pole on top of that" in Session 10, segment 21. Therefore, four employment links 'EL(U)-P.6: WK_{P-In} --● WK_{A-Be}', 'EL(U)-P.7: WK_{P-In} --● WK_{A-Fe}', 'EL(U)-P.8: WK_{P-In} --● WK_{A-Se}', and 'EL(U).9: WK_{P-In} --● WK_{A-Sis}' could be deduced from these four usage links.

Further analysis of link 'WK_{P-A} ◆—● WK_{A-Ct}', showed that the constraints were used as information resource during the design process. For example, constraint "you can't have springs and hinges for a long period of time in the ground" was used by a "Decision making" activity "I decided not to make it too complicated" in a sense that it was employed as a resource by the activity. Thus the link 'EL(U)-P.10: WK_{P-R} --● WK_{A-Ct}' can be deduced accordingly.

Finally, the usage link 'WK_{P-A} ◆—● WK_{A-R}' indicates that resource was used by design activity, which was represented by the process model introduced in Chapter 3, meaning that no employment link will be deduced from it. Overall, the following 10 employment links were deduced from the 10 main usage links. These employment links will be discussed further in Section 7.2.5 along with other employment links.

EL(U)-P.1 : $WK_{P\text{-}In}$ --● $DK_{A\text{-}G}$

EL(U)-P.2 : $WK_{P\text{-}R}$ --● $DK_{A\text{-}G}$

EL(U)-P.3 : $WK_{P\text{-}In}$ --● $DK_{A\text{-}Bit}$

EL(U)-P.4 : $WK_{P\text{-}In}$ --● $DK_{A\text{-}Fit}$

EL(U)-P.5 : $WK_{P\text{-}In}$ --● $DK_{A\text{-}Sis}$

EL(U)-P.6 : $WK_{P\text{-}In}$ --● $WK_{A\text{-}Be}$

EL(U)-P.7 : $WK_{P\text{-}In}$ --● $WK_{A\text{-}Fe}$

EL(U)-P.8 : $WK_{P\text{-}In}$ --● $WK_{A\text{-}Se}$

EL(U)-P.9 : $WK_{P\text{-}In}$ --● $WK_{A\text{-}Sis}$

EL(U)-P.10 : $WK_{P\text{-}R}$ --● $WK_{A\text{-}Ct}$

7.2.4 Link of containment

The last type of link identified from the protocols is *link of containment*, which is the link between two knowledge elements if one contains the other. For example, the design goal "to define the context by including a roadside furniture family with different functions" contained a domain artefact knowledge element "roadside furniture family". If element A contains B, it is represented as 'A ←● B' in this thesis. Hence a containment link '$WK_{P\text{-}G}$ ←● $DK_{A\text{-}G}$' existed in the above example.

Table D-4 in Appendix D lists the eight containment links identified through the protocol analysis. The upper half of the table shows the links' occurrence times over the 12 sessions (from row "Session 1" to "Session 12"), their total occurrence times over the 12 sessions (in the row "Sum"), and their overall percentages of all the 31 occurrences (in the row "Overall %"). The lower half of the table shows the links' occurrence percentages within each session (from row "Session 1" to "Session 12") and their average percentages over the 12 sessions (in the row "Average %"). Due to the limitation of representing arrows in Excel, this type of link is represented with open arrow in the table (that is if element 'A' contains 'B', it is represented as 'A → B'). This link, however, is represented with oval arrow '←●' throughout this thesis as well as in the protocol analysis of the design project (Wang 2008b).

As can be seen in Table D-4, there were only 31 occurrences of this type of link. Three links occurred only once with an overall percentage of 3.23%. As a result, all of the eight containment links were considered as main links and therefore no another table with descending ordered links and percentage pies was needed to identify the main links.

As Table D-4 shows, the containing elements of these eight links are all design process knowledge elements, which include design goal, resource, and context. Moreover, all of the contained elements are artefact knowledge elements, which include domain artefact knowledge, current working functional, behavioural, and structural knowledge. This type of link can be deduced directly to *link of employment* because the artefact knowledge that contained in these design process knowledge elements implies that the artefact knowledge was being employed by these design process elements.

Specifically, the analysis showed that the link '$WK_{P\text{-}G}$ ←● $DK_{A\text{-}G}$' happened in the course of understanding the barrier by the designers. For example, the goal "to define the context by including a roadside furniture family with different functions" contained domain artefact general knowledge "a roadside furniture family with different functions". This link indicated that domain artefact general knowledge was employed in the design goal. Therefore, an employment link 'EL(C)-P.1: WK_{P-G} --● DK_{A-G}' could be deduced. EL(C)-P means it is an employment link deduced from containment link through protocol analysis. Further analysis of the three containment links of 'WK_{P-G} ←● WK_{A-Be}', 'WK_{P-G} ←● WK_{A-Fe}', and 'WK_{P-G} ←● WK_{A-Se}' also revealed that expected artefact knowledge elements were employed in design goal by design activity. These three containment links could therefore be generalised into one employment link 'EL(C)-P.2: WK_{P-G} ---● $WK_{A/E}$'.

The next containment link 'WK_{P-R} ←● DK_{A-G}' could be deduced to 'EL(C)-P.3: WK_{P-R} --● DK_{A-G}', which indicated that domain artefact general knowledge was employed as resources of design process.

The remaining two containment links 'WK_{P-C} ←● DK_{A-G}' and 'WK_{P-C} ←● WK_{A-Se}' indicated that the context contained both the domain artefact general as well as current working artefact structural knowledge. As discussed in Chapter 6, context includes factors that affect the current design. Through the two interviews with the student designer while analysing the protocols, it was found that while these factors were often considered by designers, they were not explicitly mentioned in the project. Since the factors affecting the current design could include all the knowledge elements of the artefact and design process, the design context is considered to include the domain and current working knowledge of the artefact and design process. Thus, three containment links 'WK_{P-C} ←● DK_A', 'WK_{P-C} ←● WK_A', and 'WK_{P-C} ←● WK_P' could be deduced. Similarly, these three containment links could be deduced to employment links in that DK_A, WK_A, and WK_P were employed in the design context of design process. These three employment links were represented as 'EL(C)-P.4: WK_{P-C} ---● DK_A', 'EL(C)-P.5: WK_{P-C} ---● WK_A', and 'EL(C)-P.6: WK_{P-C} ---● WK_P'.

Overall, the following six employment links have been deduced from the *link of containment*:

EL(C)-P.1 : WK_{P-G} ---● DK_{A-G}

EL(C)-P.2 : WK_{P-G} ---● $WK_{A/E}$

EL(C)-P.3 : WK_{P-R} --● DK_{A-G}

EL(C)-P.4 : WK_{P-C} ---● DK_A

EL(C)-P.5 : WK_{P-C} ---● WK_A

EL(C)-P.6 : WK_{P-C} ---● WK_P

7.2.5 Link of employment

In the light of similarity among the following links and the fact that some of these links are composed of others, they all can be generalised into the employment links of the coupling: the six employment links deduced from link of creation in Section 7.2.1, the nine deduced links from *link of referral* in Section 7.2.2, the ten deduced links from *link of usage* in Section 7.2.3, and the six deduced links from *link of containment* in Section 7.2.4. This section explains how these employment links are generalised into the employment links of the coupling, which are identified by Roman numerals following EL, such as EL.i.

Links employed by WK_{P-G}

Employed by WK_{P-G}, the two employment links EL(C)-P.1 and EL(C)-P.2, which were deduced in 7.2.4, are considered as two employment links of the coupling and are identified by **EL-P.i** WK_{P-G} ---● DK_{A-G} and **EL-P.ii** WK_{P-G} ---● $WK_{A/E}$.

Links employed by $WK_{P\text{-}In}$

The following employment links were identified in the previous four sections with domain artefact knowledge as their employed elements:

- EL(Cr)-P.1 : $WK_{P\text{-}In}$ ---● DK_A identified in Section 7.2.1,
- EL(R)-P.1 : $WK_{P\text{-}In}$ ---● $DK_{A\text{-}G}$ identified in Section 7.2.2,
- EL(R)-P.3 : $WK_{P\text{-}In}$ ---● $DK_{A\text{-}Sis}$ identified in Section 7.2.2,
- EL(U)-P.1 : $WK_{P\text{-}In}$ ---● $DK_{A\text{-}G}$ identified in Section 7.2.3,
- EL(U)-P.3 : $WK_{P\text{-}In}$ ---● $DK_{A\text{-}Bit}$ identified in Section 7.2.3,
- EL(U)-P.4 : $WK_{P\text{-}In}$ ---● $DK_{A\text{-}Fit}$ identified in Section 7.2.3, and
- EL(U)-P.5 : $WK_{P\text{-}In}$ ---● $DK_{A\text{-}Sis}$ identified in Section 7.2.3.

Further analysis of the above seven links showed that they all could be generalised into the first one, because DK_A covers the domain artefact knowledge elements of the other six links. Hence **EL-P.iii** $WK_{P\text{-}In}$ ---● DK_A was generalised as an employment link of the coupling.

For the following employment links with current working artefact knowledge are regarded as employed elements:

- EL(Cr)-P.2 : $WK_{P\text{-}In}$ ---● $WK_{A/F}$ identified in Section 7.2.1,
- EL(R)-P.5 : $WK_{P\text{-}In}$ ---● $WK_{A\text{-}Be}$ identified in Section 7.2.2,
- EL(R)-P.6 : $WK_{P\text{-}In}$ ---● $WK_{A\text{-}Fe}$ identified in Section 7.2.2,
- EL(R)-P.7 : $WK_{P\text{-}In}$ ---● $WK_{A\text{-}Se}$ identified in Section 7.2.2,
- EL(R)-P.8 : $WK_{P\text{-}In}$ ---● $WK_{A\text{-}Sis}$ identified in Section 7.2.2,
- EL(U)-P.6 : $WK_{P\text{-}In}$ ---● $WK_{A\text{-}Be}$ identified in Section 7.2.3,
- EL(U)-P.7 : $WK_{P\text{-}In}$ ---● $WK_{A\text{-}Fe}$ identified in Section 7.2.3,
- EL(U)-P.8 : $WK_{P\text{-}In}$ ---● $WK_{A\text{-}Se}$ identified in Section 7.2.3, and
- EL(U)-P.9 : $WK_{P\text{-}In}$ ---● $WK_{A\text{-}Sis}$ identified in Section 7.2.3.

It was also found that the above nine links could be generalised into the first one, because $WK_{A/F}$ covers the current working artefact knowledge elements of the other eight links. Hence **EL-P.iv** $WK_{P\text{-}In}$ ---● $WK_{A/F}$ was generalised as another employment link of the coupling.

Links employed by $WK_{P\text{-}Out}$

The four employment links identified in Section 7.2.1 (EL(Cr)-P.3, EL(Cr)-P.4, EL(Cr)-P.5, and EL(Cr)-P.6) employed by $WK_{P\text{-}Out}$ could be considered as **EL-P.v** $WK_{P\text{-}Out}$ ---● $DK_{A\text{-}G}$, **EL-P.vi** $WK_{P\text{-}Out}$ ---● $DK_{A/It}$, **EL-P.vii** $WK_{P\text{-}Out}$ ---● $WK_{A/F}$, and **EL-P.viii** $WK_{P\text{-}Out}$ ---● $WK_{A\text{-}Rq}$, because no other links employed by $WK_{P\text{-}Out}$ were identified.

Links employed by $WK_{P\text{-}R}$

In a similar vein, the three same links, EL(R)-P.2 in Section 7.2.2, EL(U)-P.2 in Section 7.2.3, and EL(C)-P.3 in Section 7.2.4, were combined as **EL-P.ix** $WK_{P\text{-}R}$ ---● $DK_{A\text{-}G}$. The employment link EL(R)-P.4 deduced in Section 7.2.2 was identified as **EL-P.x** $WK_{P\text{-}R}$ ---● $DK_{A\text{-}Sis}$ and EL(Cr)-P.7 in Section 7.2.1 was identified as **EL-P.xi** $WK_{P\text{-}R}$ ---● $WK_{A\text{-}CR}$. In addition, the two same employment links, EL(R)-P.9 deduced in Section 7.2.2 and EL(U)-P.10 deduced in Section 7.2.3, were identified as **EL-P.xii** $WK_{P\text{-}R}$ ---● $WK_{A\text{-}Ct}$.

Links employed by $WK_{P\text{-}C}$

Finally, the three employment links, EL(C)-P.4, EL(C)-P.5, and EL(C)-P.6 identified in Section 7.2.4, were considered as three employment links of the coupling employed by the design context, i.e., **EL-P.xiii** $WK_{P\text{-}C}$ ---● DK_A, **EL-P.xiv** $WK_{P\text{-}C}$ ---● WK_A, and **EL-P.xv** $WK_{P\text{-}C}$ ---● WK_P.

Employment links of the coupling: Key findings

Overall, the following 15 links were regarded as the employment links of the coupling, which were deduced from the main creation, referral, usage, and containment links. EL-P represents employment link obtained from protocol analysis.

EL-P.i : $WK_{P\text{-}G}$ ---● $DK_{A\text{-}G}$

EL-P.ii : $WK_{P\text{-}G}$ ---● $WK_{A/E}$

EL-P.iii : $WK_{P\text{-}In}$ ---● DK_A

EL-P.iv : $WK_{P\text{-}In}$ ---● $WK_{A/F}$ (exclude $WK_{P\text{-}In}$ ---● $WK_{A\text{-}Bis}$)

EL-P.v : $WK_{P\text{-}Out}$ ---● $DK_{A\text{-}G}$

EL-P.vi : $WK_{P\text{-}Out}$ ---● $DK_{A/It}$

EL-P.vii : $WK_{P\text{-}Out}$ ---● $WK_{A/F}$ (exclude $WK_{P\text{-}Out}$ ---● $WK_{A\text{-}Bis}$)

EL-P.viii : $WK_{P\text{-}Out}$ ---● $WK_{A\text{-}Rq}$

EL-P.ix : $WK_{P\text{-}R}$ ---● $DK_{A\text{-}G}$

EL-P.x : $WK_{P\text{-}R}$ ---● $DK_{A\text{-}Sis}$

EL-P.xi : $WK_{P\text{-}R}$ ---● $WK_{A\text{-}CR}$

EL-P.xii : $WK_{P\text{-}R}$ ---● $WK_{A\text{-}Ct}$

EL-P.xiii : $WK_{P\text{-}C}$ ---● DK_A

EL-P.xiv : $WK_{P\text{-}C}$ ---● WK_A (include $WK_{A/F}$ and $WK_{A/C}$)

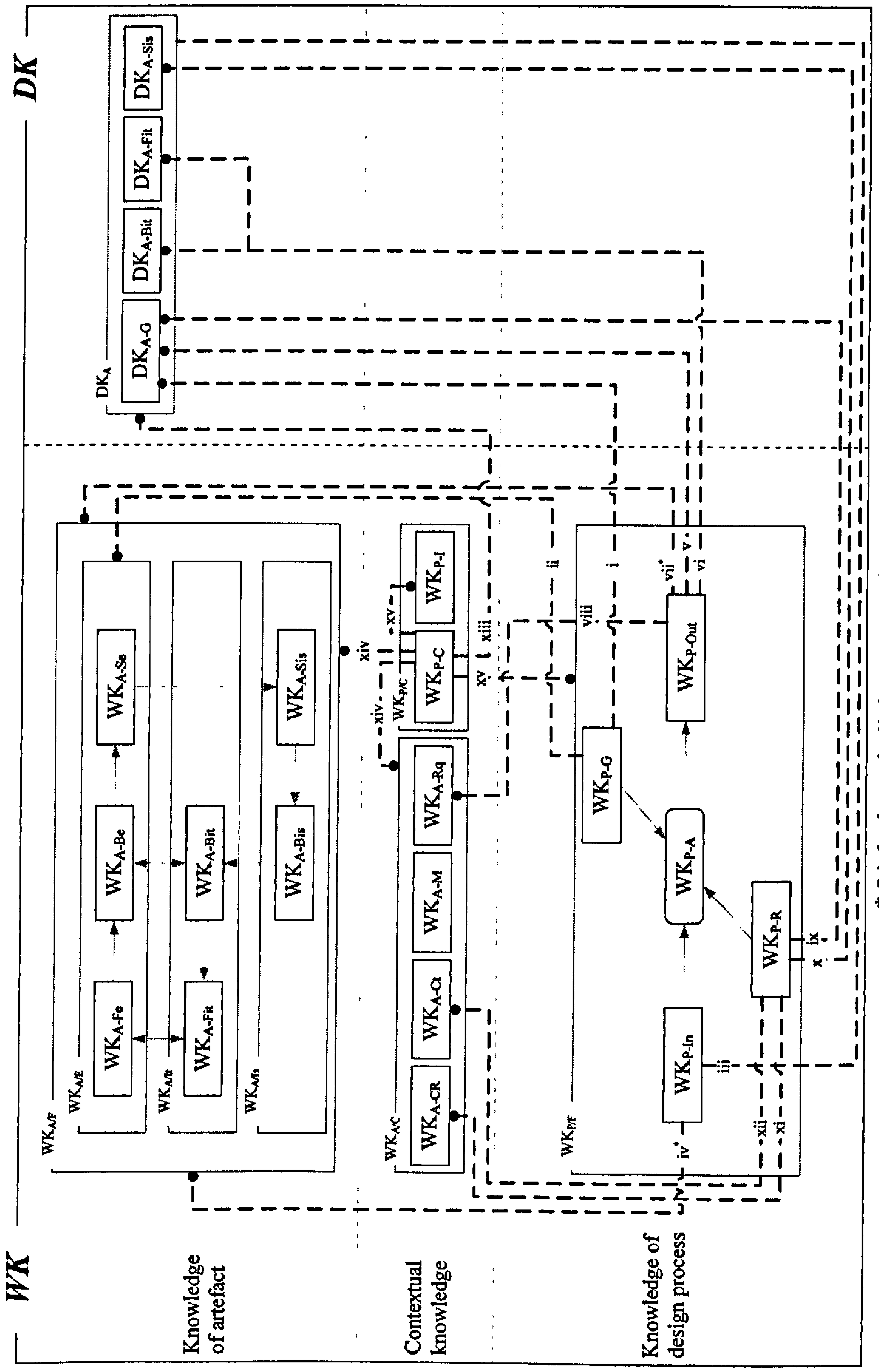
EL-P.xv : $WK_{P\text{-}C}$ ---● WK_P (include $WK_{P/F}$ and $WK_{P/C}$)

As a result of the above analysis of employment links of the coupling based on the four basic types of links, Table 7-5 summarises the numbers of identified different types of links, by listing the number of links, main links, and deduced employment links from link of creation, referral, usage, and containment in the 2nd, 3rd, and 4th columns. Altogether, 15 employment links of the coupling were generalised from the 31 deduced employment links.

Table 7-5: A summary of deduced employment links based on the protocol analysis

	Links	Main links	Deduced employment links	Generalised employment links of the coupling
Link of creation (Table 7-1)	51	31	7 EL(Cr)-P.1 – EL(Cr)-P.7	15
Link of referral (Table 7-3)	17	10	9 EL(R)-P.1 – EL(R)-P.9	
Link of usage (Table 7-4)	11	10	10 EL(U)-P.1 – EL(U)-P.10	
Link of containment (Table D-4)	7	7	6 EL(C)-P.1 – EL(C)-P.6	
Total	**86**	**58**	**31**	**15**

The 15 employment links of the coupling, which constitute another main part of the coupling of the artefact and design process knowledge, are depicted in Figure 7-9 by dashed oval arrows. The links are identified by their sequence letters without EL-P, such as 'i' and 'ii'.



* Links iv and vii do not contain $WK_{A\text{-}Bis}$

Figure 7-9: Employment links of the coupling - based on the protocol analysis

7.3 EVOLVED COUPLING MODEL

After creation links of the coupling from the protocol analysis were identified, they were combined with those identified from the content analysis. This resulted in the 19 creation links of the coupling, which are listed in the first column of Table 7-6. The links are identified with 'CL.' followed with Roman numerals. The combination process mainly accommodates the results obtained from both methods. Links, identified from both methods (eg. CL.4 and CL.11) or only one of them (eg. CL.1 and CL.2), are included in the final list. In addition, if links identified from one method are generalised links of those from another method, the generalised links that are highlighted in grey background in the table are included in the final list (eg. CL.10 and CL.12).

Table 7-6: Creation links of the coupling model

Creation links of the coupling	Content analysis	Protocol analysis
CL.1 : $DK_A \rightarrow WK_{P-A}$		CL-P.1 : $DK_A \rightarrow WK_{P-A}$
CL.2 : $DK_{A-G} \rightarrow WK_{P-G}$		CL-P.2 : $DK_{A-G} \rightarrow WK_{P-G}$
CL.3 : $DK_{A-G} \rightarrow WK_{P-I}$		CL-P.3 : $DK_{A-G} \rightarrow WK_{P-I}$
CL.4 : $WK_{A/F} \rightarrow WK_{P-A}$ (exclude $WK_{A-Bis} \rightarrow WK_{P-A}$)	CL-C.1: $WK_{A/F} \rightarrow WK_{P-A}$ (exclude $WK_{A-Bis} \rightarrow WK_{P-A}$)	CL-P.4 : $WK_{A/F} \rightarrow WK_{P-A}$ (exclude $WK_{A-Bis} \rightarrow WK_{P-A}$)
CL.5 : $WK_{A-M} \rightarrow WK_{P-A}$	CL-C.2: $WK_{A-M} \rightarrow WK_{P-A}$	
CL.6 : $WK_{A-Rq} \rightarrow WK_{P-A}$	CL-C.3: $WK_{A-Rq} \rightarrow WK_{P-A}$	
CL.7 : $WK_{A-S} \rightarrow WK_{P-G}$		CL-P.5 : $WK_{A-S} \rightarrow WK_{P-G}$
CL.8 : $WK_{A-S} \rightarrow WK_{P-I}$		CL-P.6 : $WK_{A-S} \rightarrow WK_{P-I}$
CL.9 : $WK_{A-Rq} \rightarrow WK_{P-G}$		CL-P.7 : $WK_{A-Rq} \rightarrow WK_{P-G}$
CL.10 : $WK_{P-A} \rightarrow DK_A$	CL-C.4: $WK_{P-A} \rightarrow DK_A$	CL-P.8 : $WK_{P-A} \rightarrow DK_{A-G}$
		CL-P.9 : $WK_{P-A} \rightarrow DK_{A/It}$
CL.11 : $WK_{P-A} \rightarrow WK_{A/F}$ (exclude $WK_{A-Bis} \rightarrow WK_{P-A}$)	CL-C.5: $WK_{P-A} \rightarrow WK_{A/F}$ (exclude $WK_{A-Bis} \rightarrow WK_{P-A}$)	CL-P.10 : $WK_{P-A} \rightarrow WK_{A/F}$ (exclude $WK_{P-A} \rightarrow WK_{A-Bis}$)
CL.12 : $WK_{P-A} \rightarrow WK_{A/C}$	CL-C.6: $WK_{P-A} \rightarrow WK_{A/C}$	CL-P.11 : $WK_{P-A} \rightarrow WK_{A-Rq}$
CL.13 : $WK_{P-A} \rightarrow WK_{P-G}$		CL-P.12 : $WK_{P-A} \rightarrow WK_{P-G}$
CL.14 : $WK_{P-A} \rightarrow WK_{P-Out}$		CL-P.13 : $WK_{P-A} \rightarrow WK_{P-Out}$
CL.15 : $WK_{P-G} \rightarrow WK_{P-A}$		CL-P.14 : $WK_{P-G} \rightarrow WK_{P-A}$
CL.16 : $WK_{P-G} \rightarrow WK_{P-G}$		CL-P.15 : $WK_{P-G} \rightarrow WK_{P-G}$
CL.17 : $WK_{P/C} \rightarrow WK_{P-A}$		CL-P.16 : $WK_{P/C} \rightarrow WK_{P-A}$
CL.18 : $WK_{P-C} \rightarrow WK_{P-I}$		CL-P.17 : $WK_{P-C} \rightarrow WK_{P-I}$
CL.19 : $WK_{P-I} \rightarrow WK_{P-G}$		CL-P.18 : $WK_{P-I} \rightarrow WK_{P-G}$

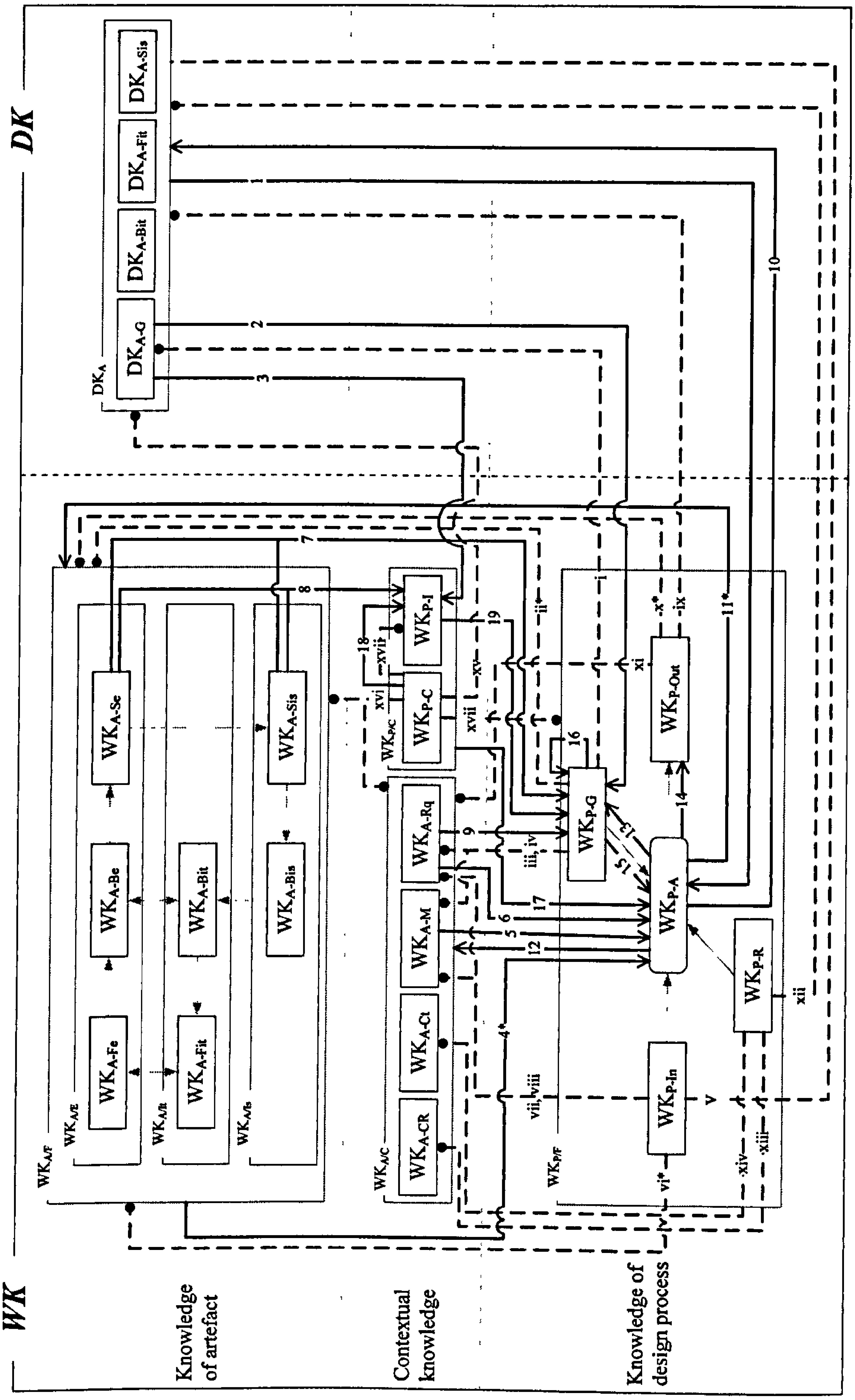
Similarly, the employment links of the coupling were identified by combining those identified from both the protocol analysis and content analysis. The results, 17 employment links of the coupling, are listed in the first column of Table 7-7, which are identified with 'EL.' followed with Arabic numerals. With the same combination process, links, identified from both methods (eg. EL.v and EL.vi) or only one of them (eg. EL.i and EL.iii), are included in the final list. In addition, if links identified from one method are generalised links of those from another method, the generalised links that are highlighted in grey background in the table are included in the final list (eg. EL.ii and EL.ix).

Table 7-7: Employment links of the coupling model

Employment links of the coupling	**Content analysis**	**Protocol analysis**
EL.i : WK_{P-G} --● DK_{A-G}		EL-P.i : WK_{P-G} --● DK_{A-G}
EL.ii : WK_{P-G} --● $WK_{A/F}$ (exclude WK_{P-G} --● WK_{A-Bis})	EL-C.i : WK_{P-G} --● $WK_{A/F}$ (exclude WK_{P-G} --● WK_{A-Bis})	EL-P.ii : WK_{P-G} --● $WK_{A/E}$
EL.iii : WK_{P-G} --● WK_{A-M}	EL-C.ii : WK_{P-G} --● WK_{A-M}	
EL.iv : WK_{P-G} --● WK_{A-Rq}	EL-C.iii : WK_{P-G} --● WK_{A-Rq}	
EL.v : WK_{P-In} --● DK_{A}	EL-C.iv : WK_{P-In} --● DK_{A}	EL-P.iii : WK_{P-In} --● DK_{A}
EL.vi : WK_{P-In} --● $WK_{A/F}$ (exclude WK_{P-In} ---● WK_{A-Bis})	EL-C.v : WK_{P-In} --● $WK_{A/F}$ (exclude WK_{P-In} ---● WK_{A-Bis})	EL-P.iv : WK_{P-In} --● $WK_{A/F}$ (exclude WK_{P-In} --● WK_{A-Bis})
EL.vii : WK_{P-In} --● WK_{A-M}	EL-C.vi : WK_{P-In} --● WK_{A-M}	
EL.viii : WK_{P-In} --● WK_{A-Rq}	EL-C.vii : WK_{P-In} --● WK_{A-Rq}	
EL.ix : WK_{P-Out} --● DK_{A}	EL-C.viii : WK_{P-Out} --● DK_{A}	EL-P.v : WK_{P-Out} --● DK_{A-G} EL-P.vi : WK_{P-Out} --● $DK_{A/It}$
EL.x : WK_{P-Out} --● $WK_{A/F}$ (exclude WK_{P-Out} ---● WK_{A-Bis})	EL-C.ix : WK_{P-Out} --● $WK_{A/F}$ (exclude WK_{P-Out} ---● WK_{A-Bis})	EL-P.vii : WK_{P-Out} --● $WK_{A/F}$ (exclude WK_{P-Out} --● WK_{A-Bis})
EL.xi : WK_{P-Out} --● $WK_{A/C}$	EL-C.x : WK_{P-Out} --● $WK_{A/C}$	EL-P.viii : WK_{P-Out} -● WK_{A-Rq}
EL.xii : WK_{P-R} --● DK_{A}	EL-C.xi : WK_{P-R} --● DK_{A}	EL-P.ix : WK_{P-R} --● DK_{A-G} EL-P.x : WK_{P-R} --● DK_{A-Sis}
EL.xiii : WK_{P-R} --● WK_{A-CR}	EL-C.xii : WK_{P-R} --● WK_{A-CR}	EL-P.xi : WK_{P-R} --● WK_{A-CR}
EL.xiv : WK_{P-R} --● WK_{A-Ct}	EL-C.xiii : WK_{P-R} --● WK_{A-Ct}	EL-P.xii : WK_{P-R} --● WK_{A-Ct}
EL.xv : WK_{P-C} --● DK_{A}	EL-C.xiv : WK_{P-C} --● DK_{A}	EL-P.xiii : WK_{P-C} --● DK_{A}
EL.xvi : WK_{P-C} --● WK_{A}	EL-C.xv : WK_{P-C} --● WK_{A}	EL-P.xiv : WK_{P-C} --● WK_{A} (include $WK_{A/F}$ and $WK_{A/C}$)
EL.xvii : WK_{P-C} --● WK_{P}		EL-P.xv : WK_{P-C} --● WK_{P} (include $WK_{P/F}$ and $WK_{P/C}$)

In light of the 19 creation links of the coupling, and the 17 employment links of the coupling deduced from both the protocol analysis and content analysis, the coupling of the artefact and design process knowledge is considered to be composed of these 36 links of the coupling. In this respect, Figure 7-10 presents the coupling model by combining the **creation links of the coupling** (listed in Table 7-6) and the **employment links of the coupling** (listed in Table 7-7).

The coupling presented in Figure 7-10 reveals two main types of relationships between the artefact and design process on the knowledge level. Design knowledge evolution, therefore, is triggered by the coupling of the artefact and design process, i.e., the creation and employment links of the coupling depicted in the figure.



* The $WK_{A/F}$ in links 4, 11, vi, and x do not contain $WK_{A\text{-}Bis}$

Figure 7-10: Coupling of artefact and design process knowledge

7.4 CONCLUSION

It was found that design knowledge evolves through the creation and employment links between them, which compose the coupling of the artefact and design process knowledge. This chapter presented the evolved coupling through protocol analysis of a supervised student design project that covered task clarification, conceptual, and embodiment design. As a result of the protocol analysis, four basic types of links, i.e., *cause-effect link of creation*, *link of referral*, *link of usage*, and *link of containment*, were identified with 86 links and 1007 occurrences. The main links of these four types were identified by using their overall and average percentage methods. It was found that the last three types of links could be deduced to one type, i.e., *link of employment*, and some employment links could be deduced from some creation links as well, because the artefact knowledge elements were employed in the *goal*, *input*, *output*, *resource* of the design process. Hence 18 *creation* and 15 *employment links of the coupling* were deduced based on the protocol analysis of those main links.

The evolved coupling was then obtained by combining the creation and employment links identified from both the content and protocol analysis, which is composed of 19 *creation links of the coupling* (See Table 7-6) and the 17 *employment links of the coupling* (See Table 7-7). These coupling links are depicted in Figure 7-10. Having presented the coupling model, the next part of the thesis presents the evaluation of the work through two workshops with engineering designers from two design and manufacture companies. It also discusses the work presented in this thesis, followed with a conclusion of the thesis.

Part Three: Evaluation and discussion

Chapter 8 EVALUATION

Part two of this thesis presented the main findings of the nature of the coupling, which includes the occurrence trend of the knowledge elements involved in the coupling and the coupling model. It was found that different elements exhibited different occurrence trend patterns over task clarification, conceptual, and embodiment design in the analysed project. The different trend patterns, such as increase, decrease, or relatively stable, revealed that different elements occurred with different proportions during the design development, and an element also occurs with different proportions over different design phases. The coupling model had also been investigated as being composed of a number of creation and employment links between the artefact and design process knowledge elements. To evaluate the work presented in this thesis, this chapter presents an evaluation of the findings through workshops, during which questionnaires were answered by engineering designers, regarding to the knowledge elements occurrence trends and coupling links. Section 8.1 presents the evaluation approach including the pilot studies and the workshops. Section 8.2 shows the evaluation results of knowledge elements involved in the coupling, and Section 8.3 shows the evaluation results of the coupling. Finally Section 8.4 summarises this chapter.

8.1 EVALUATION APPROACH

8.1.1 Pilot studies

During the research design, questionnaire was chosen to evaluate the research, which was designed to be answered by engineering designers during workshops. The duration of each workshop was designed to be approximately 1.5 hours. Such length could ensure the evaluation to be done. Meanwhile, it would keep the participants' attention during that period. The question part of the questionnaire was decided to be composed of two parts: 'Design knowledge elements exploration' and 'Link product with design process'[9]. In order to extract enough information in the limited 1.5 hours, enhance validity and reliability of the questionnaire findings, as well as to make the evaluation questions more understandable for the participants, i.e. engineering designers, the format of the questionnaire went through three pilot studies. The pilot studies were helped by two teaching assistants and one research fellow in the Department of Design, Manufacture and Engineering Management, University of Strathclyde. Of these three studies, two were involved in the analysis of the questionnaire format and content, and another was used to test the time needed for the questionnaire.

Overall, as a result of the three pilot studies, the format of the questionnaire went through three main changes. The first main change was to collect designers' view of the knowledge elements and coupling rather than to show them the research results. This eliminated the possibility that designers might be affected by the research results while answering the questionnaire. Secondly, in order to enable designers to have a holistic view of the research, the questions were embedded into one table and two diagrams on two A2 papers. Originally, individual questions were distributed in nine A4 papers. This change intended to help designers to have a better understanding towards the research. The last main change was to have designers draw the two types of coupling links between the artefact and design process knowledge elements on two knowledge elements diagrams, rather than asking them to select the link in two knowledge elements matrices[10]. One main reason for committing the third change was that the matrix was seen to take too much time to finish in the limited duration of

[9] See next paragraph for explanation of using 'product' instead of 'artefact'.

[10] The original matrix includes the knowledge elements listed in the top row and first column, representing the two ends of link.

the workshops. In addition to these three main changes, some other improvements were also made to the questionnaire so that the questions could be easily readable and understandable by designers and could also contribute in collecting reliable information from the designers for the evaluation. For example, more readily understandable terms, such as "product" (rather than "artefact"), which were common in companies were used in the questionnaire, though the essence of what they reflect remained the same. The finalised questionnaire can be found in Appendix G, which is composed of four parts: 1) Introduction and participants' information; 2) Design knowledge elements exploration (Figure G-1); 3) Link product with design process (Figure G-2); and 4) Appendices of knowledge elements explanation and a list of trend patterns ready to be chosen for Part 2. Part 2 and Part 3 are the main parts of the questionnaire.

In Part 2 of the questionnaire, designers were asked to select the knowledge elements' (identified through the literature review and protocol analysis) occurrence frequency during design development from "Never", "Occasionally", "Often", and "Very often". They were also asked to choose occurrence pattern of each element from 12 patterns listed from A to L in appendix of the questionnaire (numbered as Appendix G-1 in this thesis). If none of the listed patterns apply to an element, they could draw its occurrence trend in the table. In addition, the questionnaire also includes one column for the designers to make notes for each element, which was also intended to help designers to understand the elements. In Part 3 of the questionnaire, designers were then asked to draw the two types of links, *cause-effect link of creation* and *link of employment*, between knowledge elements in two diagrams.

8.1.2 Evaluation workshops

Two workshops were organised in two companies on Tuesday, the 4th, and Friday, the 7th of March, 2008. The first one was held in BAE Systems Surface Fleet Solutions Limited (SFS) where five engineering designers participated. The second one was in Company A with three designers participated. Company A is the same company based on which the content analysis (Chapter 5) was conducted. Both workshops lasted one and half hour. An introduction of the research work was presented at the beginning of the workshop. In particular, the knowledge elements and the types of links were explained to the designers. The explanations of the elements were also listed in the appendix of the questionnaire, which is listed in this thesis as Appendix G-2. The designers were then asked to complete Part 2 and Part 3 of the questionnaire, by using one design project they participated earlier in their work.

Table 8-1 summarises the profile of the eight designers who participated the workshops. Each of the designers was given a reference number listed in the first column "Ref No" and their companies are listed in the second column "Company". Except designers 3 and 5, who worked with the same product focus, and used the same project for the evaluation, all the other designers worked with different product types (listed in the third column "Product focus"), and they used different projects for the evaluation. The duration of the scenario projects used for the evaluation varied from 3 months to 7 years (listed in the fourth column "Project duration"). Moreover, the designers' experiences ranged from 0.5 year to 30 years (column "Design experience").

Table 8-1: Profile of the designers participated in the workshops

Ref No.	Company	Product focus	Project duration	Design experience
1	SFS	Ship electrical systems	7 years	25 years
2	SFS	Ship concepts assessments	3 months	25 years
3	SFS	Shipbuilding	2 years	12 years
4	SFS	Ship combat systems	1.5 year	12 years

Ref No.	Company	Product focus	Project duration	Design experience
5	SFS	Shipbuilding	2.5 years	10 years
6	Company A	Specific product	3 years	7 years
7	Company A	Specific product	4 years	35 years
8	Company A	Model product in cardboard	6 months	0.5 year

The initial analysis of the evaluation data showed that there were several inconsistencies within the results given by designer 8. To minimise the impact of such inconsistency on the validity of the evaluation, the questionnaire answered by designer 8 was excluded from the evaluation. Therefore, the questionnaires answered by designers 1 to 7 were used as the basis and main source of the evaluation. The answered questionnaires by designers 1 to 7 are listed in Appendix H. The following two sections, 8.2 and 8.3, present the evaluation results obtained within Part 2 and Part 3 of the questionnaire respectively.

8.2 KNOWLEDGE ELEMENTS OCCURRENCE TRENDS

In the Part 2 of the questionnaire, designers' view of 22 knowledge elements' occurrence frequency and trend were collected. The frequency were selected from options "Never", "Occasionally", "Often", and "Very often". In addition, their trends over task clarification, conceptual, and embodiment design were chosen by the designers from the 12 sample trend patterns ('A' to 'L') listed in the appendix of the questionnaire, or drawn by themselves if none of the patterns match. As the result of the evaluation, in addition to the 12 patterns listed in Appendix G, another four trends were sketched by the designers, which were numbered from 'M' to 'P'. Moreover, there was one more pattern resulted from the protocol analysis that was not listed in the questionnaire. It was then numbered 'Q'. Figure 8-1 lists these five additional occurrence trends.

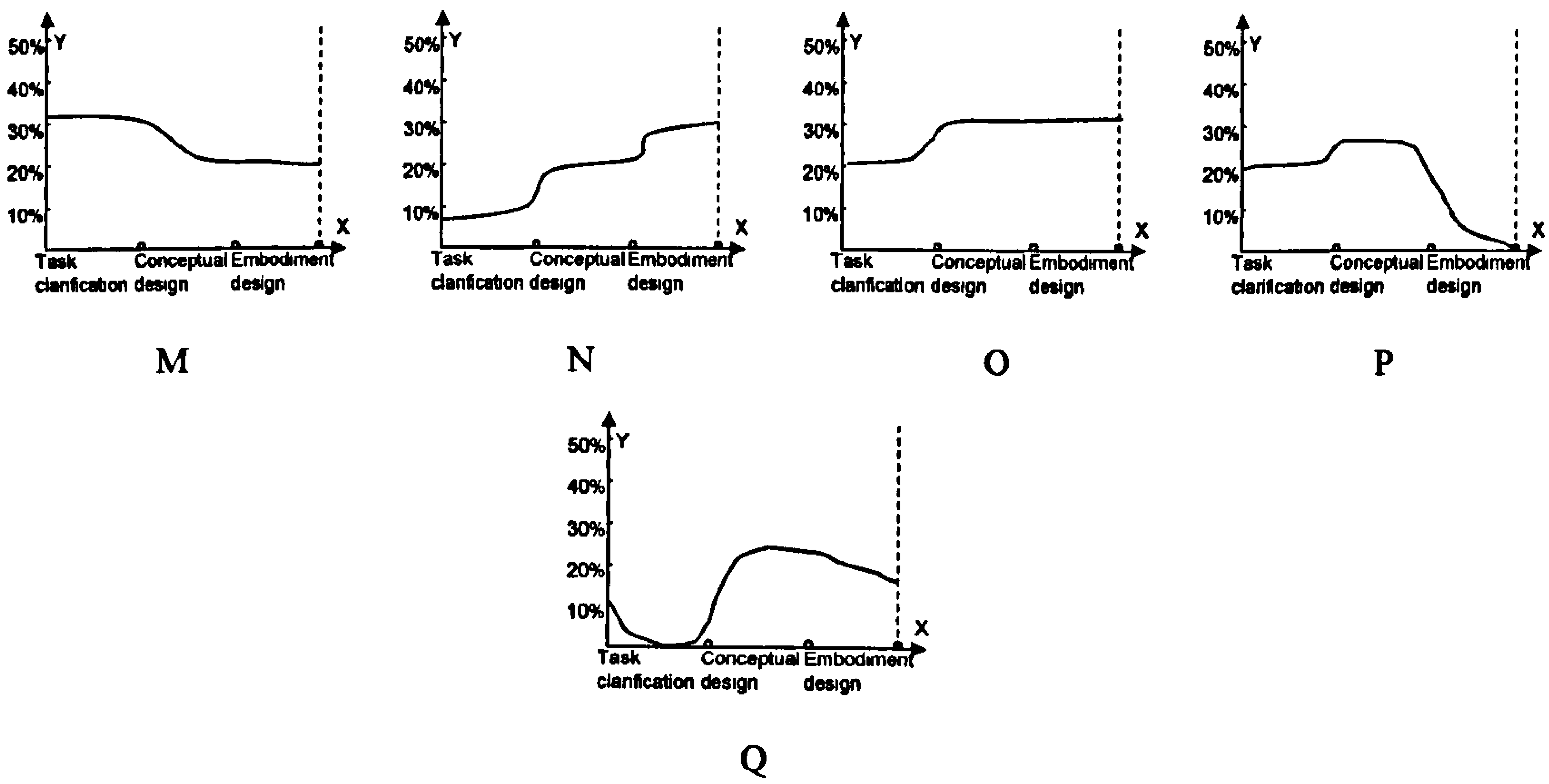


Figure 8-1: Five additional elements occurrence trends (from M to Q)

In Figure 8-1, the X-Axis of each chart lists the three design phases and the Y-Axis is the value axis indicating the occurrence percentage of knowledge elements over the three design phases. It should be noted that the percentage value of the Y-Axis of the trend patterns was not intended to accurately show the percentage of the elements. Rather, it was used to indicate the elements' occurrence trend over the three design phases.

Table 8-2 lists the evaluation results of Part 2 of the seven designers' answered questionnaires. The table includes the element frequency and occurrence trend over the three design phases.

While an initial analysis of the evaluation results showed that some elements' trends viewed by the designers were the same or similar to those derived from the protocol analysis, some were different. In addition, the seven designers had different views of the same question, which resulted in a diversity of answers. Consequently, it was decided that the three designers with 30, 25, and 25 years' experience were given higher weight than the designers with less work experience. Thus, these three experienced designers' views were always considered in the evaluation. However, the views of the remaining four designers with 12, 12, 10, and 7 years' work experience, were only considered in the evaluation if they gave the same answer to a question with anyone else. For example, if only the designer with 10 years' experience chose trend A for $WK_{P\text{-}A}$, 'A' would not be analysed. However, 'A' would be analysed if there was another designer who also chose A for $WK_{P\text{-}A}$.

In the remainder of this section, 8.2.1, 8.2.2, and 8.2.3 present evaluation of the elements trend analysis in three groups of domain artefact, current working artefact and design process knowledge. Section 8.2.4 compare the evaluation results by different designers in order to identify the factors might affect the variety of answers. A summary of this section is given in Section 8.2.5.

Table 8-2: Evaluation result data of knowledge elements

Element names used in workshop	Knowledge elements	Ref.1 - 25 years					Ref.2 - 25 years					Ref.3 - 12 years					Ref.4 - 12 years					Ref.5- 10 years					Ref.5 - 7 years					Ref.7 - 30 years				
		Nv	Oc	Of	Vf	Tr	Nv	Oc	Of	Vf	Tr	Nv	Oc	Of	Vf	Tr	Nv	Oc	Of	Vf	Tr	Nv	Oc	Of	Vf	Tr	Nv	Oc	Of	Vf	Tr	Nv	Oc	Of	Vf	Tr
General knowledge	DK_{A-G}				1	I			1		B				1	H				1	H				1	H				1	K			1		H
Behaviour (B)	DK_{A-Bit}			1		A				1	E				1	A		1			H		1			D			1		H			1		B
Function (F)	DK_{A-Fit}			1		A				1	H				1	A			1		H		1			I			1		H				1	M
Structure (S)	DK_{A-Sis}				1	A			1		E			1		C				1	E			1		K				1	P			1		B
Need/Motivation (M)	WK_{A-M}			1		L		1			B		1			C				1	A				1	A				1	P				1	A
Requirement (Rq)	WK_{A-Rq}				1	H				1	B				1	A				1	A				1	A				1	P			1		G
Function (Fe)	WK_{A-Fe}			1		H		1			C				1	A				1	B			1		B			1		P			1		H
Behaviour (Be)	WK_{A-Be}			1		I		1			C				1	A			1		E			1		B			1		B		1			G
Structure (Se)	WK_{A-Se}			1		B			1		C			1		C				1	A			1		C			1		E				1	A
Structure (Sw)	WK_{A-Sis}		1			E				1	F		1			F				1	A			1		E				1	K			1		E
Behaviour (Bw)	WK_{A-Bis}		1			L				1	E		1			F			1		B				1	F			1		K		1			F
Behaviour (Bi)	WK_{A-Bit}			1		D				1	E			1		E				1	E				1	K			1		K			1		G
Function (Fi)	WK_{A-Fit}			1		A			1		F			1		E				1	B				1	L			1		P			1		H
Inter-connections (Cn)	WK_{A-CR}		1			D				1	K				1	A				1	F				1	F		1			D				1	A
Constraint (Ctr)	WK_{A-Ct}		1			D		1			J				1	A				1	A			1		C			1		P		1			N
Activity (A)	WK_{P-A}			1		C				1	E				1	F			1		H			1		E			1		E			1		H
Goal (G)	WK_{P-G}		1			K		1			G				1	E				1	B			1		L			1		K			1		H
Input (In)	WK_{P-In}				1	A			1		H				1	A			1		L		1			I		1			K				1	I
Output (Out)	WK_{P-Out}			1		F				1	E				1	A			1		F			1		F		1			E			1		K
Resource (Rs)	WK_{P-R}				1	A				1	N				1	A				1	F				1	D			1		O				1	N
Context (C)	WK_{P-C}			1		A			1		B			1		F				1	A		1			L			1		O			1		H
Issue (I)	WK_{P-I}			1		F				1	I				1	F				1	A			1		F				1	O			1		H

Nv: Never
Oc: Occasionally
Of: Often
Vf: Very often
Tr: Trend (Refer to Appendix G-1 for a list of trend chart options)

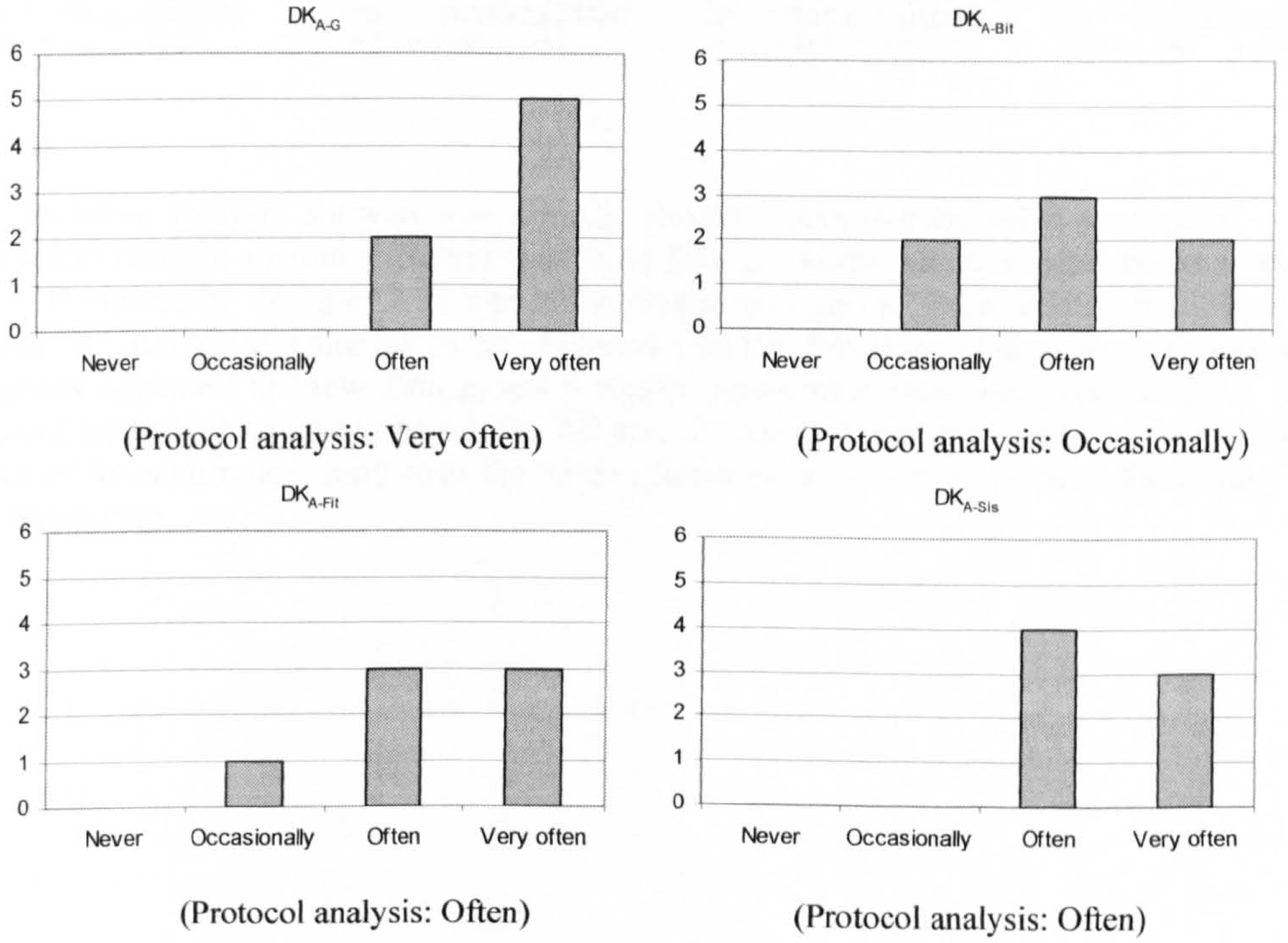
8.2.1 Domain artefact knowledge

Frequency

Table 6-6 lists the basic elements' average occurrence percentage over the 12 sessions resulted from the protocol analysis. In this thesis, if an element's average occurrence percentage equals to or higher than 10%, it is regarded as occurred very often. If the value is between 1% and 10%, it is regarded as occurred often. If the value equals to or less than 1%, it is regarded as occurred occasionally. Finally, if the value is zero, it is regarded as never occurred.

The frequency results of the four domain artefact knowledge elements ($DK_{A\text{-}G}$, $DK_{A\text{-}Bit}$, $DK_{A\text{-}Fit}$, and $DK_{A\text{-}sis}$) viewed by the seven designers are shown in the charts in Figure 8-2. The horizontal axis lists the four options of occurrence frequency from "Never" to "Very often", and the vertical axis indicates the number of designers who selected the same option. The charts could reveal whether designers had similar views of the frequency of knowledge elements used in their work. It could be found that the seven designers had similar views of the frequency of $DK_{A\text{-}G}$ and $DK_{A\text{-}Sis}$. That is, all of them considered the frequency of $DK_{A\text{-}G}$ and $DK_{A\text{-}Sis}$ to be either "often" or "very often" during designing. However, $DK_{A\text{-}Bit}$ and $DK_{A\text{-}Fit}$ were viewed by the seven designers with three answer, i.e., Occasionally, Often, and Very often. Specifically, two and one designers chose "Occasionally" for $DK_{A\text{-}Bit}$ and $DK_{A\text{-}Fit}$ respectively.

Because designers had at least two different views of the element's frequency, compare to their average occurrence percentage listed in Table 6-6, it is regarded that if more than two designers had the same view of an element's frequency as the result obtained from the protocol analysis, the two results were viewed similar. Figure 8-2 shows that the results of all the four DK_A elements obtained from the evaluation are similar to that obtained from the protocol analysis.



(Protocol analysis: Very often) (Protocol analysis: Occasionally)

(Protocol analysis: Often) (Protocol analysis: Often)

Figure 8-2: Occurrence frequency of DK_A – Evaluation

Occurrence trend

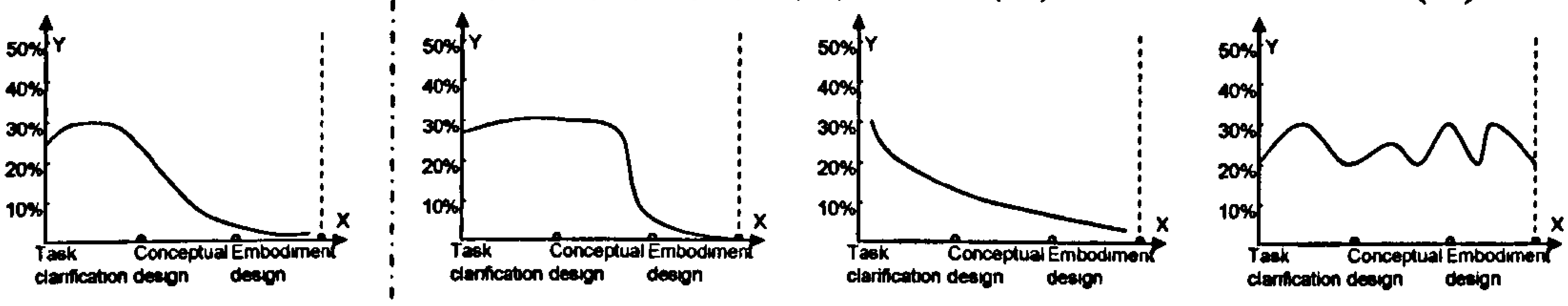
The occurrence trends of the four domain artefact knowledge elements resulted from both the protocol analysis and evaluation questionnaires are compared below. In each of the comparison figure listed below, the result obtained from the protocol analysis is listed on the left side of the dash dotted line and those obtained from evaluation workshops are listed on the right side, along with the reference number of designers who chose the trends and the duration of their design experience.

$DK_{A\text{-}G}$

The protocol analysis resulted in trend 'G' for $DK_{A\text{-}G}$. The trend has its peak in task clarification phase and decreases in the conceptual and embodiment design phases. However, the evaluation result shows that designers 7, 3, 4, and 5 with 30, 12, 12, and 10 years design experiences chose 'H', another two designers with 25 years design experience (designers 1 and 2) chose I and B respectively. While H and I are similar to 'G', the occurrence of $DK_{A\text{-}G}$ in H has a longer duration in conceptual design than in trend 'G', and that the occurrence of $DK_{A\text{-}G}$ in I has shorter duration in task clarification phase. The selection of trend 'B' by designer 2 showed that $DK_{A\text{-}G}$ was considered to be occurred in a relatively stable proportion over the three design phases. Generally, compare to the result obtained from the protocol analysis, $DK_{A\text{-}G}$ was considered by industrial designers to occur either in a similar manner or with higher proportion in conceptual and embodiment design.

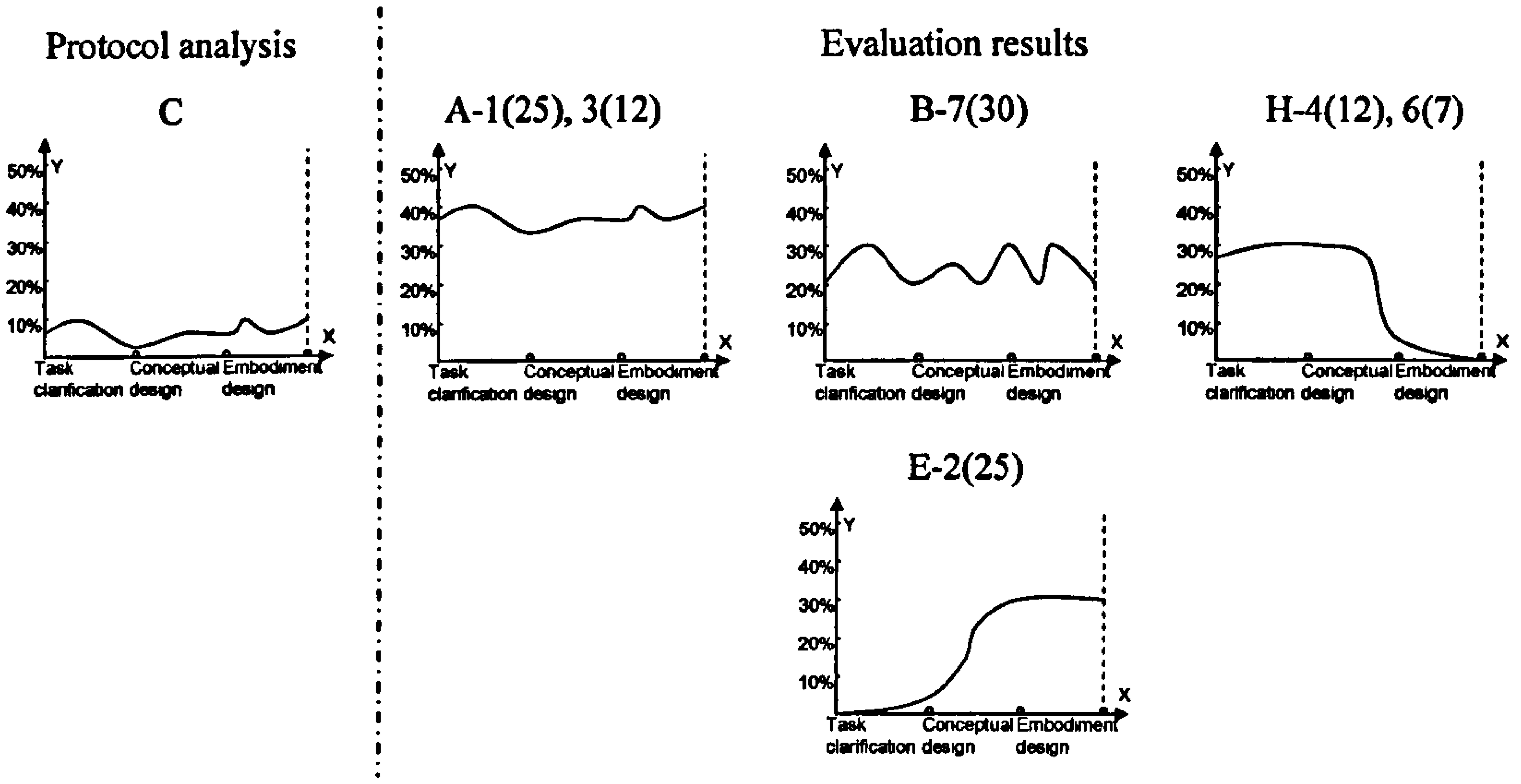
Protocol analysis | Evaluation results

G | H -7(30), 3(12), 4(12), 5(10) | I-1(25) | B-2(25)



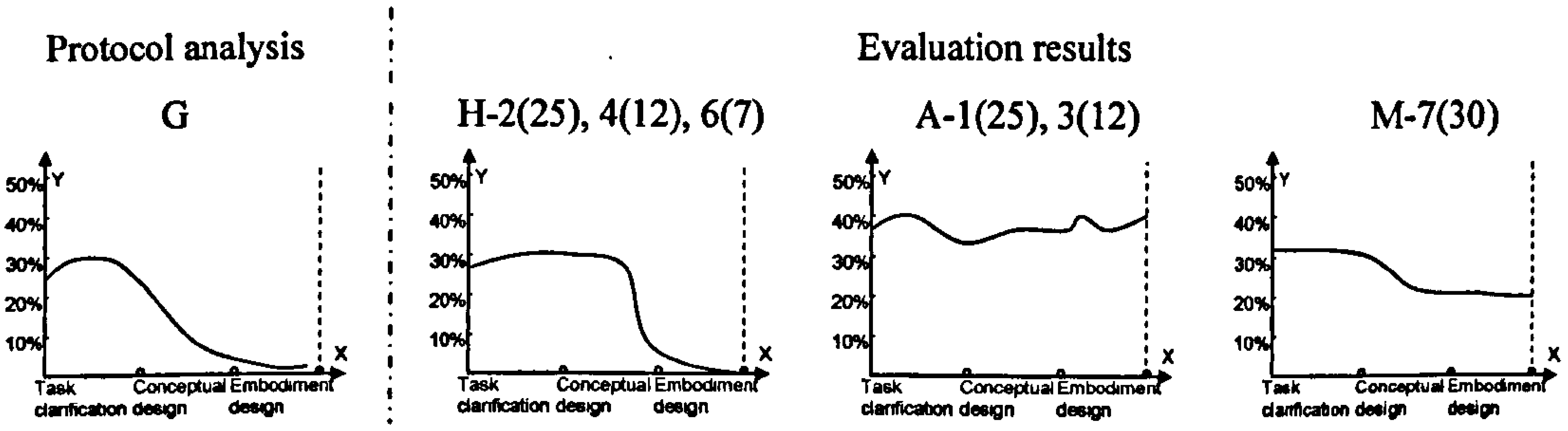
$DK_{A\text{-}Bit}$

The protocol analysis showed that $DK_{A\text{-}Bit}$ occurred occasionally with a trend 'C'. The evaluation resulted in four different results of $DK_{A\text{-}Bit}$, which are A viewed by designers 1 and 3, B viewed by designer 7, H viewed by designers 4 and 6, and E viewed by designer 2. Trends 'A' and 'B' are similar to 'C'. However, as the following charts indicate, industrial designers appeared to view $DK_{A\text{-}Bit}$ has a higher occurrence than the result obtained from protocol analysis. Moreover, the results 'H' and 'E' showed that designers also had different views of its occurrence trend over the three phases because while 'H' was decreasing, 'E' was increasing.



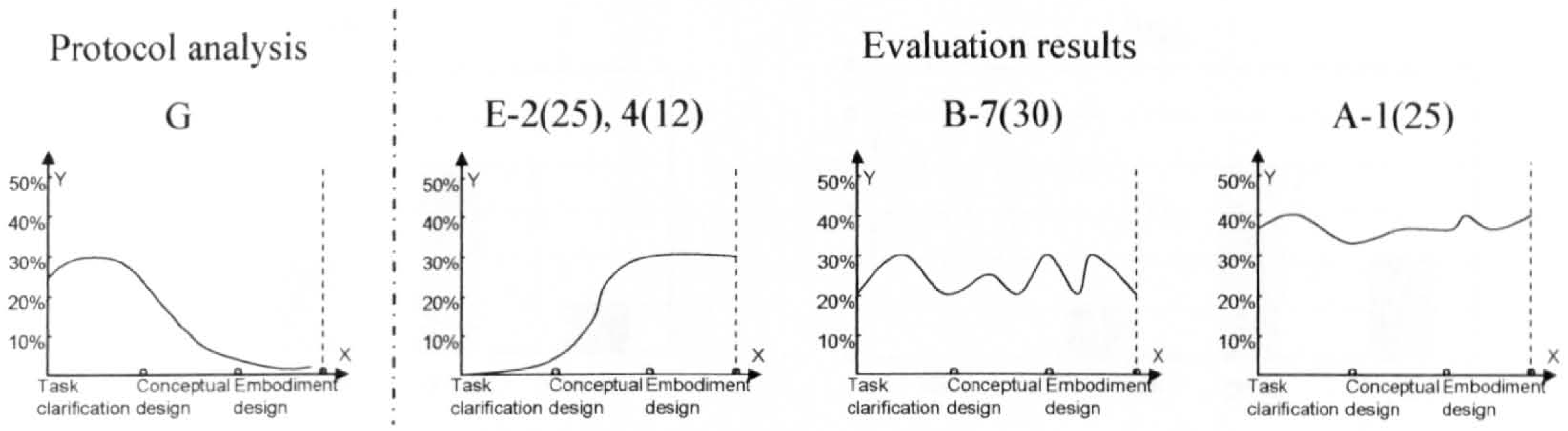
DK$_{A-Fit}$

The protocol analysis resulted in trend 'G' for $DK_{A\text{-}Fit}$, which is a decreasing trend, with higher occurrence only in task clarification. As the following charts show, three main trends of $DK_{A\text{-}Fit}$, 'H', 'A', and 'M', resulted from the evaluation workshop. Trend 'H' has a higher occurrence in conceptual design than G. Trend A has a higher occurrence in both conceptual and embodiment design than 'G'. Though trend 'M' is also a decreasing trend, it has higher occurrence proportion in both conceptual and embodiment design than 'G'. Overall, similar to $DK_{A\text{-}G}$, the designers viewed $DK_{A\text{-}Fit}$ to have higher occurrence than that obtained from the protocol analysis in conceptual and embodiment design. It could also be seen that designers with different product focuses and design experiences had different views of $DK_{A\text{-}Fit}$'s occurrence trend.



DK$_{A-Sis}$

As the following charts indicate, the protocol analysis resulted in decreasing trend 'G' for $DK_{A\text{-}G}$. However, three main trends resulted from the evaluation workshop, i.e., trend 'E' viewed by designers 2 and 4, trend 'B' viewed by designer 7, and trend 'A' viewed by designer 1. In contrast to 'G', trend 'E' shows that designers viewed $DK_{A\text{-}Sis}$ as increasing during designing. This view might be explained that company emphasised and involved in accumulating domain knowledge. Especially with a design's accomplishment, the product itself can become $DK_{A\text{-}Sis}$. The other two trends 'B' and 'A' show that designers considered $DK_{A\text{-}Sis}$ to occur relatively with same proportion, though both of them have a higher proportion in conceptual and embodiment design than trend 'G' obtained from the protocol analysis.



Key findings of the evaluation of DK_A:

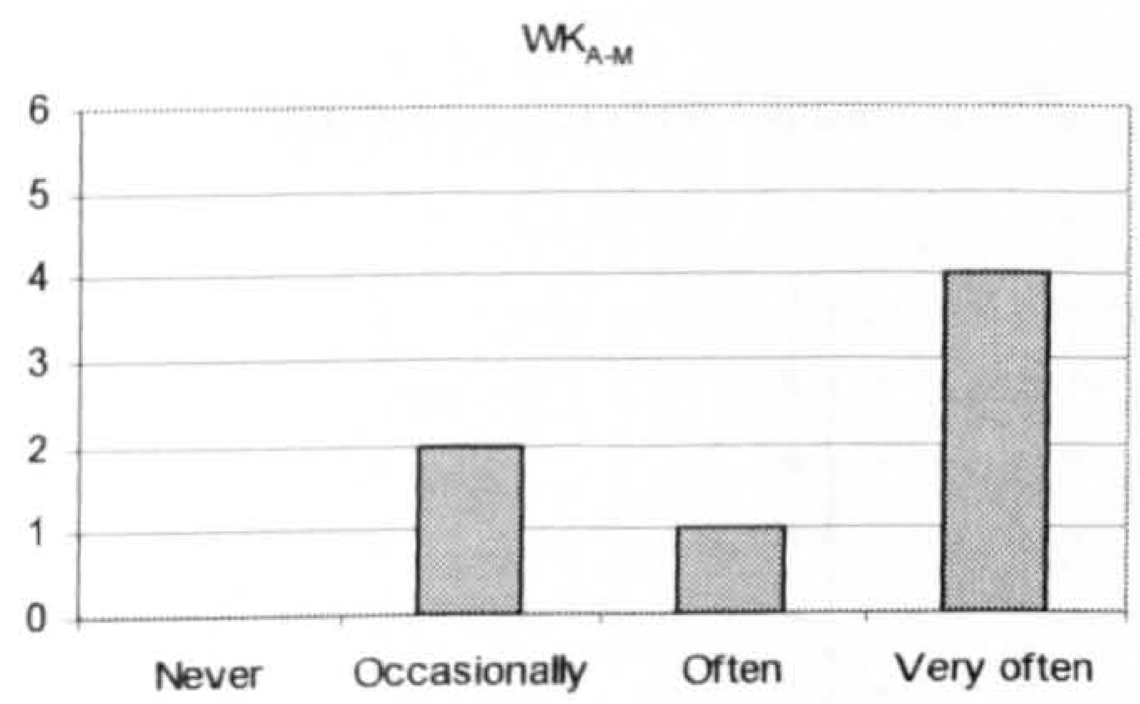
- $DK_{A\text{-}G}$ and $DK_{A\text{-}Sis}$ were regarded as occurring either "Often" or "Very often" during the design development, and that their occurrence were viewed more frequent than that of $DK_{A\text{-}Bit}$ and $DK_{A\text{-}Fit}$.
- The occurrence frequencies of the four DK_A elements obtained from the evaluation are similar to that obtained from the protocol analysis, in that at least two designers had the same view as the results obtained from the protocol analysis.
- Overall, designers from industry had similar views of three DK_A elements' ($DK_{A\text{-}G}$, $DK_{A\text{-}Bit}$, and $DK_{A\text{-}Fit}$) trends, and different view of one DK_A element ($DK_{A\text{-}Sis}$) as the results obtained from the protocol analysis.
- Different from increasing trend 'G' that resulted from the protocol analysis, some designers considered DK_A has a relatively same proportion over the three design phases.

8.2.2 Current working artefact knowledge

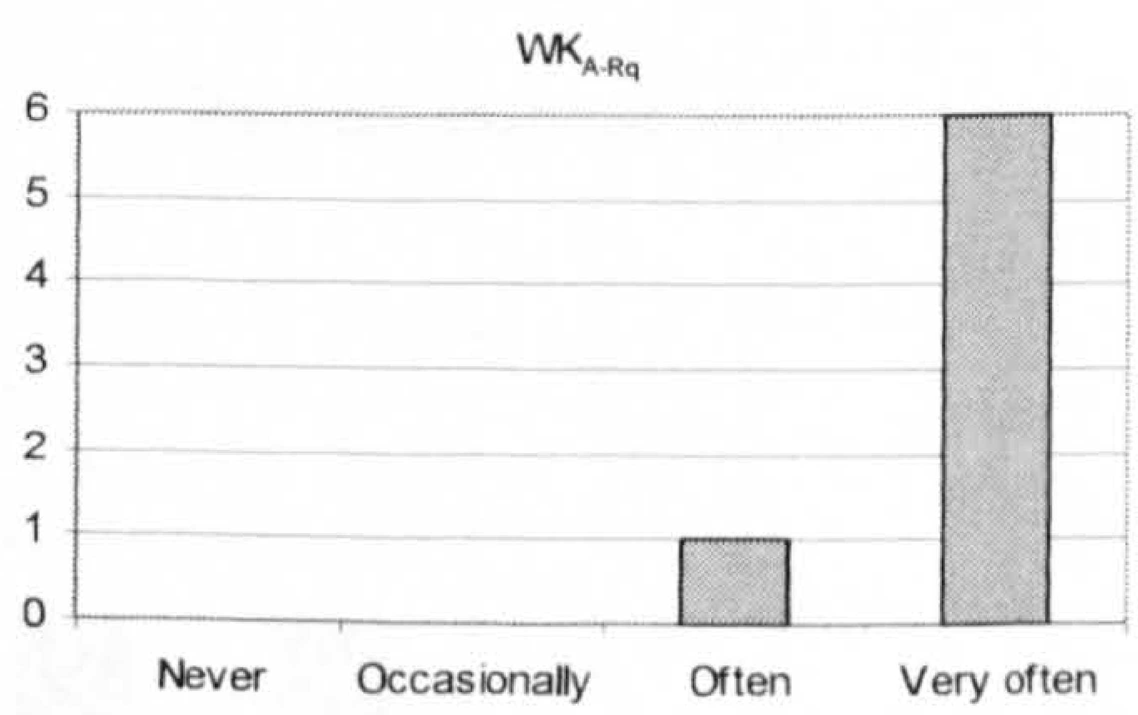
Frequency

Figure 8-3 shows the frequency results of the current working artefact knowledge viewed by the seven designers. According to the charts listed below, all the elements were considered by the designers to occur during design development with different levels of frequency. Among them, $WK_{A\text{-}Rq}$, $WK_{A\text{-}Se}$, $WK_{A\text{-}Fit}$, and $WK_{A\text{-}Bit}$ were considered by all the designers to occur either "Often" or "Quite often", while the results of other elements included "Occasionally".

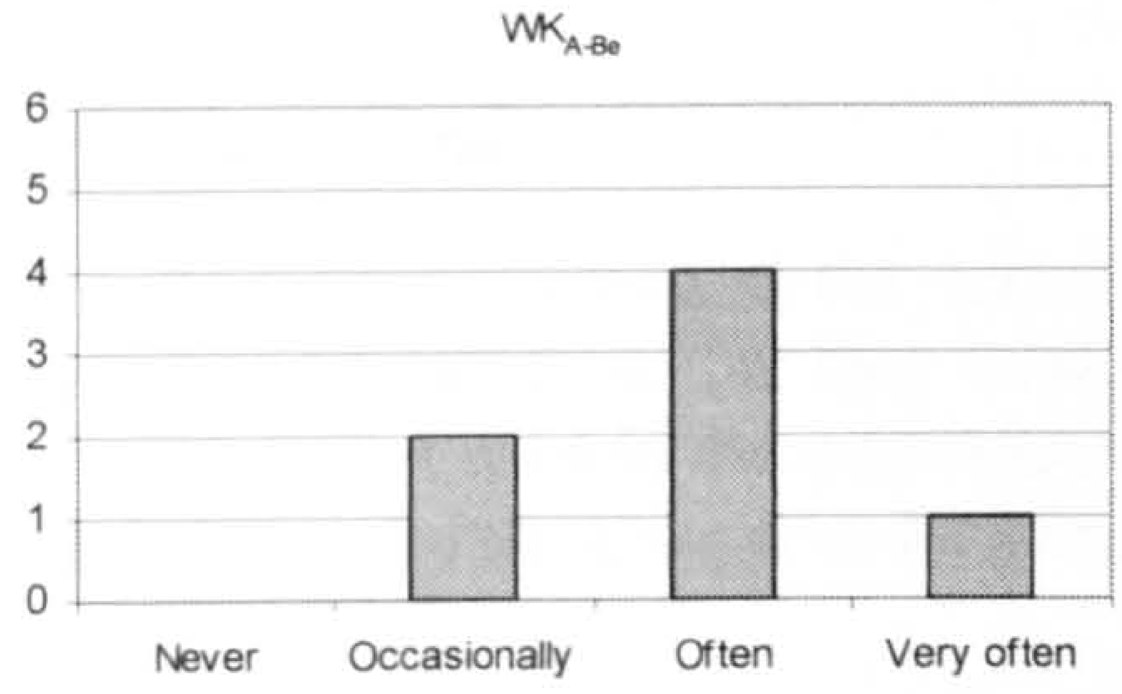
Compare to their average occurrence percentage listed in Table 6-6, it can be found that of the eleven knowledge elements, five of them had different results from that obtained from the protocol analysis, i.e., $WK_{A\text{-}Rq}$, $WK_{A\text{-}Bis}$, $WK_{A\text{-}Bit}$, $WK_{A\text{-}Fit}$, and $WK_{A\text{-}CR}$. For other elements, there were at least two designers had the same view of the elements' frequency as that obtained from the protocol analysis.



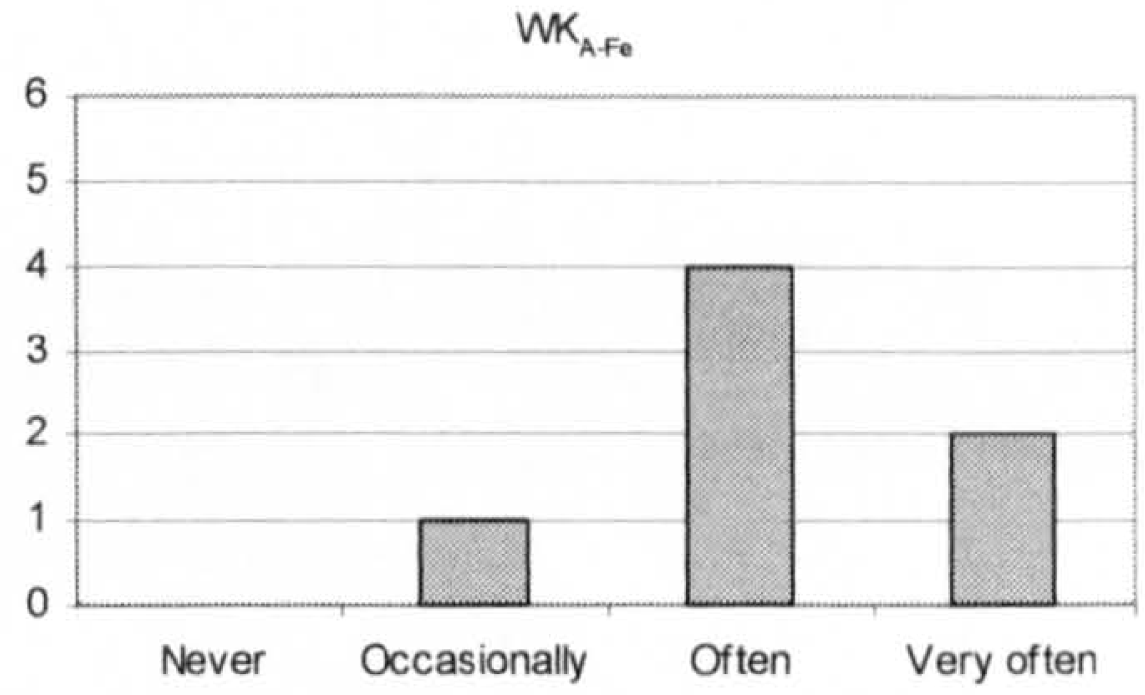
Protocol analysis: Occasionally



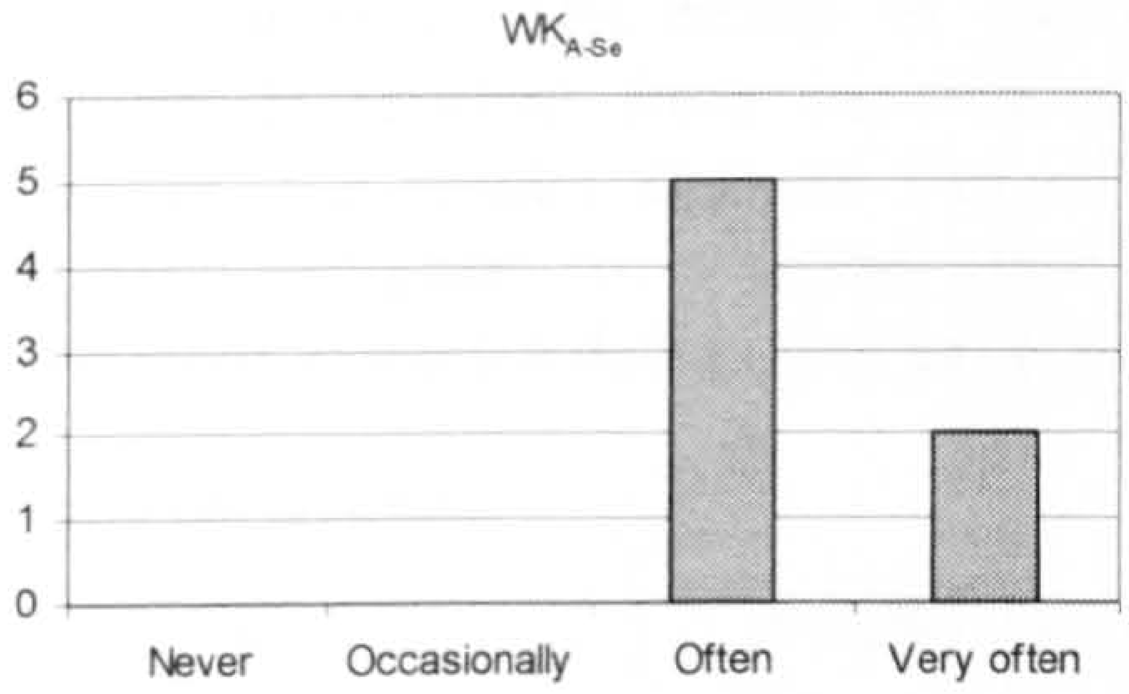
Protocol analysis: Occasionally



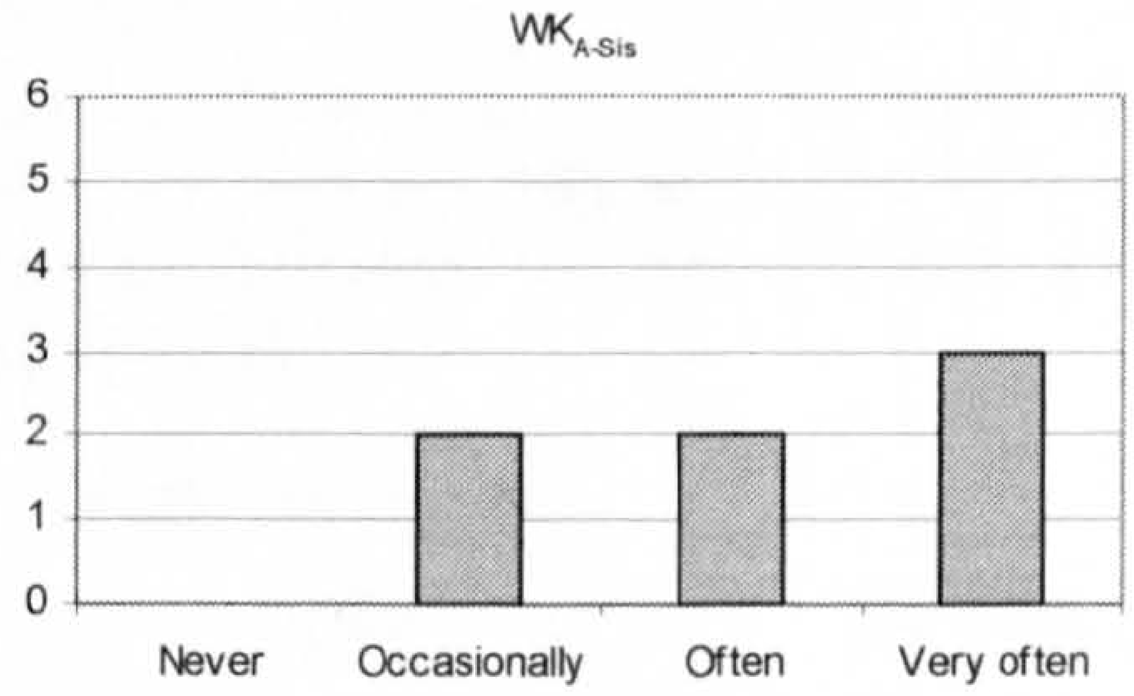
Protocol analysis: Often



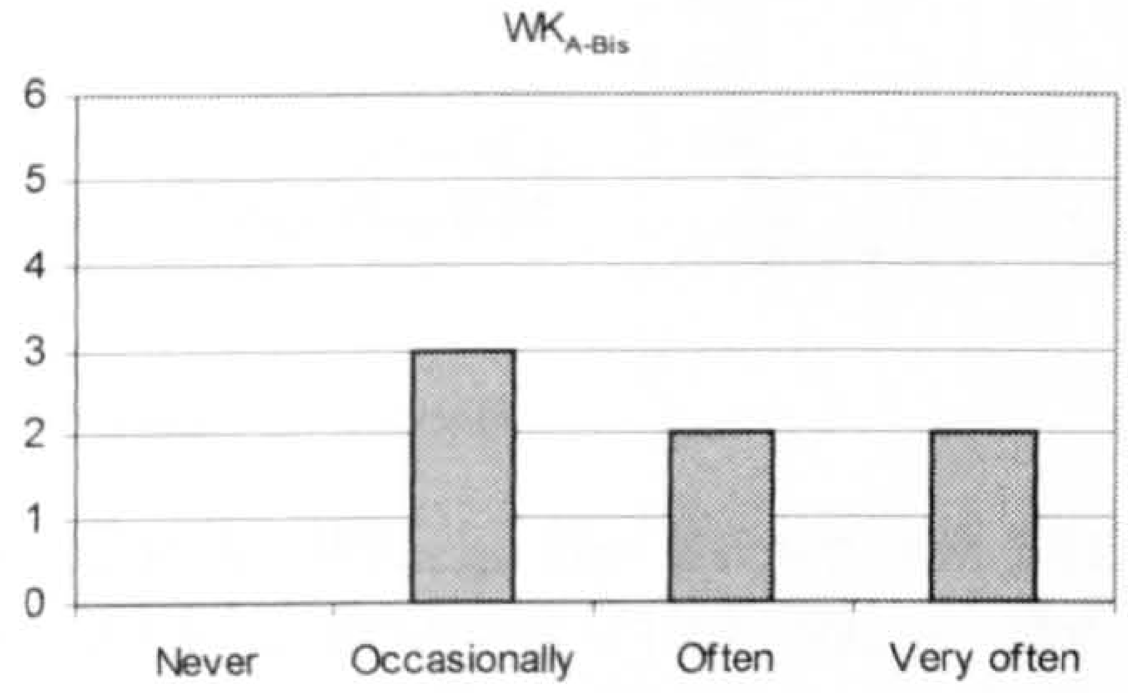
Protocol analysis: Often



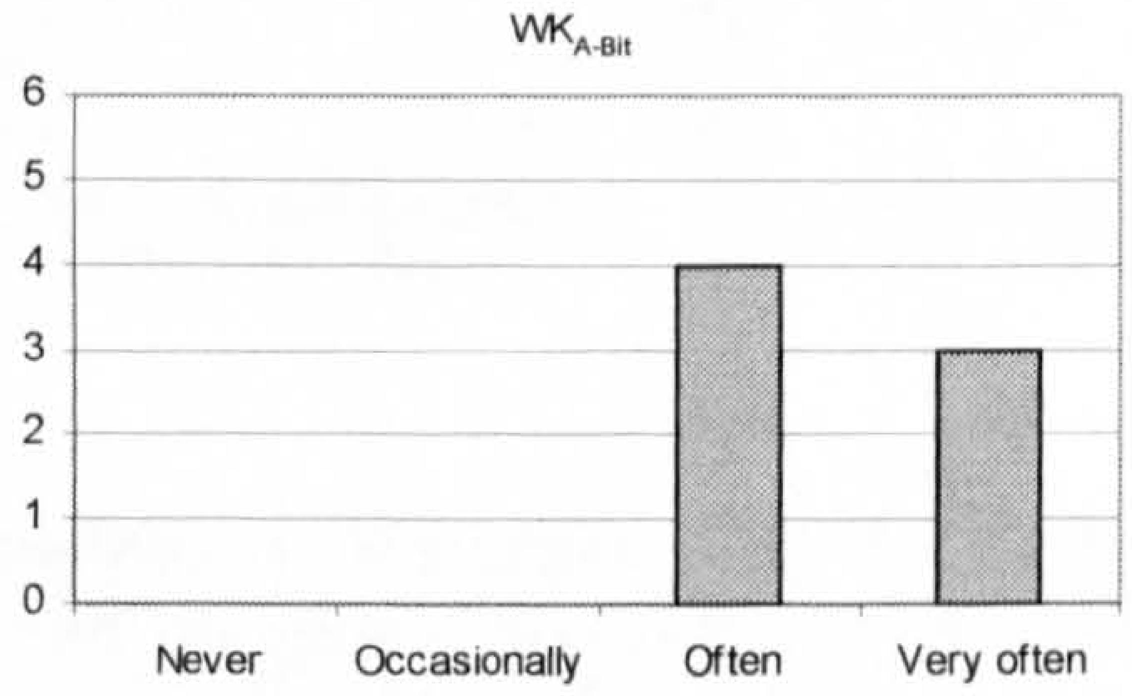
Protocol analysis: Very often



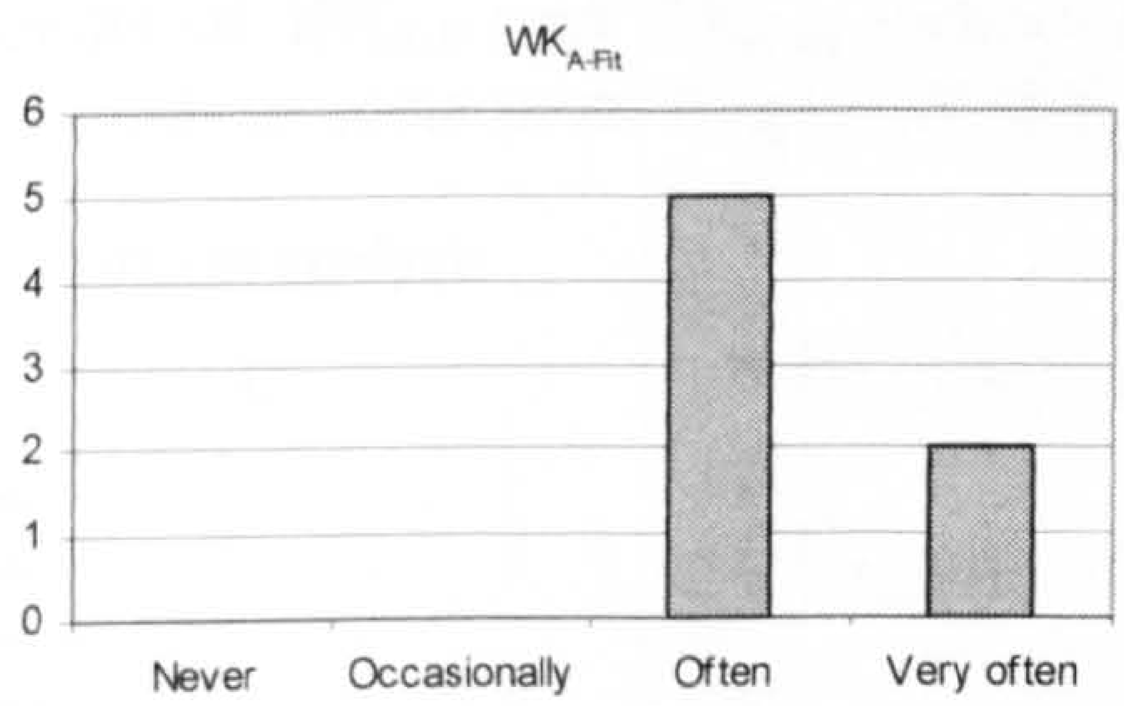
Protocol analysis: Often



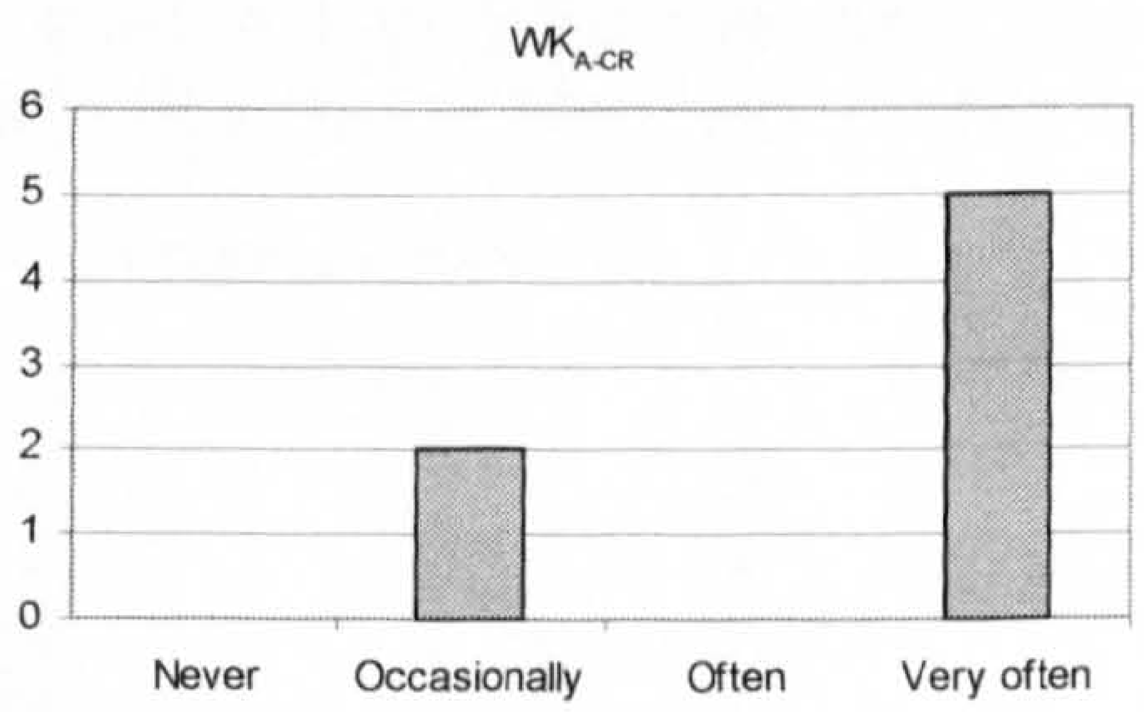
Protocol analysis: Never



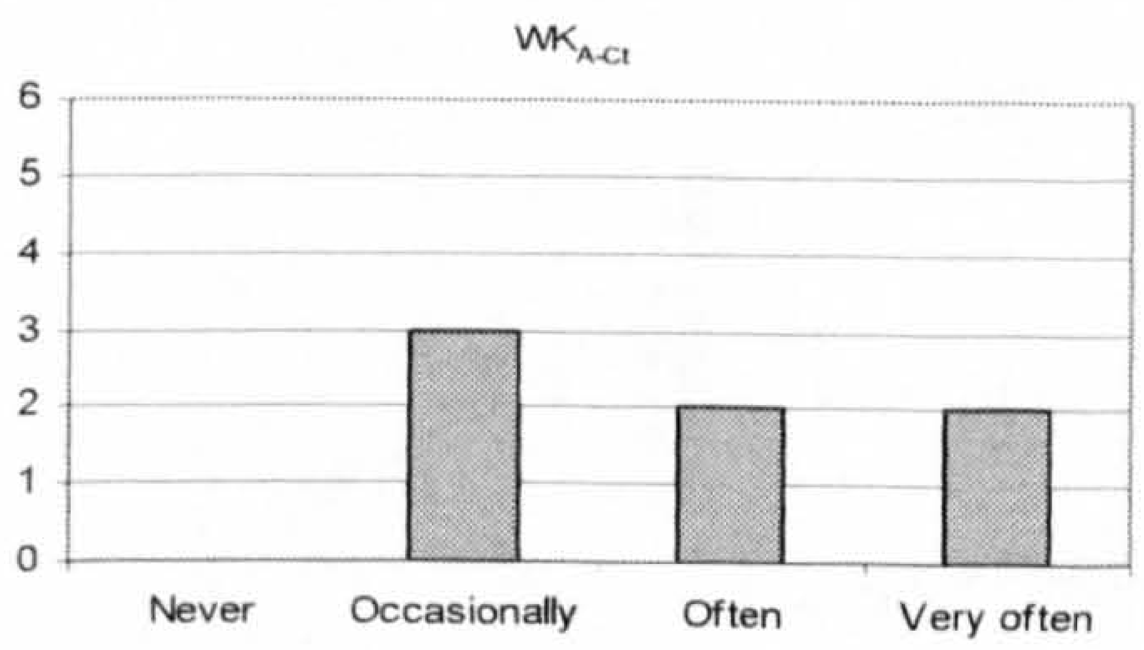
Protocol analysis: Occasionally



Protocol analysis: Occasionally



Protocol analysis: Never



Protocol analysis: Often

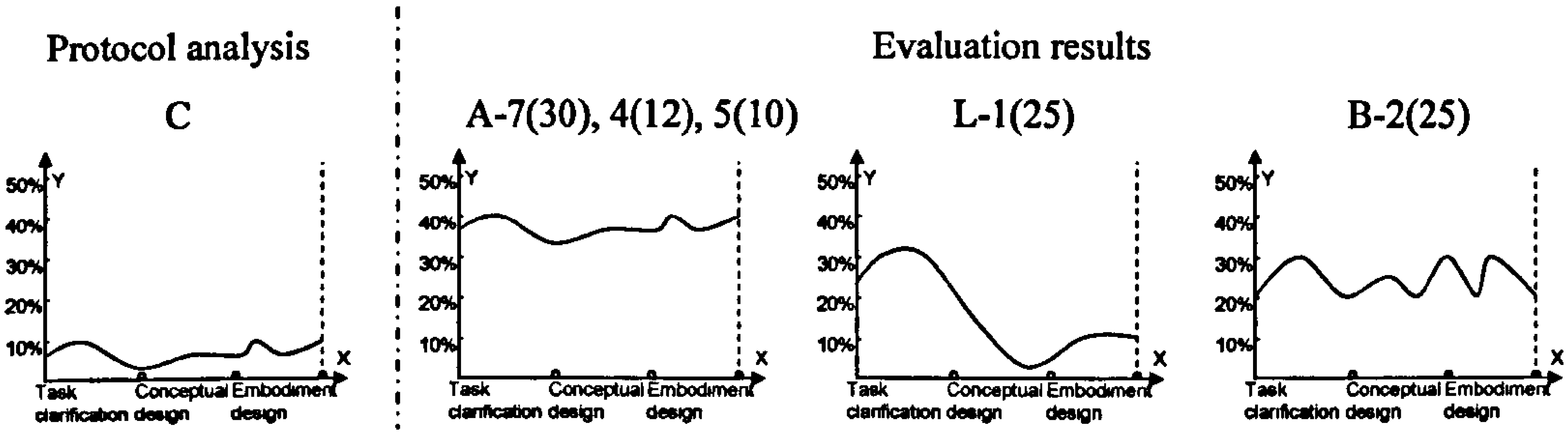
Figure 8-3: Occurrence frequency of WK_A – Evaluation

Occurrence trend

The following discussion of the current working artefact knowledge elements are not listed in the same sequence as that they were mentioned in this thesis. Rather, they are in the same sequence as that used in the questionnaire for the evaluation workshops. Such sequence was intended to make them more understandable by the designers.

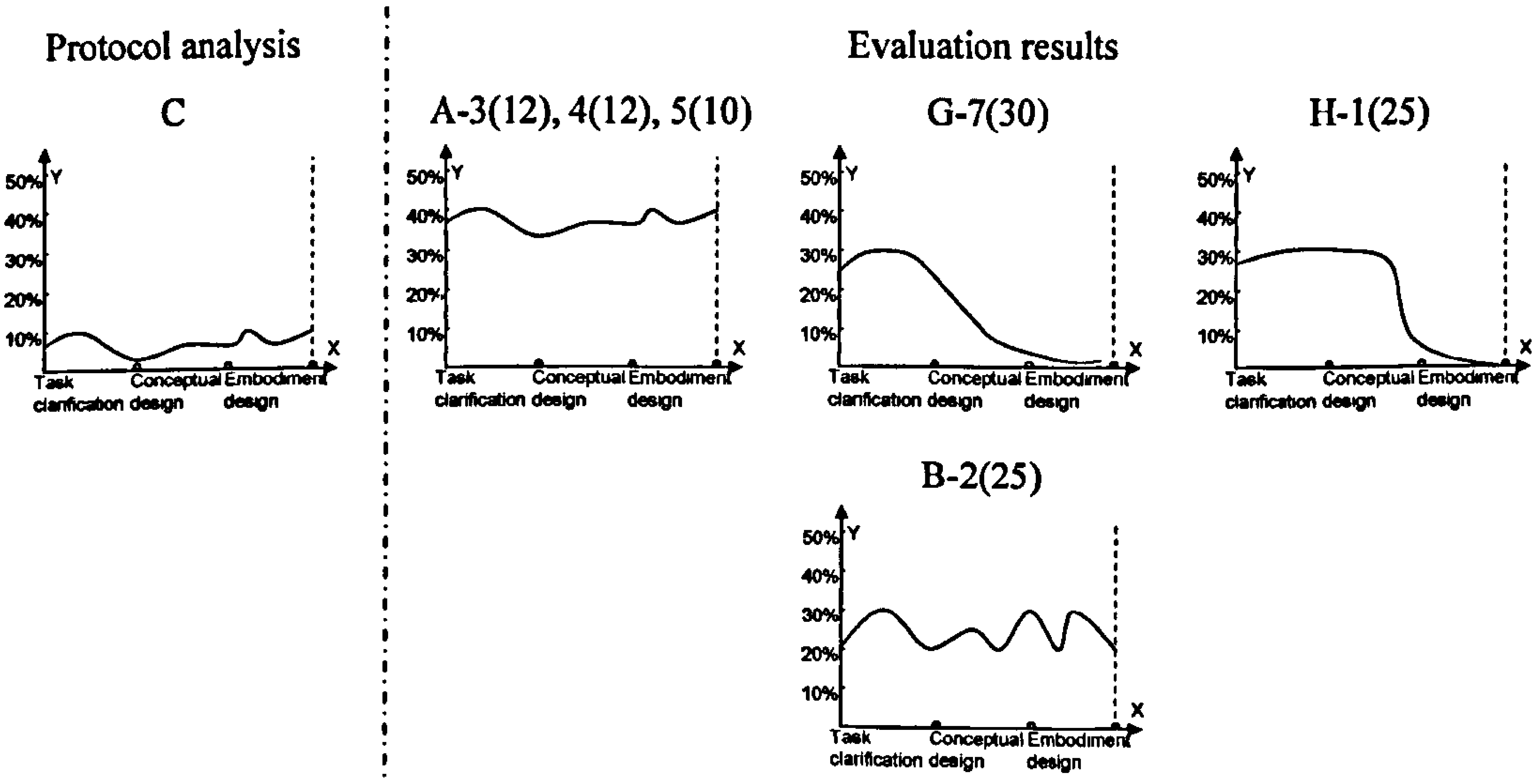
$WK_{A\text{-}M}$

The occurrence of $WK_{A\text{-}M}$ was analysed to be a low and relatively stable one ('C') from the protocol analysis. The trends 'A' (viewed by designers 7, 4, and 5) and 'B' (viewed by designer 2) resulted from the evaluation workshop have similar overall trend to 'C'. However, the results showed that it was considered to have higher occurrence by the industrial designers. In addition, trend 'L' viewed by designer 1 showed that it was also considered to have a decreasing trend over the three phases.



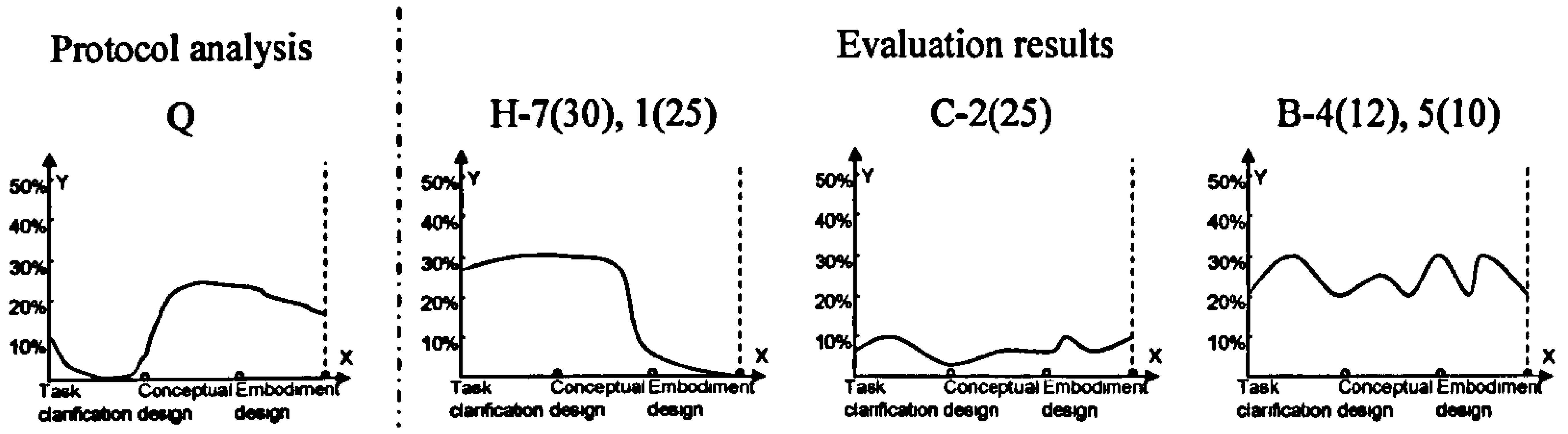
$WK_{A\text{-}Rq}$

Similar to $WK_{A\text{-}M}$, the evaluation results 'A' (viewed by designers 3, 4, and 5) and 'B' (viewed by designer 2) of $WK_{A\text{-}Rq}$ showed that most designers (four) had a similar view of $WK_{A\text{-}Rq}$'s overall trend, but with higher occurrence. Moreover, two experienced designers (designer 7 and 1) viewed $WK_{A\text{-}Rq}$ as decreasing as shown in trends 'G' and 'H'. Overall, the results of $WK_{A\text{-}M}$ and $WK_{A\text{-}Rq}$ indicated that the industrial designers considered these two elements to occur more frequently than those results obtained from the protocol analysis.



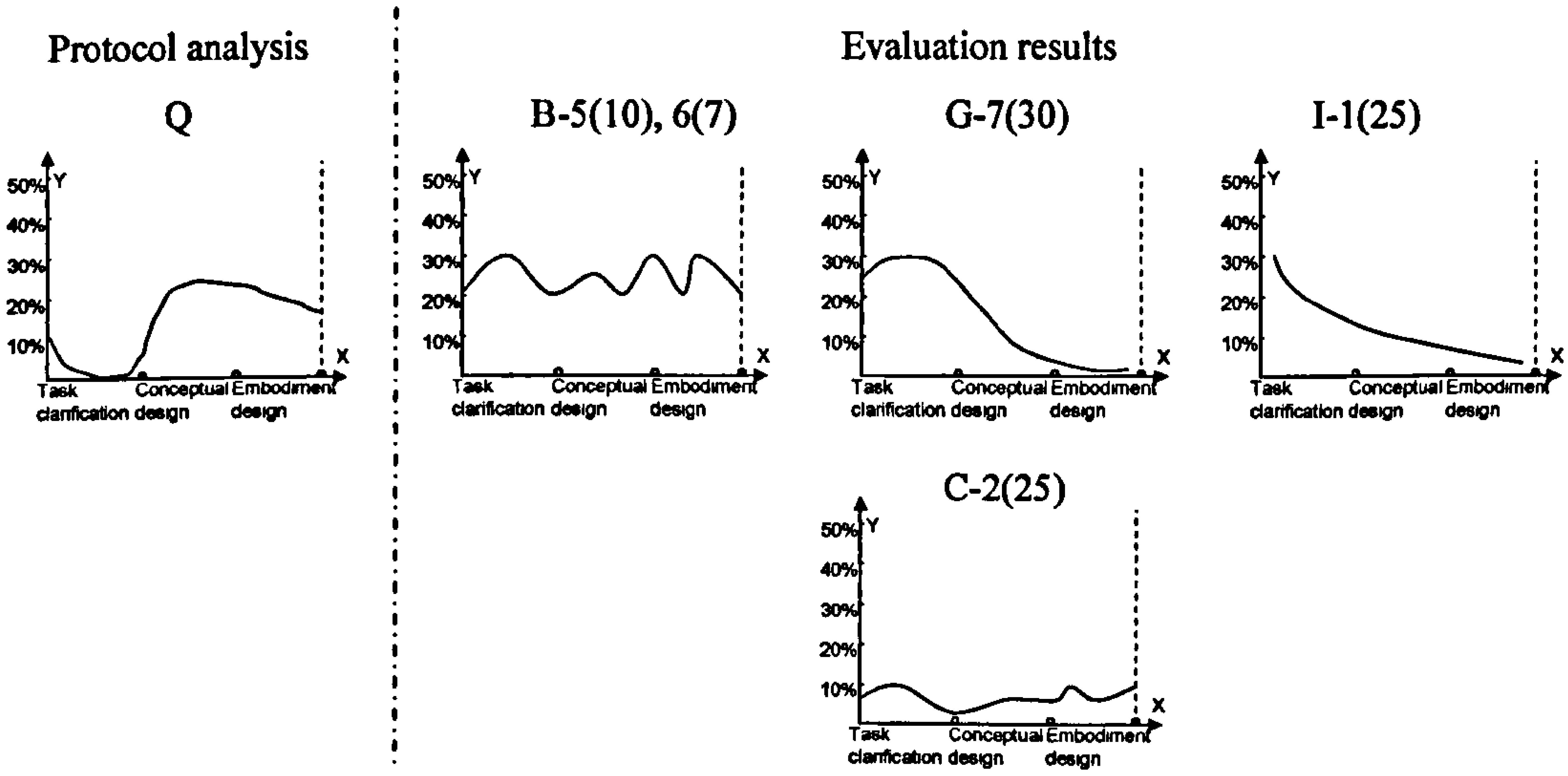
$WK_{A\text{-}Fe}$

Through the protocol analysis, $WK_{A\text{-}Fe}$ was seen to have trend 'Q' over the three design phases. Having little occurrence at the beginning of the design, its occurrence decreased to none and then increased and reached its peak in conceptual design, followed with a slight decrease in embodiment design phase. In contrast to the protocol analysis, the evaluation results for $WK_{A\text{-}Fe}$ were either decreasing ('H') or relatively stable ('C 'and 'B') over the three phases.



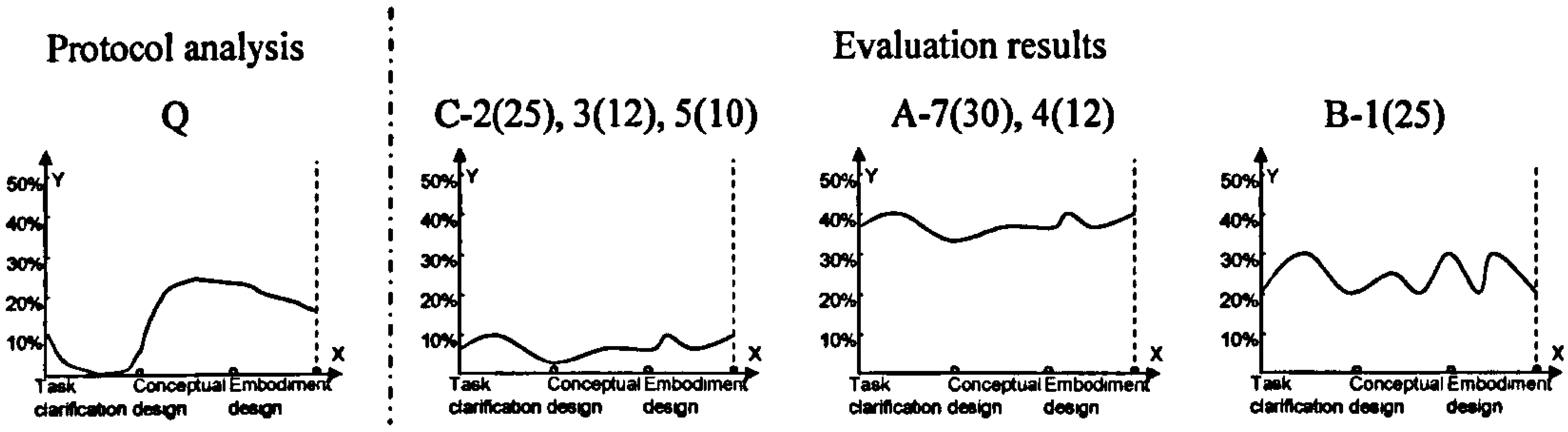
$WK_{A\text{-}Be}$

The trend of $WK_{A\text{-}Be}$ obtained from the protocol analysis was the same as that of $WK_{A\text{-}Fe}$, i.e., 'Q'. However, the evaluation resulted in four different main views, which were either decreasing (G viewed by designer 7 and I viewed by designer 1) or relatively stable ('B' viewed by designers 5 and 6 and 'C' viewed by designer 2) but with different proportions over the three phases. The difference between the results obtained from the protocol analysis and evaluation might be due to the difference between the student and commercial design projects, or individual and collaborative design.



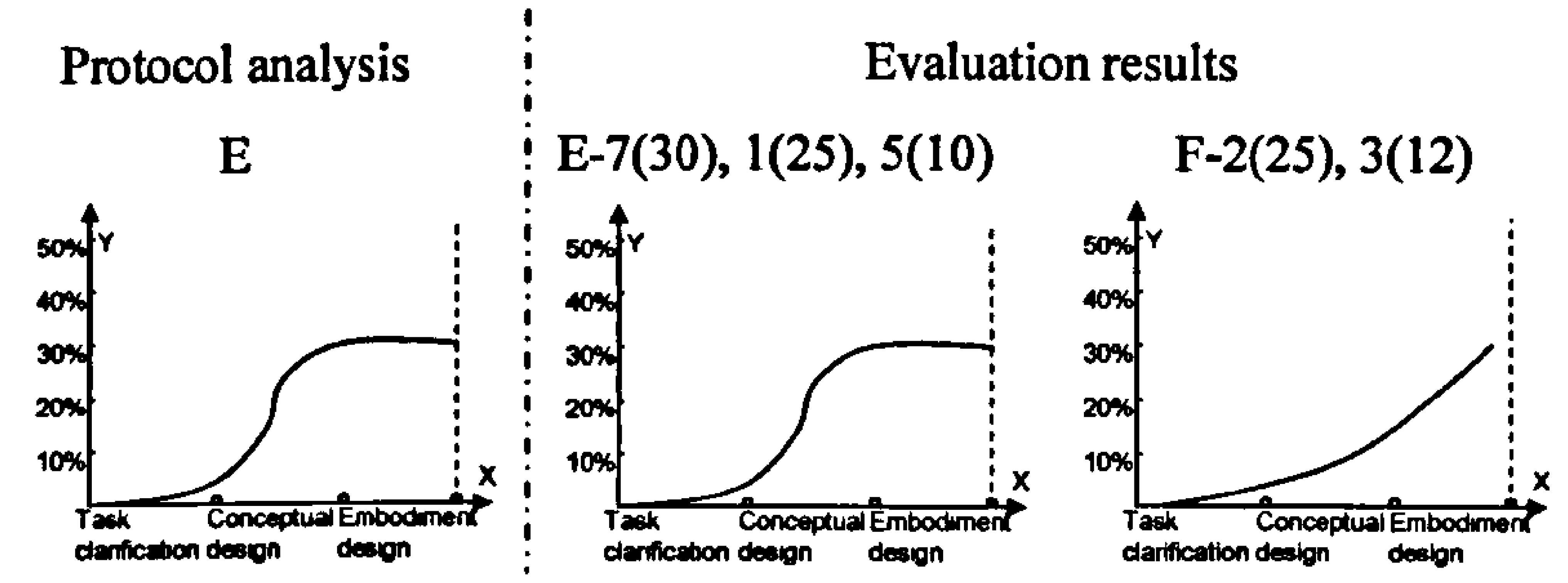
$WK_{A\text{-}Se}$

Similar to $WK_{A\text{-}Fe}$ and $WK_{A\text{-}Be}$, the protocol analysis resulted in trend 'Q' for $WK_{A\text{-}Se}$. In comparison, the evaluation showed that $WK_{A\text{-}Se}$ was considered by six designers to have a relatively stable trend, but with different degrees of proportion. The results are trend 'C' viewed by designers 2, 3, and 5, trend 'A' viewed by designers 7 and 4, and trend 'B' viewed by designer 1. The difference between the results obtained from the protocol analysis and evaluation might be due to the difference between the student and commercial design projects, or individual and collaborative design.



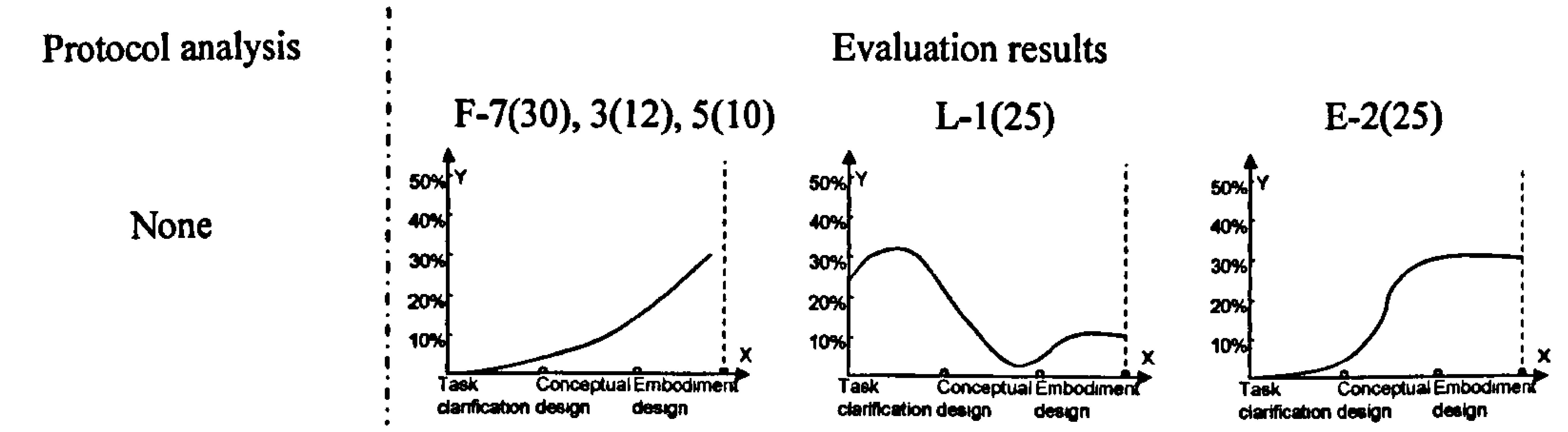
$WK_{A\text{-}Sis}$

Consistent with that obtained from the protocol analysis, the result of $WK_{A\text{-}Sis}$'s occurrence trend from the evaluation workshop is the same trend 'E', which were viewed by designers 7, 1, and 5. Moreover, designers 2 and 3 viewed it as increasing (trend 'F'), but with different proportions in conceptual design.



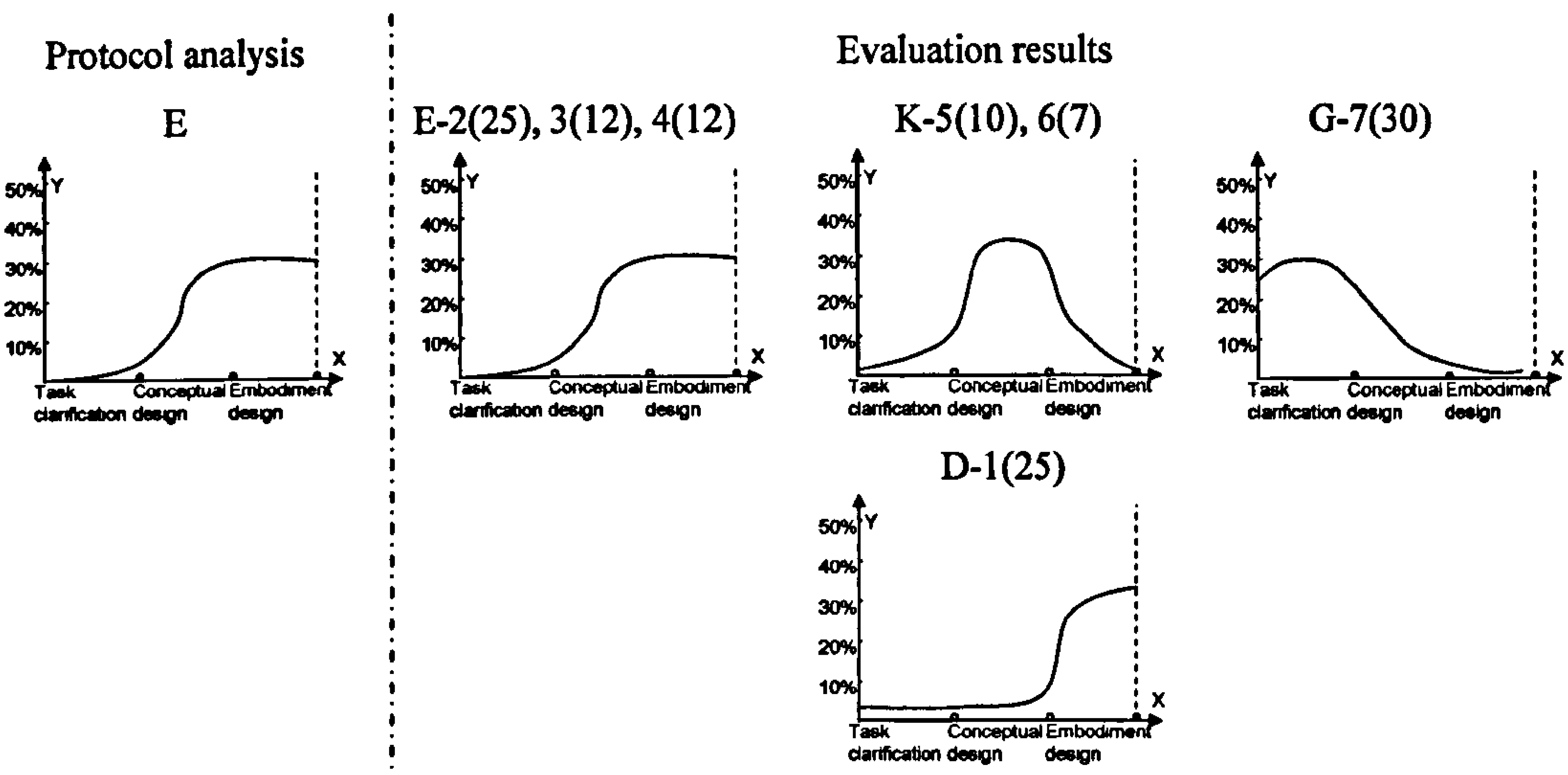
$WK_{A\text{-}Bis}$

No $WK_{A\text{-}Bis}$ was identified from the protocol analysis. However, three different results were obtained from the evaluation that had both decreasing and increasing trends. They are trend 'F' viewed by designers 7, 3, and 5, trend 'L' viewed by designer 1, and trend 'E' viewed by designer 2.



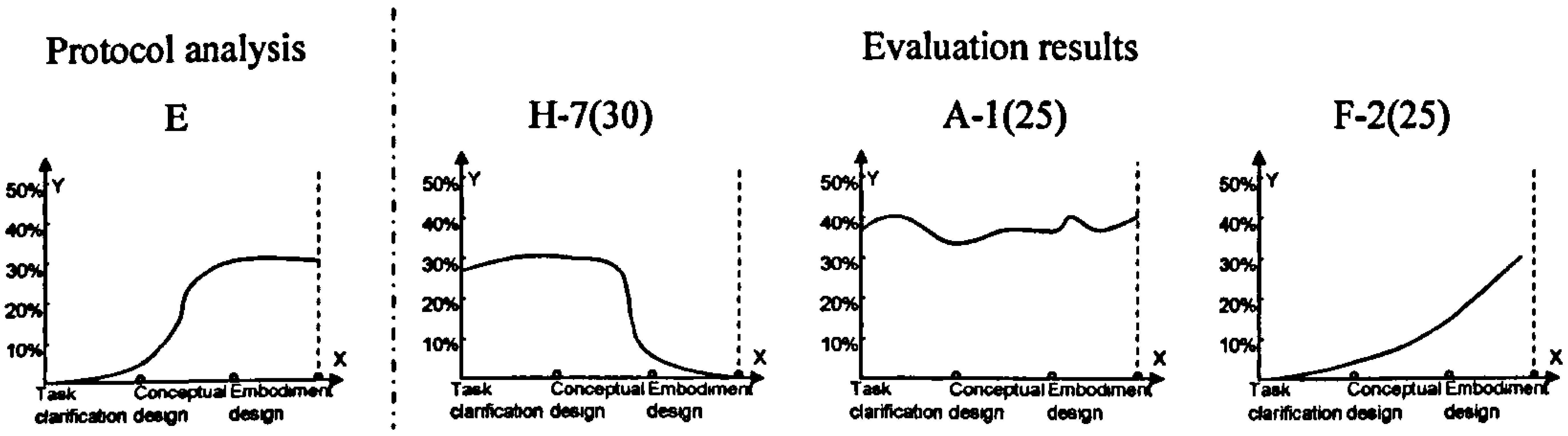
$WK_{A\text{-}Bit}$

Interpreted from $WK_{A\text{-}Sis}$, $WK_{A\text{-}Bit}$ was identified from the protocol analysis as having the same increasing trend 'E' with that of $WK_{A\text{-}Sis}$. During the evaluation, designers 2, 3, and 4 considered $WK_{A\text{-}Bit}$ had the same trend 'E' and designer 1 regarded it had a similar increasing trend 'D' with lower occurrence in conceptual design. However, there were also another two different results. One was convex 'K' viewed by designers 5 and 6 and the other was a decreasing trend 'G' viewed by designer 7.



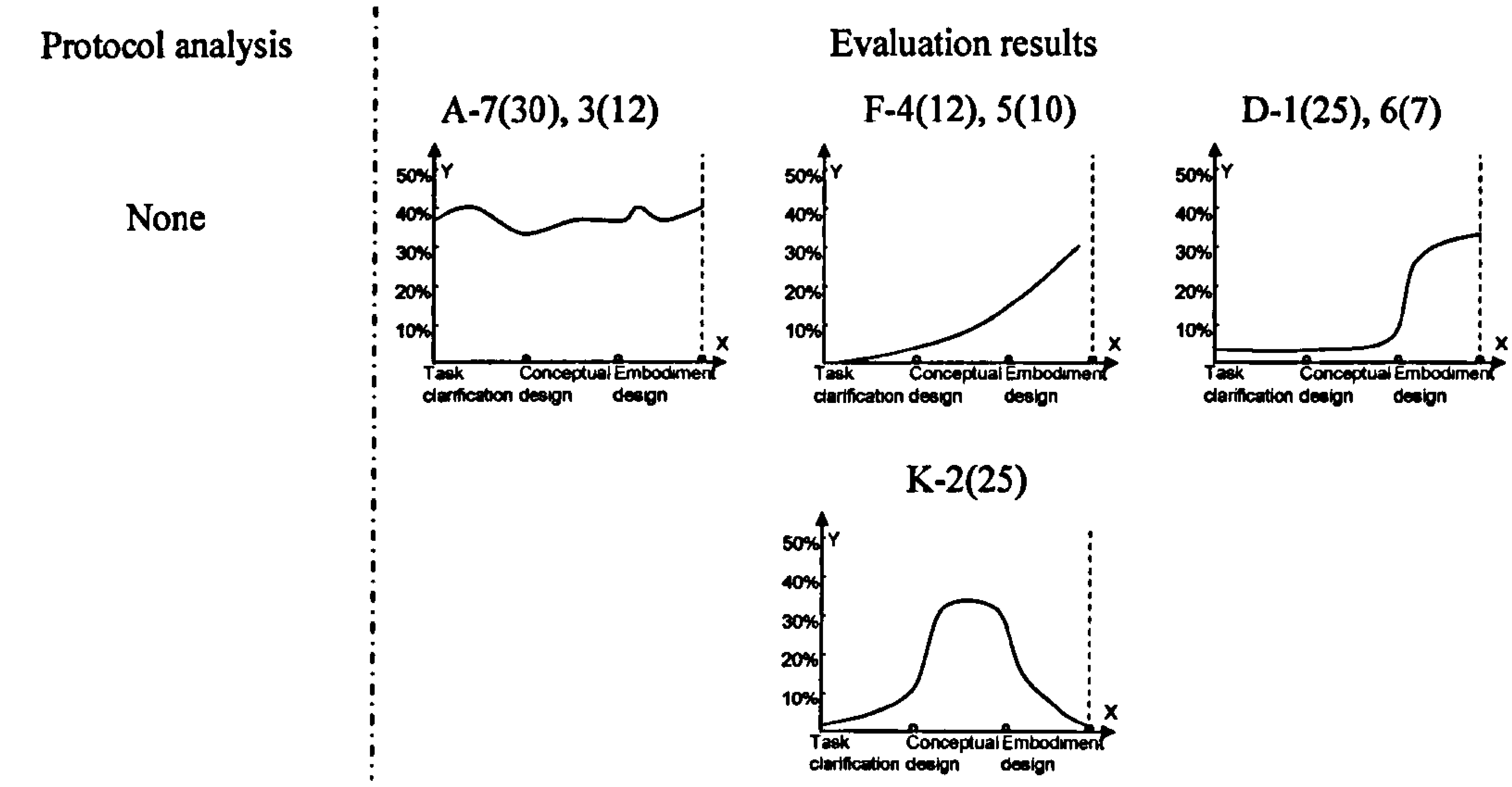
WK$_{A\text{-}Fit}$

The protocol analysis resulted in an increasing trend 'E' for *WK$_{A\text{-}Fit}$*. However, with the exception of one similar increasing trend 'F' viewed by designer 2, which lower occurrence proportion in conceptual design, the evaluation resulted in another two different trends. One was decreasing trend 'H' viewed by designer 7 and another was a relatively stable trend 'A' viewed by designer 1.



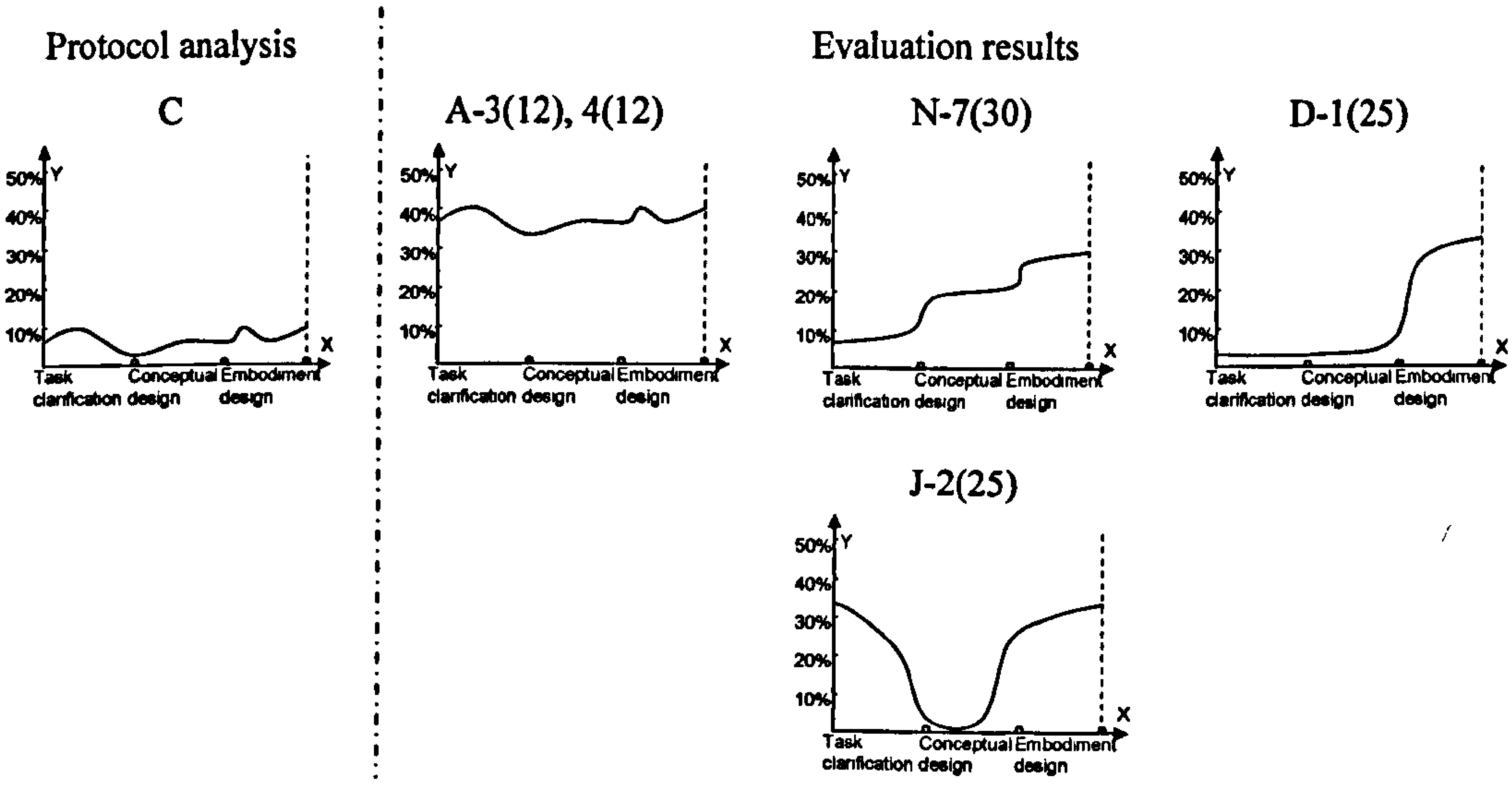
WK$_{A\text{-}CR}$

There was no *WK$_{A\text{-}CR}$* encoded during the protocol analysis. However, as mentioned in Chapter 6, this does not mean that it was not used by the designers. The results of the evaluation workshop showed that designers' views of *WK$_{A\text{-}CR}$* trend were different and four main trends were taken into account by the designers. These trends included one relatively stable trend 'A' viewed by designers 7 and 3, two increasing trends 'F' (viewed by designers 4 and 5) and 'D' (viewed by designers 1 and 6) with different increase rates at conceptual design, and one convex trend 'K' viewed by designer 2.



$WK_{A\text{-}Ct}$

$WK_{A\text{-}Ct}$ was identified to have a stable trend, 'C', with relatively little occurrence through the protocol analysis. However, the evaluation workshop resulted in four different views of its trend. Designers 3 and 4 viewed $WK_{A\text{-}Ct}$ had a relatively stable trend 'A', which is similar to trend 'C' but with higher proportion. Two other experienced designers (7 and 1) considered that $WK_{A\text{-}Ct}$ had an increasing trend but with different proportions during conceptual design ('N' and 'D'). There was also one experienced designer (2) who regarded $WK_{A\text{-}Ct}$ had a concave trend 'J'. In comparison to the results obtained from the protocol analysis, designers generally believed that $WK_{A\text{-}Ct}$ had a higher proportion.



Key findings of the evaluation of WK_A:

- $WK_{A\text{-}Rq}$, $WK_{A\text{-}Se}$, $WK_{A\text{-}Fit}$, and $WK_{A\text{-}Bit}$ were considered by all the designers to occur "Often" or "Very often". Besides "Often" and "Very often", other elements were considered by only one, two or three designers to occur "Occasionally".
- Designers had similar view of six WK_A elements' frequency as that obtained from the protocol analysis. The other five i.e., $WK_{A\text{-}Rq}$, $WK_{A\text{-}Bis}$, $WK_{A\text{-}Bit}$, $WK_{A\text{-}Fit}$, and $WK_{A\text{-}CR}$, had different results of frequency.

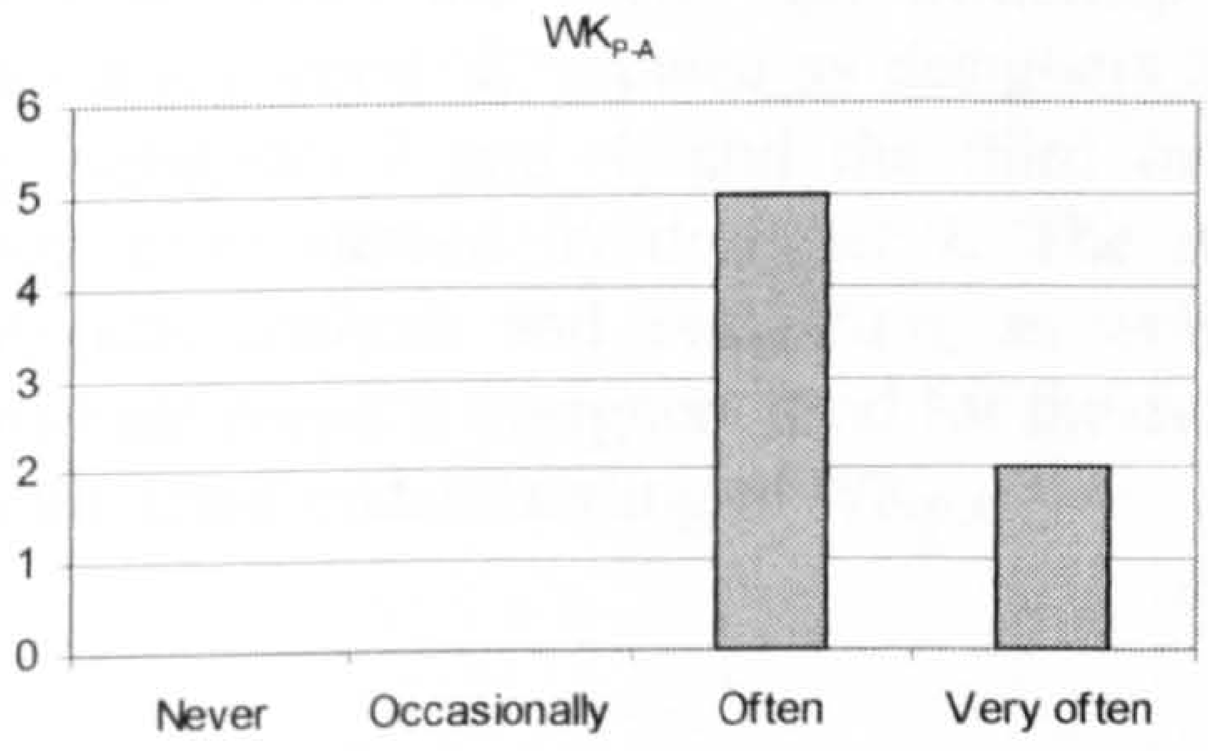
- Of the 11 current working artefact knowledge elements, two ($WK_{A\text{-}Sis}$ and $WK_{A\text{-}Bit}$) were viewed by the designers to have the same trends as those obtained from the protocol analysis, two ($WK_{A\text{-}M}$ and $WK_{A\text{-}Rq}$) were considered to have similar trends, and seven other elements were regarded to have different results with those obtained from the protocol analysis.
- Not only there was difference between the results obtained from the protocol analysis and evaluation, but also a diversity of views was found among designers' towards the elements' occurrence trends.
- The different results obtained from the evaluation with that from the protocol analysis might because of the difference between the analysed student project and commercial design projects, as well as between individual and collaborative design projects.

8.2.3 Current working design process knowledge

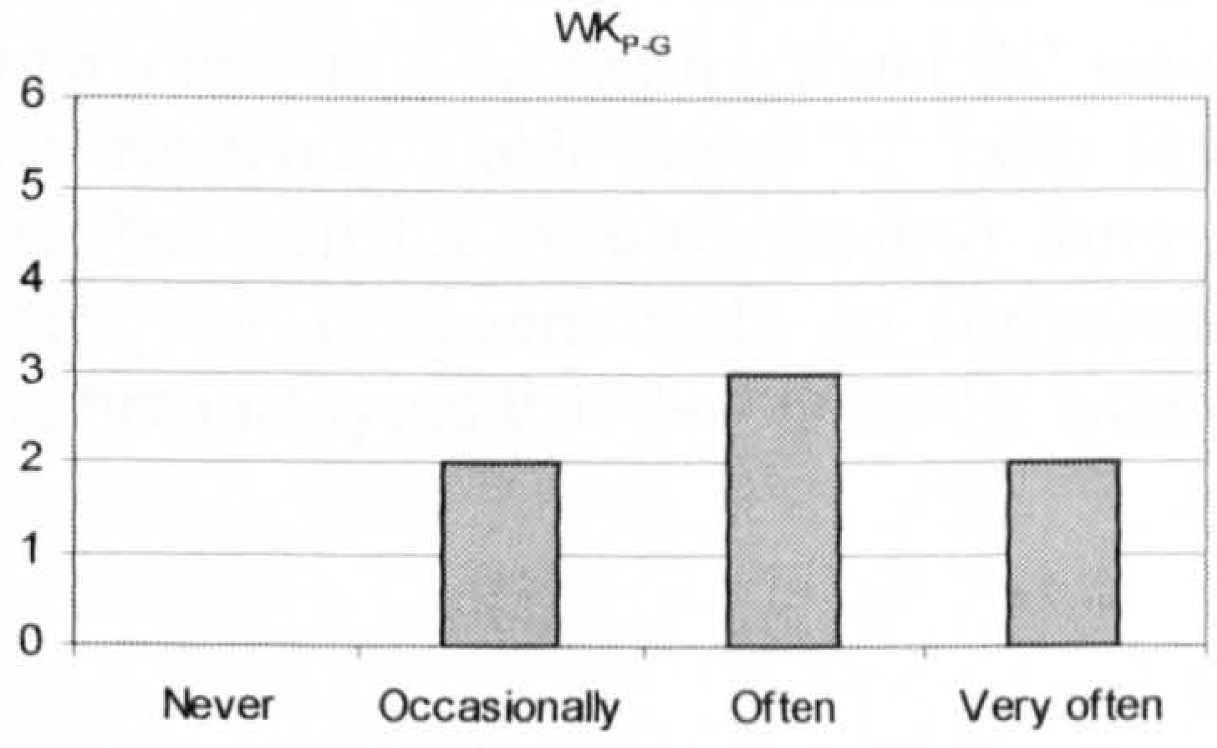
Frequency

The seven designers' views of the frequency of the seven current working design process knowledge elements are shown in Figure 8-4. The charts in the figure reveal whether designers had similar view of the occurrence frequency of the elements or not. It can be seen that all the elements were considered by the designers to occur during designing with different levels of frequency. Among them, $WK_{P\text{-}A}$, $WK_{P\text{-}R}$, and $WK_{P\text{-}I}$ were considered by all the designers to occur "Often" or "Very often", while the other four elements were considered by one or two designers to occur "Occasionally".

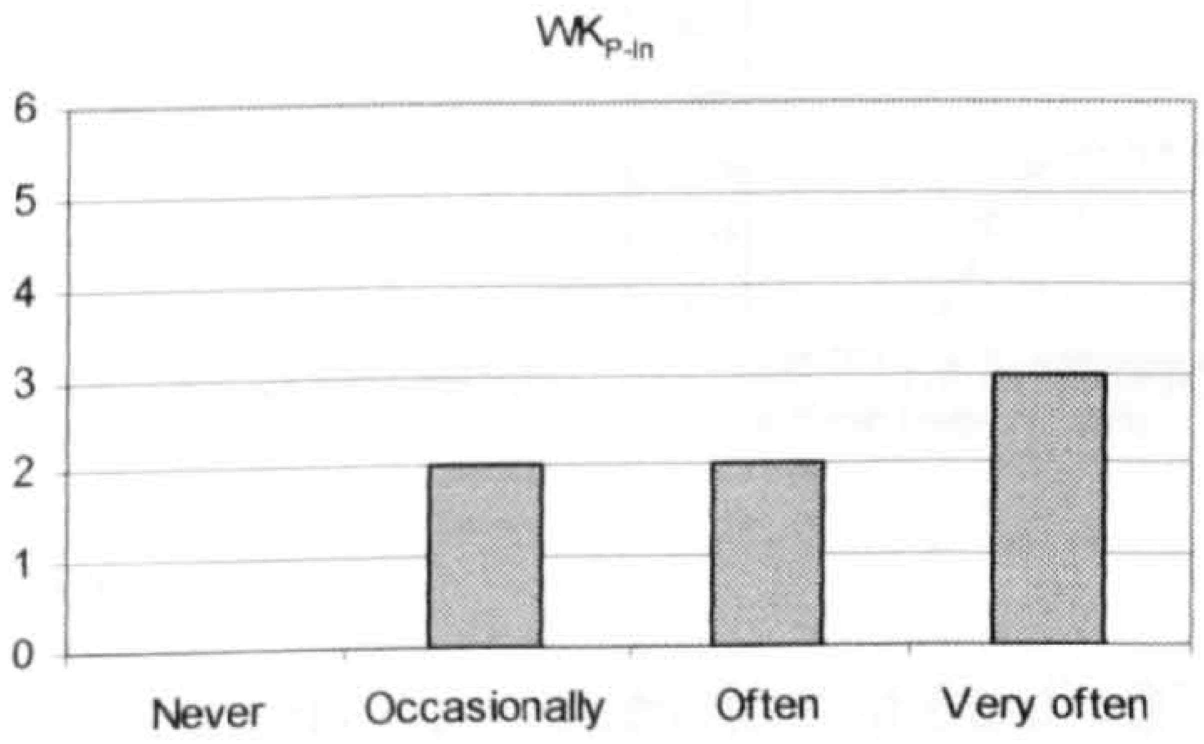
Compare to their average occurrence percentage listed in Table 6-6, it can be found that of the eleven knowledge elements, three of them had different results from that obtained from the protocol analysis, i.e., $WK_{P\text{-}In}$, $WK_{P\text{-}Out}$, and $WK_{P\text{-}R}$. For other four process elements, there were at least two designers had the same view of the elements' frequency as that obtained from the protocol analysis. Hence they are considered as had the similar results as that of the protocol analysis.



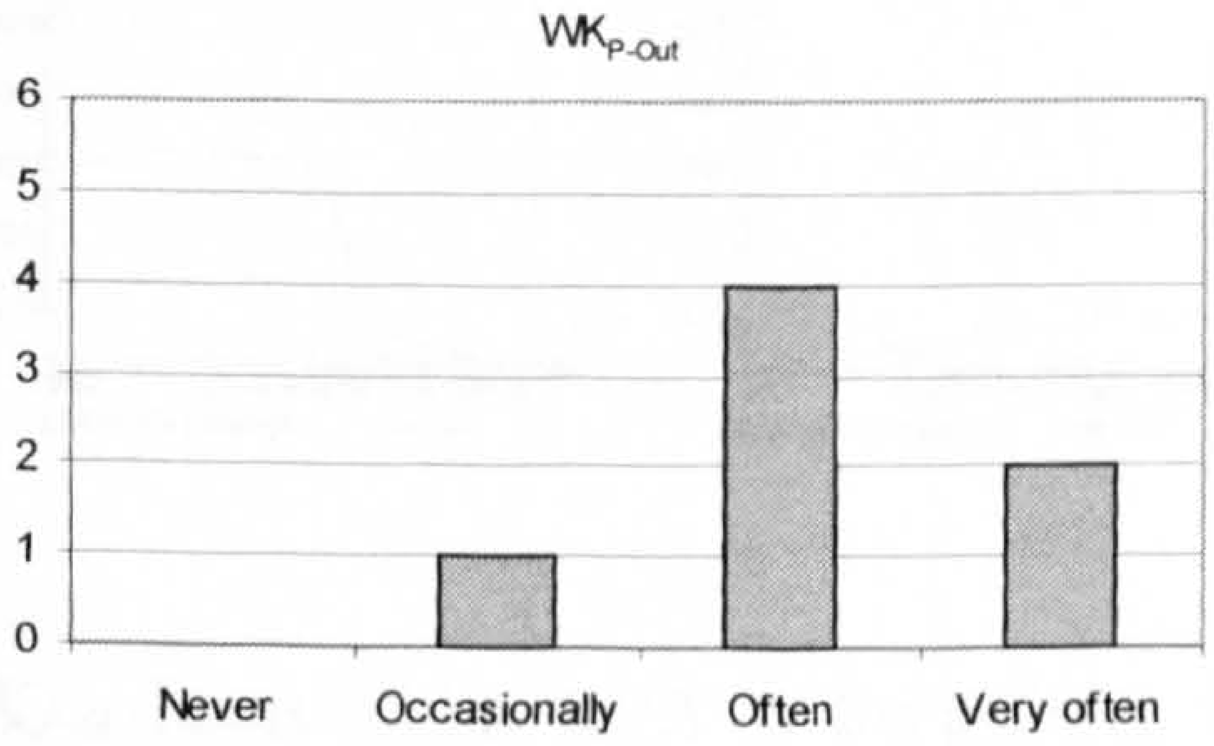
Protocol analysis: Very often



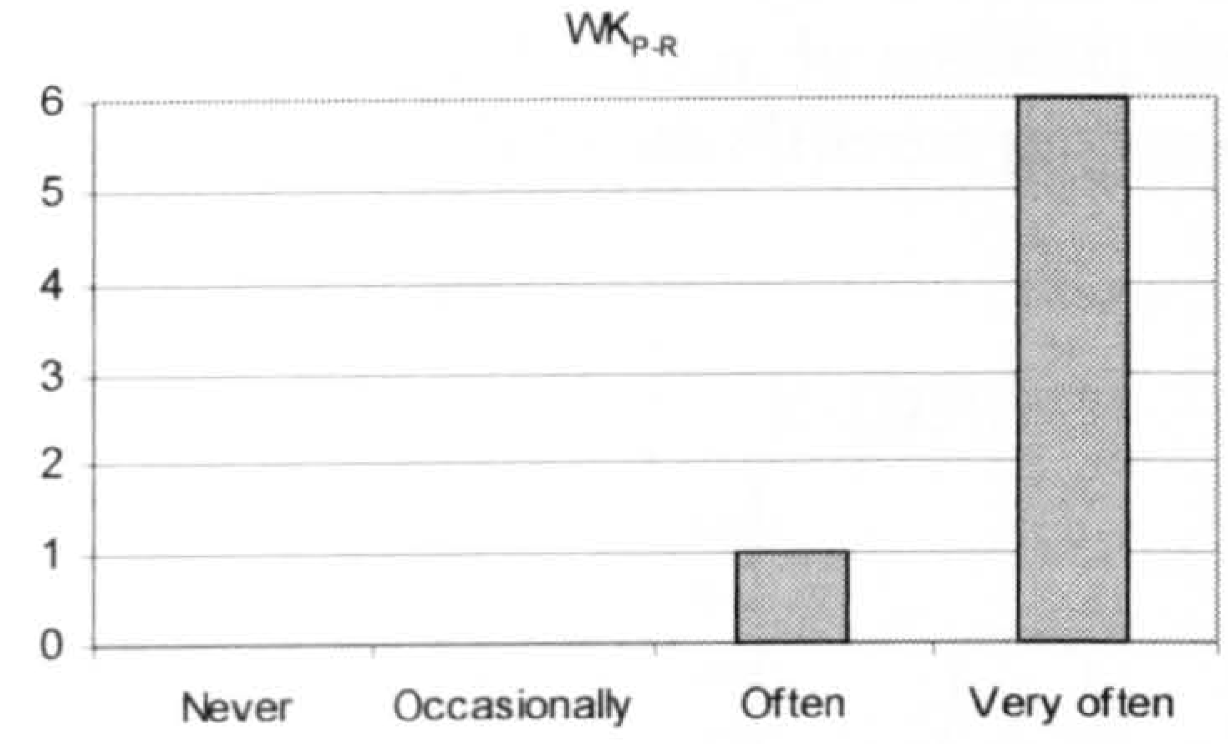
Protocol analysis: Often



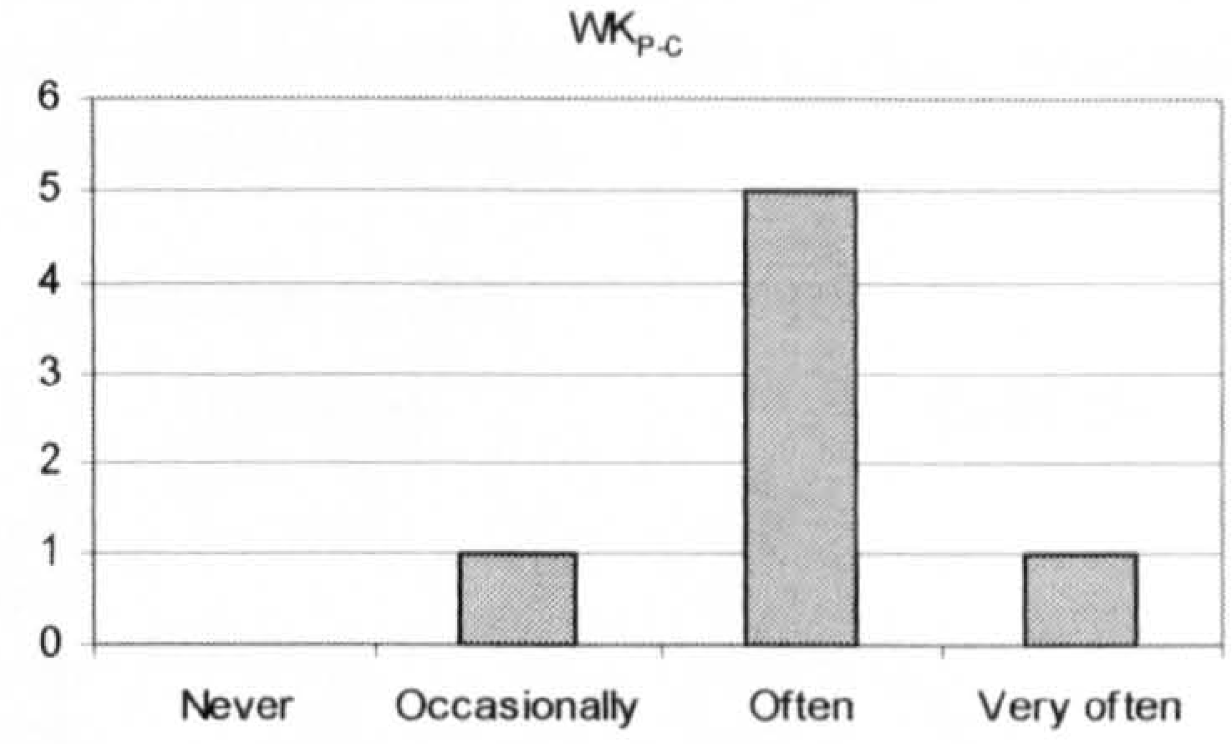
Protocol analysis: Never



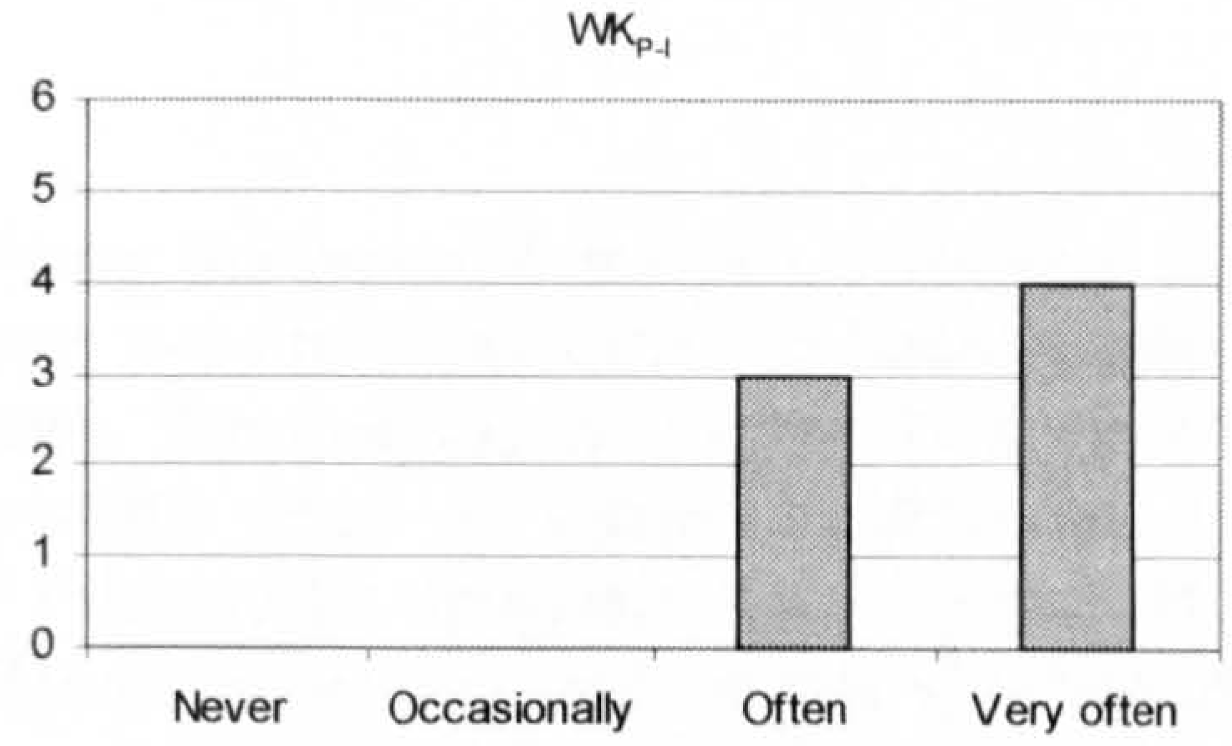
Protocol analysis: Occasionally



Protocol analysis: Often



Protocol analysis: Often



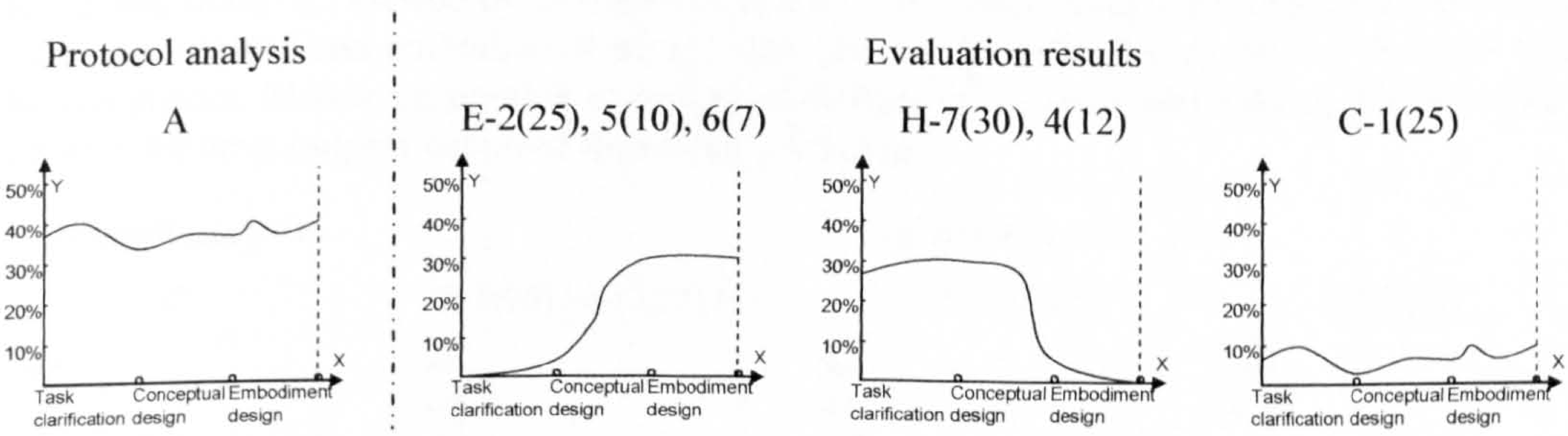
Protocol analysis: Often

Figure 8-4: Occurrence frequency of WK_P – Evaluation

Occurrence trend

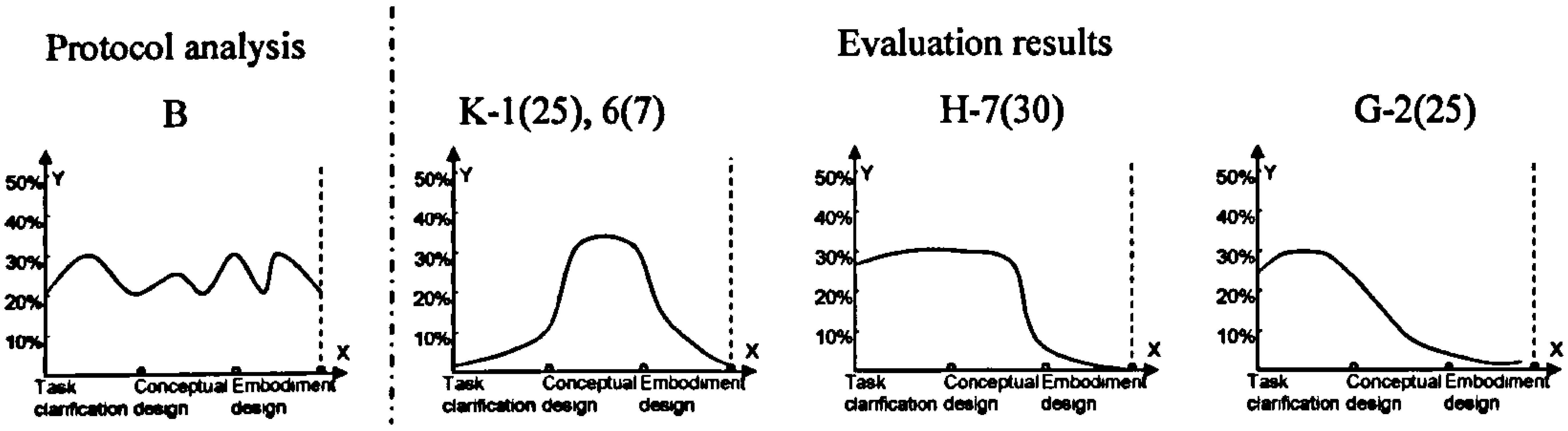
$WK_{P\text{-}A}$

Based on the protocol analysis, the occurrence trend of $WK_{P\text{-}A}$ was a relatively stable trend 'A' with relatively higher frequency than other elements. However, the three main trends obtained from the evaluation workshop were seen to be different in that one was an increasing trend 'E' viewed by designers 2, 5, and 6, one was a decreasing trend 'H' viewed by designers 7 and 4, and the third one was a relatively stable trend 'C' with lower proportion viewed by designer 1. The difference between the results obtained from the protocol analysis and evaluation, as well as among the designers could be attributed to different projects designers used for the evaluation, product types that they normally work on, or different understanding of $WK_{P\text{-}A}$.



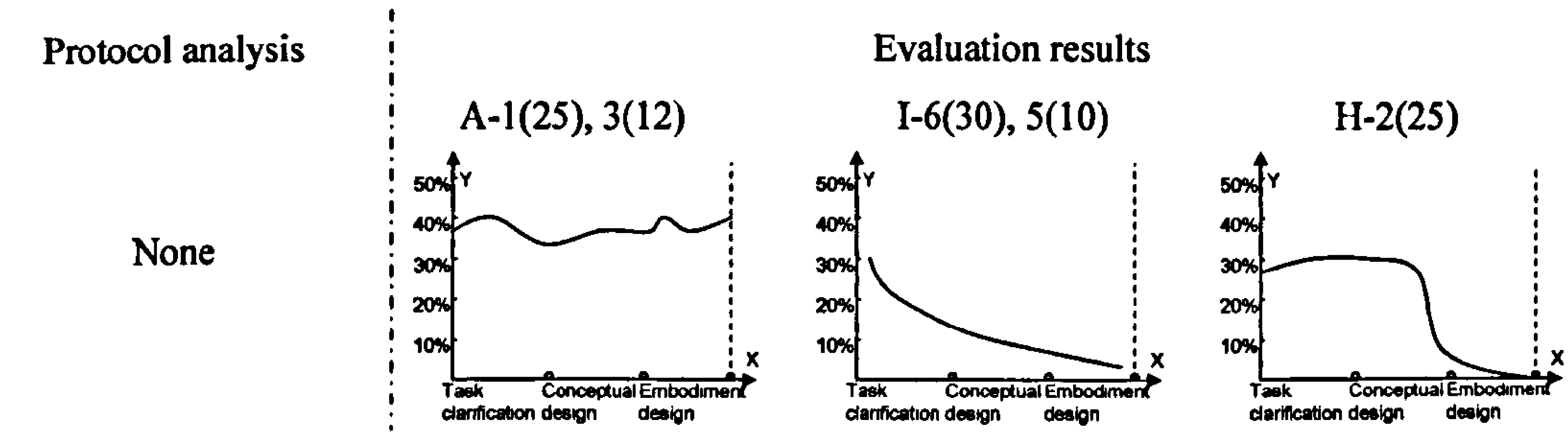
$WK_{P\text{-}G}$

The protocol analysis resulted in trend 'B' for $WK_{P\text{-}G}$ that is similar to 'A' of the activity, but with lower occurrence proportion. However, the results of the evaluation workshop revealed three different trends. Designers 1 and 6 thought that $WK_{P\text{-}G}$ had a convex trend 'K' with its peak in conceptual design. In addition, designers 7 and 2 considered $WK_{P\text{-}G}$ had decreasing trends ('H' and 'G') with different proportions in conceptual design.



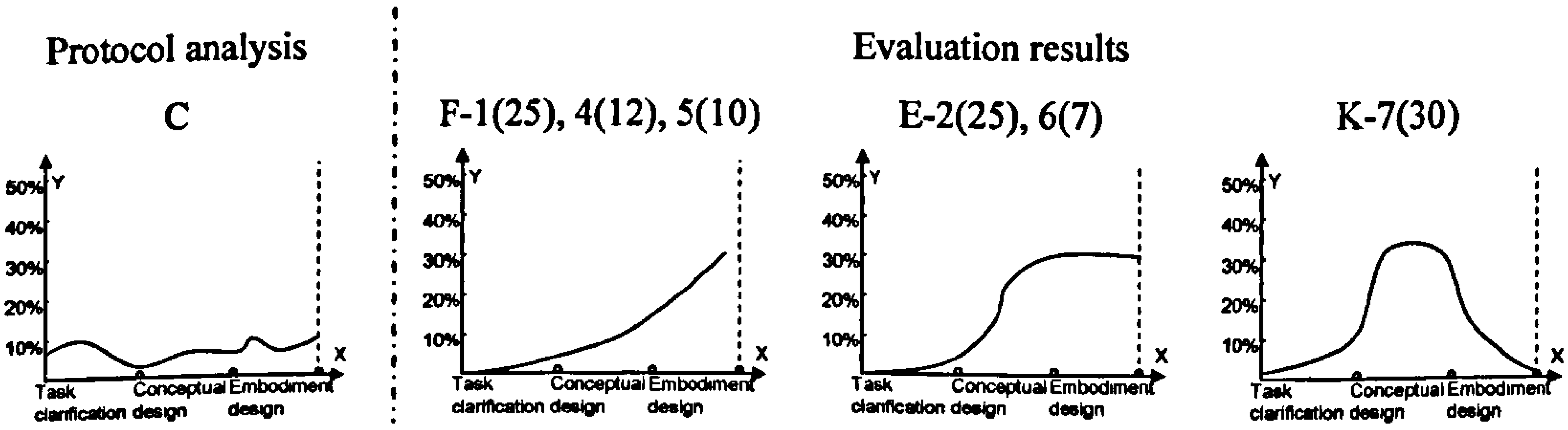
$WK_{P\text{-}In}$

No $WK_{P\text{-}In}$ was encoded during the protocol analysis. However, as mentioned in Chapter 6, this does not mean that there were no input elements because most inputs were encoded as artefact knowledge elements. The evaluation resulted in three main trends of $WK_{P\text{-}In}$. Of these, one was a relatively stable trend 'A' viewed by designers 1 and 3, and the other two were decreasing trends 'I' (viewed by designers 6 and 5) and 'H' (viewed by designer 2). These two trends have different decreasing rates in task clarification and conceptual design, which resulted in different proportion in different design phase.



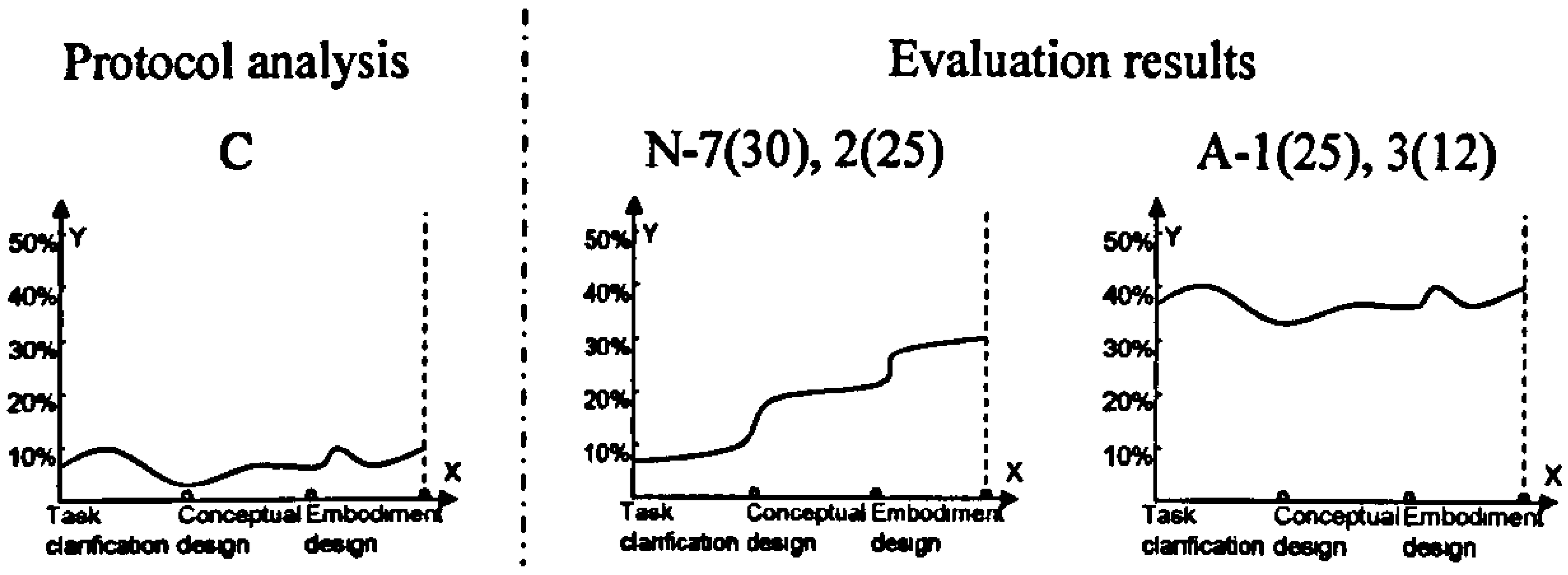
$WK_{P\text{-}Out}$

$WK_{P\text{-}Out}$ was encoded with a little occurrence during the protocol analysis and this in turn had resulted in trend C. Similar to the input, its low occurrence was because most outputs were encoded as artefact knowledge elements. Through the evaluation workshop, three main trends were identified. In two of them, the designers considered that the output had an increasing trend over the three design phases. They are trend 'F' viewed by designers 1, 4, and 5 and trend 'E' viewed by designers 2 and 6. These two trends have different increasing ratios conceptual and embodiment design that resulted in different proportion in these two design phases. Moreover, another experienced designer (7) considered $WK_{P\text{-}Out}$ had a convex trend, with most outputs occurred in conceptual design.



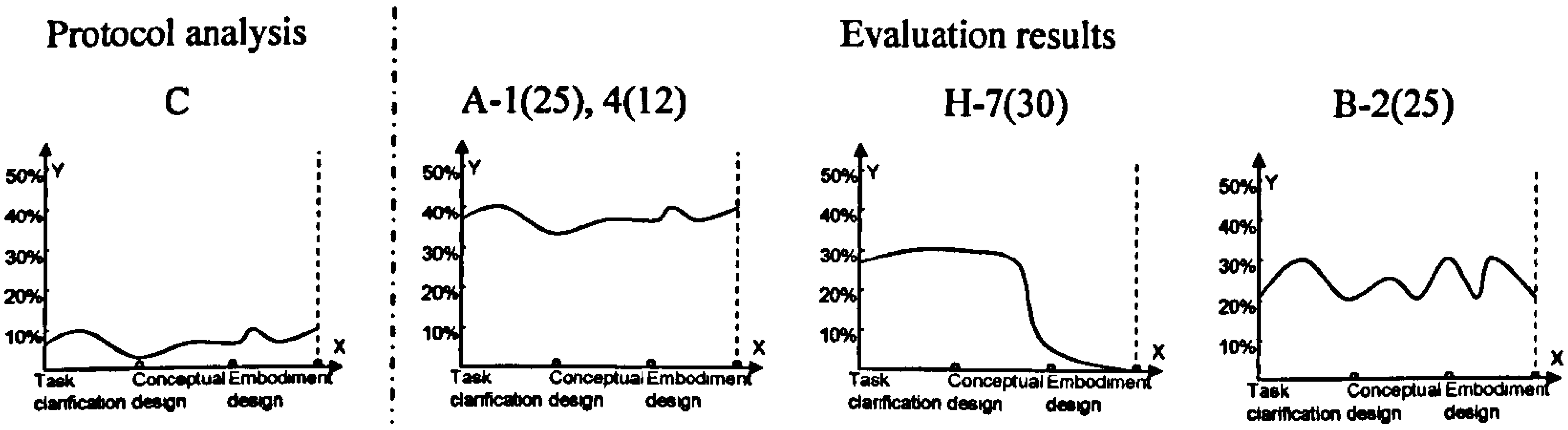
$WK_{P\text{-}R}$

$WK_{P\text{-}R}$ was encoded with a little occurrence during the protocol analysis, which resulted in a relatively stable trend 'C'. As mentioned in Chapter 6, its low occurrence of $WK_{P\text{-}R}$ was because resource allocation in the analysed individual project was relatively low, and also that most information resources were encoded as artefact knowledge elements rather than resource elements. As a result of the evaluation workshop, two main results of $WK_{P\text{-}R}$'s trend were identified that were different from or similar to trend 'C'. One was increasing trend 'N' viewed by designers 7 and 2, and the other was the relatively stable trend 'A' viewed by designers 1 and 3. Trend 'A' is a similar stable trend as 'C' but with higher frequency. The difference between the results obtained from the protocol analysis and evaluation workshop might be explained that the analysed resources were not a complete set of resources that occurred during the design.



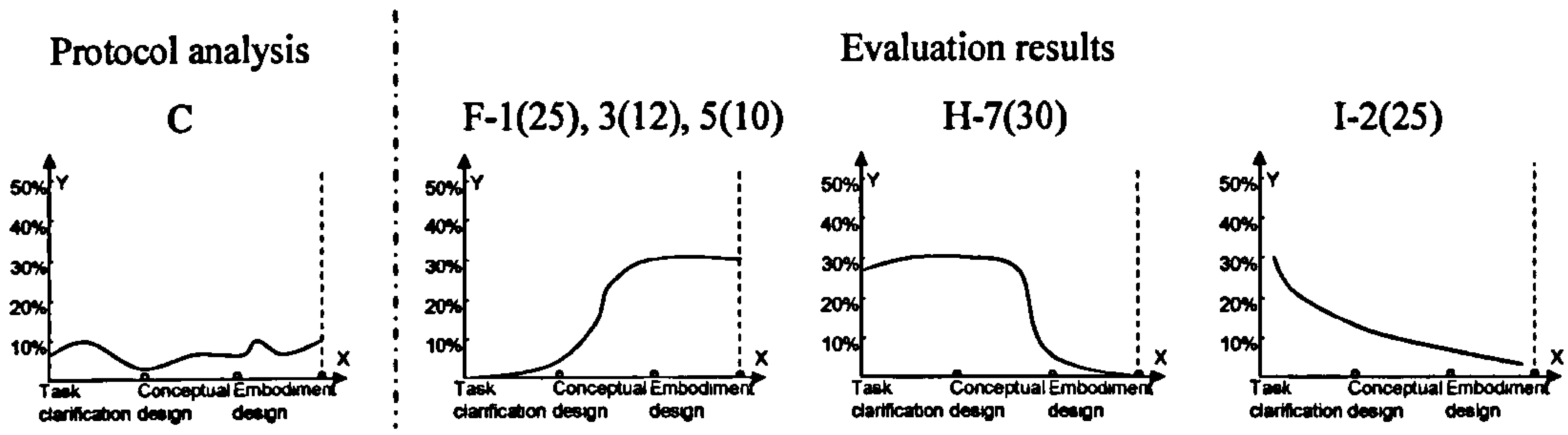
$WK_{P\text{-}C}$

Similar to the resource, $WK_{P\text{-}C}$ was encoded a little during the protocol analysis and resulted in trend 'C'. The evaluation resulted in three main trends. Two of them ('A' viewed by designers1 and 4 and 'B' viewed by designer 2) were similar to 'C', but with higher occurrence proportion. Another result was 'H' viewed by experienced designer 4, which occurred with a higher proportion in task clarification and conceptual design and decreased during embodiment design. The results obtained from the protocol analysis and evaluation were different partially because the encoded context during the protocol analysis was not the complete set of context.



$WK_{P\text{-}I}$

Similar to the previous three elements, $WK_{P\text{-}I}$ was encoded a little during the protocol analysis, which resulted in trend 'C'. The evaluation resulted in three main different trends. Of these, increasing trend 'F' was identified by designers 1, 3, and 5, and decreasing trends 'H' was identified by designer 7 and 'I' was identified by designer 2. Though both 'H' and 'I' are decreasing, they have different decreasing ratios at task clarification and conceptual design, which resulted in different frequency at these two phases.



Key findings of the evaluation of WK_P:

- WK_{P-A}, WK_{P-R}, and WK_{P-I} were considered by all the designers to occur either "Often" or "Very often" during the design process. The remaining four design process elements were regarded by only one or two of the designers to occur "Occasionally".
- Designers had similar view of four current working design process elements' (WK_{P-A}, WK_{P-G}, WK_{P-C}, and WK_{P-I}) frequency as that obtained from the protocol analysis. The other three, i.e., WK_{P-In}, WK_{P-Out}, and WK_{P-R}, had different results of frequency.
- Of the seven design process elements, the results of two elements (WK_{P-R} and WK_{P-C}) obtained from the evaluation workshop were similar to that obtained from the protocol analysis. The other five elements, however, were viewed to have different trends.
- One reason of the difference between the results obtained from the protocol analysis and evaluation was due to the encoding of WK_{P-G}, WK_{P-In}, WK_{P-Out}, and WK_{P-R}. That is, most of design elements were encoded as artefact knowledge elements with high priority. Hence the analysed process elements could not be regarded as complete.
- Other reasons of the difference might be caused by difference between the analysed student design project and company commercial projects, or between individual and collaborative design.

8.2.4 Comparison of different designers' views of elements trends

In the previous three sections, the results of the occurrence trends of knowledge elements the obtained from the evaluation workshop were presented and compared with the results obtained from the protocol analysis. A comparison of the results revealed that of the 22 knowledge elements, 2 elements had the same results, 7 elements had similar results, and the remaining 13 elements had different results. Table 8-3 summarises the results of the evaluation workshop.

Table 8-3: Evaluation of the knowledge elements trends

	Same	Similar	Different	Total
DK_A	0	3	1	4
WK_A	2	2	7	11
WK_P	0	2	5	7
Total	**2**	**7**	**13**	**22**

The evaluation results show that, for most of the knowledge elements, designers had different views of the same element's occurrence trend. Table 8-4 shows the number of results for the same element viewed by the designers. For example, the first column shows that there were eight elements were viewed by the seven designers with four results. It can be found from the table, that for each element, there were at least four similar or different views. There was even one element (WK_{A-Fit}) was viewed by the seven designers with seven similar or different results.

Table 8-4: Number of results of elements' trends viewed by designers

Number of results	4	5	6	7
Number of elements	8	8	5	1

Due to the diversity of designers' views on the design knowledge elements occurrence trends, this section compares the results from different designers, and discusses the factors that might cause such diversity.

➢ **Two designers with similar work experience, same working focus, and used the same project for the evaluation**

Designers 3 and 5 were both from SFS and had similar duration of design experience, which were 10 and 12 years respectively. They work with the same product focus and used the same project for the questionnaire during the workshop. A comparison between their results showed that, of the 22 design knowledge elements, 5 elements had identical results, 6 had similar but with different proportions in different design phase, and the remaining 11 elements were seen to have different occurrence trends. The results indicate that even with similar design experience and the same project used for the evaluation, the two designers had different views of half of the knowledge elements' occurrence trend. Some explanations for this finding could be related to the designers' different understanding of the knowledge elements, which in turn affected their views on the occurrence trend.

➢ **Two designers from the same company, with same work experience, but worked on different product and used different projects for the evaluation**

Working in the same company, designer 1 focused on '"Ship electrical systems" and designer 2's work focus was on "Ship concepts assessment". Both of them had 25 years design experience, and they used different projects for the evaluation. A comparison of their results showed that there were 5 similar and 17 different trends (i.e. there were no same trends). Designers 3 and 4 had also same design experience, but focused on different product and they used different projects for the evaluation. A comparison between their results showed that there were 4 same, 3 similar, and 15 different trends. As a result, it could be agued that the difference in the nature of the projects used for the evaluation and different product types that the designers normally worked on might have affected the designers' views on the element's occurrence trend.

➢ **Two designers from different companies with similar design experiences**

With similar design experiences (25 and 30 years), designers 1 and 7 came from different companies, and therefore had different product focuses and used different projects for the evaluation. A comparison of their results showed that 2 elements had the same results, 6 had similar results, and 14 elements had different results. Such results imply that different projects used for the evaluation and product types that the designers normally worked on could have affected designers' views on the same element's occurrence trend.

8.2.5 Summary of the knowledge elements trend evaluation

Having presented the evaluation results and compared with that obtained from the protocol analysis, this section summarises the trend evolution of the knowledge elements that involved in the coupling.

- While all the knowledge elements were considered by designers to occur during designing with different frequencies, some were viewed to occur either "Often" or "Very often", and some others were considered by one or two designers to occur "Occasionally". Therefore, it can be seen that the designers had common view of the frequency of only part of the knowledge elements.

- Though designers had different views of the elements' occurrence frequency, there were at least two designers had same view of the frequency of the four DK_A ($DK_{A\text{-}G}$, $DK_{A\text{-}Bit}$, $DK_{A\text{-}Fit}$, and $DK_{A\text{-}Sis}$), six WK_A ($WK_{A\text{-}M}$, $WK_{A\text{-}Fe}$, $WK_{A\text{-}Be}$, $WK_{A\text{-}Se}$, $WK_{A\text{-}Sis}$, $WK_{A\text{-}Ct}$), and four WK_P ($WK_{P\text{-}A}$, $WK_{P\text{-}G}$, $WK_{P\text{-}C}$, and $WK_{P\text{-}I}$) as that obtained from the protocol analysis.
- Of the 22 evaluated elements, 2 ($WK_{A\text{-}Sis}$ and $WK_{A\text{-}Bit}$) were viewed with same trend as that obtained from the protocol analysis, while 7 ($DK_{A\text{-}G}$, $DK_{A\text{-}Bit}$, $DK_{A\text{-}Fit}$, $WK_{A\text{-}M}$, $WK_{A\text{-}Rq}$, $WK_{P\text{-}R}$, and $WK_{P\text{-}C}$) were viewed with similar, and 13 were viewed with different trends.
- The difference between the results obtained from protocol analysis and evaluation workshop could be due to, among others, the difference between student and commercial design projects, as well as between individual and collaborative design projects.
- The difference between the process elements results obtained from the protocol analysis and the evaluation workshop might because of the encoding of $WK_{P\text{-}G}$, $WK_{P\text{-}In}$, $WK_{P\text{-}Out}$, and $WK_{P\text{-}R}$. That is, these elements were encoded as artefact knowledge elements with higher priority. Hence the analysed process elements could not be regarded as complete.
- For most of the elements, different designers appeared to have a diversity of views of the same element's trend.
- The designers' different views of design elements might stem from designers' different design experiences, different product types that they normally worked on, and different projects used by them for the evaluation. It could also be related to the designers' different understanding of the knowledge elements.

8.3 Coupling

The coupling of the artefact and design process presented in Chapter 7 is composed of 19 creation and 17 employment links among the knowledge elements. To evaluate such coupling, the designers were asked to draw links of both creation and employment links in two diagrams based on their worked projects during the workshops. It should be noted that by the time of the evaluation workshops, the *link of employment* was still termed *link of containment*, though the meaning it conveyed was the same as the phrase *link of employment* that was adopted later.

As a result of the evaluation, 48 creation and 42 employment links were identified by the designers. The results showed that while some of the coupling links identified through the protocol analysis were same to those identified through the evaluation, there are some links identified through only either the protocol analysis, or the evaluation. The following two subsections present the evaluation of the coupling with regard to the *link of creation* and *link of employment*.

8.3.1 Cause-effect link of creation

The evaluation resulted in 48 creation links between the knowledge elements, which are listed in Table H-1, Appendix H. It was found that nine of them are the same as, or included in seven links that were identified from the protocol analysis. Table 8-5 lists the seven and nine creation links identified through the protocol analysis and evaluation in the first and second columns of the table respectively. The designers who identified the links during the evaluation are listed in the third column, with their reference number followed with duration of their experiences in the bracket. The last column shows whether the links listed in the first column were partially considered by the designers as coupling links. It could be found that three links identified from the protocol analysis were partially identified from the evaluation, i.e. '$WK_{A/F} \rightarrow WK_{P\text{-}A}$', '$WK_{A\text{-}S} \rightarrow WK_{P\text{-}G}$', and '$WK_{P/C} \rightarrow WK_{P\text{-}A}$'.

Table 8-5: Creation links identified through both the protocol analysis and evaluation

Protocol analysis	Evaluation	Designers	Note
CL.3: $DK_{A\text{-}G} \rightarrow WK_{P\text{-}I}$	$DK_{A\text{-}G} \rightarrow WK_{P\text{-}I}$	2(25)	
CL.4: $WK_{A/F} \rightarrow WK_{P\text{-}A}$	$WK_{A/It} \rightarrow WK_{P\text{-}A}$	5(10), 7(35)	Partially
	$WK_{A/Is} \rightarrow WK_{P\text{-}A}$	6(7)	
	$WK_{A\text{-}Bis} \rightarrow WK_{P\text{-}A}$	7(35)	
CL.5: $WK_{A\text{-}M} \rightarrow WK_{P\text{-}A}$	$WK_{A\text{-}M} \rightarrow WK_{P\text{-}A}$	7(35)	
CL.7: $WK_{A\text{-}S} \rightarrow WK_{P\text{-}G}$	$WK_{A\text{-}Se} \rightarrow WK_{P\text{-}G}$	5(10)	Partially
CL.9: $WK_{A\text{-}Rq} \rightarrow WK_{P\text{-}G}$	$WK_{A\text{-}Rq} \rightarrow WK_{P\text{-}G}$	5(10), 7(35)	
CL.17: $WK_{P/C} \rightarrow WK_{P\text{-}A}$	$WK_{P\text{-}I} \rightarrow WK_{P\text{-}A}$	2(25), 7(35)	Partially
CL.19: $WK_{P\text{-}I} \rightarrow WK_{P\text{-}G}$	$WK_{P\text{-}I} \rightarrow WK_{P\text{-}G}$	2(25)	

The 12 coupling links listed in Table 8-6 are those links that were identified only through the protocol analysis. Although they were not identified by the designers, it could not be said that they are not links of the coupling. One explanation for this is that the limited evaluation time might have constrained the designers to draw all the links that they used in their projects. Other reasons might be different design experiences, projects used for the evaluation, product types that the designers normally worked on, or the designers' understanding of the elements caused different views of the links. Hence the below links might be coupling links, but they were not identified through the evaluation.

Table 8-6: Creation links identified only through the protocol analysis

CL.1: $DK_A \rightarrow WK_{P\text{-}A}$	CL.2: $DK_A \rightarrow WK_{P\text{-}G}$	CL.6: $WK_{A\text{-}Rq} \rightarrow WK_{P\text{-}A}$
CL.8: $WK_{A\text{-}S} \rightarrow WK_{P\text{-}I}$	CL.10: $WK_{P\text{-}A} \rightarrow DK_A$	CL.11: $WK_{P\text{-}A} \rightarrow WK_{A/F}$
CL.12: $WK_{P\text{-}A} \rightarrow WK_{A/C}$	CL.13: $WK_{P\text{-}A} \rightarrow WK_{P\text{-}G}$	CL.14: $WK_{P\text{-}A} \rightarrow WK_{P\text{-}Out}$
CL.15: $WK_{P\text{-}G} \rightarrow WK_{P\text{-}A}$	CL.16: $WK_{P\text{-}G} \rightarrow WK_{P\text{-}G}$	CL.18: $WK_{P\text{-}C} \rightarrow WK_{P\text{-}I}$

During the evaluation, designers draw 48 creation links in total. Besides the nine that were also identified through the protocol analysis, there were 39 not considered as coupling links through the protocol analysis. An analysis of these 39 links showed that some of them could be combined to one link. For example, '$DK_A \rightarrow WK_{P\text{-}C}$' was identified by designer 7. It included the other three links identified by designer 2, i.e., '$DK_{A\text{-}Bit} \rightarrow WK_{P\text{-}C}$', '$DK_{A\text{-}Fit} \rightarrow WK_{P\text{-}C}$', and '$DK_{A\text{-}Sis} \rightarrow WK_{P\text{-}C}$'. Hence these four links were combined to one link '$DK_A \rightarrow WK_{P\text{-}C}$'. After combining all the links that could be combined, 32 links were considered as the creation links that were not identified through the protocol analysis, which are listed in Table 8-7. The two columns of 'Designers' in Table 8-7 list the reference number of the designers who identified the links, followed with the duration of their experiences in bracket. The designers' reference numbers that are coloured grey in the table indicate that he/she identified only part of the link. For example, designer 2 identified '$WK_{A\text{-}Se} \rightarrow WK_{P\text{-}In}$' that is part of the generalised link '$WK_{A/E} \rightarrow WK_{P\text{-}In}$' identified by designers 5, 6 and 7. Of these 32 links, 25 were identified by the experienced designers (their design experiences were over 25 years) or by more than two designers. The cells of these 25 links are highlighted grey in the table.

With the exception of four links identified by four designers and one link by three designers, the remaining links were identified only by one or two designers. This indicates that the designers had various views of the main creation links used in their projects. Such different views could be caused by their different design experiences, different projects used for the evaluation, product types that they normally worked on, as well as the designers' different understanding of the elements and links.

Table 8-7: 32 creation links identified only through the evaluation

Links	Designers	Links	Designers
$WK_{A/E} \rightarrow WK_{P-R}$	5(10)	$WK_{A/E} \rightarrow WK_{P-G}$	7(35)
$WK_{A/E} \rightarrow WK_{P-In}$	5(10), 6(7), 7(35), 2(25)	$WK_{A/It} \rightarrow WK_{P-Out}$	6(7)
$WK_{A/Is} \rightarrow WK_{P-In}$	3(12), 5(10)	$WK_{A/Is} \rightarrow WK_{P-Out}$	5(10)
$WK_{A-Sis} \rightarrow WK_{P-Out}$	7(35)	$WK_{A-CR} \rightarrow WK_{P-In}$	2(25)
$WK_{A-Ct} \rightarrow WK_{A/It}$	7(35), 1(25)	$WK_{A-Ct} \rightarrow WK_{A-Rq}$	2(25)
$WK_{A-Ct} \rightarrow WK_{P-In}$	5(10), 4(12), 3(12), 2(25)	$WK_{A-Ct} \rightarrow WK_{P-R}$	7(35)
$WK_{A-M} \rightarrow WK_{A-Rq}$	2(25)	$WK_{A-M} \rightarrow WK_{P-G}$	5(10)
$WK_{A-M} \rightarrow WK_{P-In}$	5(10), 3(12)	$WK_{A-M} \rightarrow WK_{P-Out}$	7(35)
$WK_{A-Rq} \rightarrow WK_{A-Fe}$	2(25)	$WK_{A-Rq} \rightarrow WK_{P-In}$	5(10), 3(12), 1(25)
$WK_{P-C} \rightarrow WK_{A/It}$	7(35)	$WK_{P-C} \rightarrow WK_{P-G}$	7(35)
$WK_{P-C} \rightarrow WK_{P-In}$	5(10)	$WK_{P-I} \rightarrow WK_{P-In}$	7(35)
$WK_{P-I} \rightarrow WK_{P-Out}$	5(10)	$WK_{P-I} \rightarrow DK_{A}$	7(35)
$WK_{P/C} \rightarrow WK_{P-In}$	3(12)	$WK_{P/C} \rightarrow WK_{P-R}$	4(12), 3(12), 5(10), 7(35)
$DK_{A} \rightarrow WK_{A/F}$	4(12), 1(25)	$DK_{A} \rightarrow WK_{A-CR}$	2(25)
$DK_{A} \rightarrow WK_{A-M}$	2(25)	$DK_{A} \rightarrow WK_{P-In}$	5(10), 3(12), 7(35), 6(7)
$DK_{A} \rightarrow WK_{P-R}$	3(12), 6(7)	$DK_{A} \rightarrow WK_{P-C}$	7(35), 2(25)

8.3.2 Link of employment

The evaluation resulted in 42 employment links between the knowledge elements, which are listed in Table H-2, Appendix H. It was found that 12 of them are the same as, or included in 10 links that were identified from the protocol analysis. Table 8-8 lists these 12 and 10 creation links identified through the protocol analysis and evaluation in the first and second columns of the table respectively. The designers who identified the links during the evaluation are listed in the third column, with their reference number followed with duration of their experiences in the bracket. The last column shows whether the links listed in the first column were partially considered by the designers as coupling links. It could be found that two links identified from the protocol analysis were partially identified from the evaluation, i.e. 'WK_{P-In} —● $WK_{A/F}$' and 'WK_{P-Out} —● $WK_{A/F}$'.

Table 8-8: Employment links identified through both the protocol analysis and evaluation

Protocol analysis	Evaluation	Designers	Note
EL.iii: WK_{P-G} —● WK_{A-M}	WK_{P-G} —● WK_{A-M}	7(35)	
EL.iv: WK_{P-G} —● WK_{A-Rq}	WK_{P-G} —● WK_{A-Rq}	4(12)	
EL.v: WK_{P-In} —● DK_{A}	WK_{P-In} —● DK_{A}	5(10), 3(12), 7(35)	

EL.vi: WK_{P-In} —● $WK_{A/F}$	WK_{P-In} —● $WK_{A/E}$	5(10)	Partial
	WK_{P-In} —● $WK_{A/Is}$	3(12)	
EL.vii: WK_{P-In} —● WK_{A-M}	WK_{P-In} —● WK_{A-M}	5(10), 3(12)	
EL.viii: WK_{P-In} —● WK_{A-Rq}	WK_{P-In} —● WK_{A-Rq}	5(10), 3(12), 7(35)	
EL.ix: WK_{P-Out} —● DK_{A}	WK_{P-Out} —● DK_{A}	7(35)	
EL.x: WK_{P-Out} —● $WK_{A/F}$	WK_{P-Out} —● $WK_{A/It}$	5(10), 2(25)	Partial
	WK_{P-Out} —● $WK_{A/Is}$	5(10)	
EL.xii: WK_{P-R} —● DK_{A}	WK_{P-R} —● DK_{A}	3(12), 2(25), 1(25), 7(35), 6(7)	
EL.xv: WK_{P-C} —● DK_{A}	WK_{P-C} —● DK_{A}	2(25), 7(35)	

The seven employment links listed in Table 8-9 are those links that were identified only through the protocol analysis. Although they were not identified by the designers, it could not be said that they are not links of the coupling. One reason for this is that the limited evaluation time might have constrained the designers to draw all the links they used in their projects. In addition, different design experiences, projects used for the evaluation, product focuses, or designers' understandings of the elements and links might also have caused such difference.

Table 8-9: Employment links identified only through the protocol analysis

EL.i: WK_{P-G} —● DK_{A-G}	EL.ii: WK_{P-G} —● $WK_{A/F}$	EL.xi: WK_{P-Out} —● $WK_{A/C}$
EL.xiii: WK_{P-R} —● WK_{A-CR}	EL.xiv: WK_{P-R} —● WK_{A-Ct}	EL.xvi: WK_{P-C} —● WK_{A}
EL.xvii: WK_{P-C} —● WK_{P}		

During the evaluation, 42 employment links were drawn by the designers in total. Besides the 12 that were also identified through the protocol analysis, there were 30 were not considered as coupling links through the protocol analysis. An analysis of these 30 links showed that some of them could be combined to one link. For example, 'WK_{A-Rq} —● $WK_{P/C}$' was identified by designer 6. Meanwhile, it included another link 'WK_{A-Rq} —● WK_{P-C}' identified by designer 4. Hence these two links were combined to one link 'WK_{A-Rq} —● $WK_{P/C}$'. After combining all the links that could be combined, 28 links were considered as the employment links that were not identified through the protocol analysis, which are listed in Table 8-10. The two columns of "Designers" in Table 8-7 list the reference number of the designers who identified the links, followed with the duration of their experiences in bracket. The designers' reference numbers that are coloured grey in the table indicate that he/she identified only part of the link. Of these 28 links, 22 were identified by the experienced designers (their design experiences were over 25 years) or by more than two designers. The cells of these 22 links are highlighted grey in the table.

As can be seen from Table 8-10, with the exception of only one link that was identified by four designers and four by two designers, the remaining links in the table were identified only by one designer. This shows that the designers had various views of the main employment links used in their projects. Such different views could stem from different design experiences, different projects used for the evaluation, different product focuses they normally worked on, or the designers' different understanding of the elements and links.

Table 8-10: 28 employment links identified only through the evaluation

Links	Designers	Links	Designers
WK_{A-Bit} —● DK_{A}	1(25)	WK_{A-Fit} —● WK_{A-Ct}	1(25)
WK_{A-CR} —● DK_{A}	2(25)	WK_{A-Ct} —● DK_{A}	2(25)
WK_{A-Ct} —● $WK_{A/It}$	6(7)	WK_{A-M} —● DK_{A}	2(25)
WK_{A-M} —● WK_{P-G}	6(7)	WK_{A-Rq} —● WK_{A-Fe}	1(25)
WK_{A-Rq} —● $WK_{A/It}$	6(7)	WK_{A-Rq} —● WK_{A-Ct}	2(25)
WK_{A-Rq} —● WK_{A-M}	2(25)	WK_{A-Rq} —● WK_{P-G}	6(7)
WK_{A-Rq} —● $WK_{P/C}$	4(12), 6(7)	WK_{A-Sis} —● WK_{P-A}	6(7)
WK_{P-A} —● $WK_{A/Is}$	7(35)	WK_{P-A} —● WK_{A-M}	7(35)
WK_{P-A} —● WK_{P-I}	2(25)	WK_{P-G} —● WK_{A-Bit}	2(25)
WK_{P-In} —● WK_{A-CR}	4(12)	WK_{P-In} —● WK_{A-Ct}	5(10), 3(12), 2(25), 7(35)
WK_{P-In} —● $WK_{P/C}$	5(10), 3(12)	WK_{P-Out} —● WK_{P-I}	5(10), 1(25)
WK_{P-R} —● $WK_{A/E}$	7(35)	WK_{P-R} —● $WK_{A/Is}$	7(35)
WK_{P-R} —● WK_{A-M}	7(35)	WK_{P-R} —● $WK_{P/C}$	3(12), 4(12)
DK_{A-Bit} —● WK_{A-Bit}	4(12)	DK_{A} —● $WK_{A/E}$	6(7)

8.3.3 Summary of the coupling evaluation

Having presented the evaluation of the coupling links, the key findings of the evaluation are summarised as below:

- Among the 19 creation and 17 employment links identified from the protocol analysis, 7 creation and 10 employment links were or partly identified from the evaluation.
- Among the 48 creation and 42 employment links were identified from the evaluation, 9 creation and 12 employment links were identified from the protocol analysis. The remaining 39 creation and 30 employment links that were only identified by the designers could be generalised to 32 creation links and 28 employment links. Table 8-11 summarises the number of the links identified through the evaluation.

Table 8-11: Summary of links from the evaluation

	Protocol analysis		Evaluation		
	Total	Also by evaluation	Total	Also by protocol analysis	Main
Creation links	19	7	48	9	32
Employment links	17	10	42	12	28

- The coupling links identified from the protocol analysis were not fully identified from the evaluation. This might because of the limited time of the evaluation workshop, during which designers can only draw part of the links that they might have used in their work. It might also be caused by the different nature between the student project used for the protocol analysis and the commercial projects used for the evaluation.

- The results of the evaluation show that the designers had a diversity of views of the main creation and employment links that they used in their projects. Such diversity might be caused by difference of designers' design experiences, the projects used for the evaluation, or product focuses they normally worked on. It might also be related to the designers' different understanding of the elements and links.

8.4 SUMMARY

This chapter presents the evaluation of the coupling elements and coupling. Two workshops were organised in two companies: (i) BAE Systems Surface Fleet Solutions Limited (SFS) and (ii) Company A, on the 2nd and 7th of March 2008 respectively. Overall, 8 engineering designers (five from SFS and three from Company A) participated in the workshops. Seven results were used as the basis for the analysis. The analysis highlighted some differences between the results obtained from the protocol analysis and evaluation. In addition, it was found that the designers had a diversity of views of both the knowledge elements occurrence trends and links of the coupling. In short, the main outcomes from the evaluation are summarised as below:

- While all the knowledge elements were considered by the designers that they occurred during design development with different frequencies, some were regarded by all the seven designers to be "Often" or "Very often", and some others were considered by one or two designers to be "Occasionally". This shows that the designers did not have a common view of the frequency of the knowledge elements occurred during the design development.
- Though designers had different views of the elements' occurrence frequency, there were at least two designers had same view of the frequency of the four DK_A (DK_{A-G}, $DK_{A-Bü}$, $DK_{A-Fü}$, and DK_{A-Sis}), six WK_A (WK_{A-M}, WK_{A-Fe}, WK_{A-Be}, WK_{A-Se}, WK_{A-Sis}, WK_{A-Ct}), and four WK_P (WK_{P-A}, WK_{P-G}, WK_{P-C}, and WK_{P-I}) as that obtained from the protocol analysis.
- Of the 22 evaluated elements, 2 (WK_{A-Sis} and $WK_{A-Bü}$) were viewed with same trend as that obtained from the protocol analysis, while 7 (DK_{A-G}, $DK_{A-Bü}$, $DK_{A-Fü}$, WK_{A-M}, WK_{A-Rq}, WK_{P-R}, and WK_{P-C}) were viewed with similar, and the other 13 were viewed with different trends.
- One main reason of the difference between the results of the protocol analysis and evaluation with regard to the process elements trend was due to the encoding of WK_{P-G}, WK_{P-In}, WK_{P-Out}, and WK_{P-R}. That is, most of these four types of process elements were encoded as artefact knowledge elements with higher priority. Hence, it could be said that the analysed process elements were incomplete, which might resulted in the difference.
- Among the 48 creation and 42 employment links that were identified from the evaluation, 9 creation and 12 employment links were identified from the protocol analysis. The remaining 39 creation and 30 employment links that were only identified by the designers during the evaluation could be generalised to 32 creation links and 28 employment links.
- The difference between the results of protocol analysis and evaluation in respect of the elements' occurrence trend and coupling could be explained in terms of the limited duration of the evaluation workshops, the difference between student and commercial design projects, as well as the difference between individual and collaborative design projects.
- The results of the evaluation revealed that the designers had various views of the same element's trend as well as the main creation and employment links used in their projects. The designers' diversity of views might be caused by a number of factors, such as the designers' different design experiences, their different product focuses that they

normally worked on, different projects used by the them for the evaluation, as well as their different understanding of the knowledge elements and links.

Chapter 9 DISCUSSION

The aim of the research presented in this thesis was to model the nature of the coupling of the evolutionary artefact and design process knowledge, which included both the elements involved in the coupling presented in Chapter 6 and the relationships between these elements that compose such coupling presented in Chapter 5 and Chapter 7. The evaluation of the work was presented in Chapter 8 through questionnaire.

The work presented in this thesis is discussed in this chapter in terms of its strengths and weaknesses of the main findings (Section 9.1), research methods (Section 9.2), and methodology (Section 9.3). Section 9.4 outlines a selection of future work based upon the weaknesses and potential research directions. Section 9.5 summarises the chapter.

9.1 NATURE OF THE COUPLING

In this section, the main results of the work are discussed regarding to their strengths and weaknesses. Overall, the work presented in this thesis answered the questions raised in Chapter 3 and addressed the research gap identified in Chapter 4. Specifically, the basic artefact and design process knowledge elements involved in the coupling were identified, the occurrence trend of these elements were analysed over task clarification, conceptual, and embodiment design, and coupling links of two types were identified between these elements, which compose the coupling of the evolutionary artefact and design process knowledge.

9.1.1 Knowledge elements involved in the coupling

Through the literature review (Chapter 3), the basic knowledge elements of the artefact and design process were reviewed to be motivations (*M*), requirements (*Rq*), function (*F*), behaviour (*B*), structure (*S*), causal relationships (*CR*), and constraints (*Ct*) of the artefact, and activity (*A*), goal (*G*), input (*In*), output (*Out*), resource (*R*), context (*C*), and issues (*I*) of the design process. Further, the fundamental artefact knowledge *F*, *B*, and *S* were categorised into expected function (F_e), interpreted function (F_{it}), expected behaviour (B_e), instantiated behaviour (B_{is}), interpreted behaviour (B_{it}), expected structure (S_e), and instantiated structure (S_{is}), which distributed in three design artefact knowledge spaces, i.e., expected, interpreted, and instantiate.

At the beginning of the literature review, decisions and rationale were considered as the basic elements of the design process. However, further analysis during the review showed that decisions are the output of one specific type of activity, i.e., decision making activity. Rationale (Ullman and D'Ambrosio 1995; Brissaud et al. 2003) is a type of resource used for activities such as reasoning or decision making.

During the content analysis (see Chapter 5), except B_{is} and *I*, current working knowledge (*WK*) of other basic knowledge elements were seen to be identified from the analysed documents. All behavioural knowledge in the documents was encoded as B_{it} due to the definition of B_{is} being an intrinsic element derived directly from S_{is} and B_{it} being behaviour interpreted by designers. In addition, as mentioned earlier, the analysed documents were description of company standard product and procedure, which featured design in an expected situation, hence no issues were identified. Further, through the protocol analysis (see Chapter 6), except B_{is}, *CR*, and *In*, current working knowledge (*WK*) of other basic knowledge elements were identified to involve in the coupling. Though no B_{is}, *CR*, and *In* were identified, it does not mean that they were not used or created by designers. The behaviours encoded from the protocol were all encoded as B_{it} during the analysis, considering they were all behaviours discussed by designers, which resulted in no B_{is} was encoded. *CR* is the causal relationship between two knowledge elements. After discussion with the student designer during two interviews, it was confirmed that although causal relationship knowledge was not discussed by the designer explicitly to transfer fundamental artefact knowledge elements, it was implicitly used for the transformations. For the *In*, as mentioned in Chapter 6, that during the analysis, it was found that one chunk of knowledge could be encoded as more than one element, for example most output knowledge were also artefact knowledge. However, all the knowledge were encoded as only one type during the analysis with priority sequence being artefact, activity, goal, input, output, resource, and context. Hence, all the input knowledge elements were encoded as artefact knowledge with higher priority. This priority-based encoding could also explain why *G*, *Out*, *R*, and *C* were identified less compared to *A*, because some goals were encoded as activities, and most output, information resources, and context were encoded as artefact knowledge with higher priority. It should be noted that resource includes not only information, but also humans and equipment. Because the analysed project was conducted by one designer under supervision, limited resource was discussed/allocated in the project.

Domain artefact knowledge (DK_A) was found to closely relate to the design process knowledge during the protocol analysis. As a result, four types of domain artefact knowledge elements: general domain artefact knowledge (DK_{A-G}), B_{it}, F_{it}, and S_{ts} were identified from the protocol analysis, which were found to relate to the design process in the analysed student design project. These four types of DK_A revealed that for the analysed project, designer mainly used DK_A for understanding the roadside furniture domain. However, for industrial design projects, it was considered that the practice of accumulating DK_A might result in expected DK_A being used for creating domain knowledge. Hence, more types of DK_A might be involved in the coupling for an company design project. In addition, a few instances of domain design process knowledge were also identified during the analysis. However, rather than related to the artefact, they were found mainly to be related to design management knowledge. Due to the focus being on the coupling of the artefact and design process knowledge, they were not considered in the research. However, the coupling of design process and management knowledge could be a potential research direction, as these two types of knowledge closely relate to each other.

Through the evaluation (Chapter 8), it was found that all the basic knowledge elements identified through the literature review and protocol analysis were considered by designers and occurred during designing, with different occurrence frequencies. Consequently, it could be said that the research work presented in this thesis has identified a set of basic knowledge elements that are involved in the coupling.

The evaluation shows that though designers agreed with the set of the basic knowledge elements involved in the coupling, they had different views of the frequency of eight knowledge elements (WK_{A-Rq}, WK_{A-Bis}, WK_{A-Bit}, WK_{A-Fit}, WK_{A-CR}, WK_{P-In}, WK_{P-Out}, and WK_{P-R}) from what was obtained from the protocol analysis. The reason of this difference might be: 1) the priority-based encoding resulted in that the input, output, and resource were not fully encoded. And 2) the difference between student and commercial design projects, as well as between individual and collaborative design projects

Such divergence, however, might be partly solved through a more comprehensive analysis of knowledge elements. That is, without using priority based analysis, a chunk of knowledge should be encoded as multiple elements if it acts as multiple roles.

In addition, the result of the knowledge elements and their frequency was obtained mainly through literature review and protocol analysis of an individual supervised student design project. Though it has been evaluated by industrial designers, the result still lacks in-depth study of empirical industrial design projects.

Overall, the strengths and weaknesses of the findings of knowledge elements involved in the coupling are:

Strengths

- ✓ A basic set of knowledge elements that involved in the coupling was identified.

Weaknesses

- ✗ The priority-based encoding affected the result of some knowledge elements' frequency, which were also different from that resulted from the evaluation.
- ✗ The result of the knowledge elements and their frequency was obtained mainly based on literature review and protocol analysis of an individual supervised student design project. Hence it lacks in-depth study of empirical industrial design projects.

9.1.2 Elements occurrence trends

The protocol analysis showed that the coupling knowledge elements exhibit different occurrence patterns through task clarification, conceptual, and embodiment design. Some are increasing, some are decreasing, and some are relatively stable. For example, the overall increasing trend of $WK_{A/E}$ shows that the designer had expectations towards the structure of the roadside furniture at the beginning of the design. It then decreased to non-occurrence until the end of task clarification and increased to its peak in conceptual design, which followed with a slight decrease in embodiment design. This tendency could reflect that the novice designer tried to discuss the structure of the design from the beginning of the design, such tendency is also practised in the industry by some designers. This finding has provided an initial insight of the knowledge elements occurrence trends.

It should be noted that the occurrence trends identified from the protocol analysis could not be applied for different types of design, because it was obtained by analysing only one student design project. However, the analysed trends results suggest that different types of design, such as routine, innovative, and creative design, might have different occurrence trends for the same element. In addition, trends in different domains, such as mechanical, architecture, or industrial design, might also be different. Though it can not be ascertained that the trends obtained in this work reflect best practice of designers, because it was based on a single student project under supervision, further analysis of different types of design projects in companies might reveal some best practice, which could be used by designers in directing their design.

Through the evaluation (see Chapter 8), it was found that among the 22 coupling knowledge elements, only two were viewed by designers as having the same trends as that resulted from the protocol analysis. Seven of them were viewed as having similar trends and 13 were viewed as different. Because the analysed design project was an individual student project under supervision and the six projects used by designers for the evaluation were all collaborative commercial design. The difference between the results obtained from the protocol analysis and the evaluation might be caused by different characteristics of the projects. In addition, this difference might also be caused by the aforementioned priority-based encoding, i.e., some chunk of knowledge were encoded as artefact knowledge with higher priority, though they could also be encoded as goal, input, output, resource of the design process. Consequently, the trend analyses of these elements could not reflect how they occur over the three design phases. Therefore, such divergence might be partly solved by conducting a more comprehensive encoding of the knowledge elements.

It was also found that, among the designers who participated in the workshops, there was no consensus about most of the knowledge elements' trends. Each element was viewed as having at least four trends, either different or similar (see Chapter 8). For example, there were eight elements were viewed with four results and eight with five results. One element, $WK_{A\text{-}Fu}$, was even viewed by the seven designers with seven results. Such different views among designers might be caused by multiple factors. The seven designers came from two companies that design different products. They have various design experiences ranging from 7 years to 30 years. They worked on six different product types and they used six different design projects for the evaluation. All these factors are likely to cause different views. In addition, the different views could also be related to the designers' different understanding of the knowledge elements. Such different understanding would suggest that industry still does not have a common view of the artefact and design process knowledge elements.

Overall, the strengths and weaknesses of the findings of knowledge elements occurrence trends are:

Strengths

- ✓ The result of knowledge elements occurrence trends obtained from the protocol analysis provided an initial insight of the knowledge elements occurrence trends.
- ✓ The result suggests that there might exist some best practice of knowledge elements occurrence trends, which could be used in directing designers' design.

Weaknesses

- ✗ The priority-based encoding affected the result of some knowledge elements' occurrence trends.
- ✗ The result of the knowledge elements occurrence trends was obtained mainly based on protocol analysis of an individual student design project, which is an innovative engineering design of roadside furniture. Hence it might not reflect the trends of elements in other design types, or other design domains.
- ✗ The results obtained from the student design project might not reflect the knowledge elements trends in industry, which still needs to be evolved through study of more empirical industrial design projects.

9.1.3 Coupling

The coupling was found to be composed of two main types of links: *link of creation* and *link of employment*. The initial coupling (see Chapter 5) was obtained through content analysis of eight design documents from Company A, which was seen to be composed of 6 creation and 15 employment links between the artefact and design process knowledge elements (see Figure 5-7 and Figure 5-8). Through the protocol analysis (see Chapter 7), 18 creation and 15 employment links were derived seen to be the coupling links (see Figure 7-4 and Figure 7-9). The links obtained from both the content analysis and protocol analysis were then combined, which resulted in an evolved coupling model presented in this thesis composing 19 creation and 17 employment links (see Table 7-6, Table 7-7, and Figure 7-10). Through such combination, the coupling not only applies to an individual design conducted by a novice designer, but also applies to high level design practice in the industry because the analysed documents described company standard product and procedures. However, it should be noted that, based on the content analysis of industrial design documents and protocol analysis of student design project, such coupling still lacks empirical study of industrial design cases, hence it might not apply to other engineering design types such as routine design. Different projects might have different main links. Some minor links were not considered in this project might become main ones in another different type of design. For example, there were no creation links creating $DK_{A\text{-}Be}$ by $DK_{P\text{-}A}$ in the analysed project because little emphasis was given to accumulating domain knowledge. However, this link might become main one if a project from industry was analysed, because industry emphasises more on accumulating domain artefact knowledge than academe design. Therefore, more analyses of different types of design might help to identify a generalised coupling model. In addition, the coupling might not apply to other company because the analysed documents are from only one company.

The evaluation of the coupling by having engineering designers from two companies that design different product answered questionnaire showed, in spite of there are convergence between the coupling resulted from the content and protocol analysis and designers' views of the coupling links, there are divergence as well. Almost half of the links identified from the content and protocol analysis were not identified by designers (12 out of 19 creation links and 7 out of 17 employment links). Meanwhile, designers identified 48 creation and 42 employment links. Of which, only 9 creation and 12 employment links were identified from the content and protocol analysis. Such difference indicates that some links within the analysed coupling model might not apply to empirical design in industry. However, it might also suggest that different types of design might exhibit different coupling. Moreover, the difference between the links identified from the protocol analysis and those from the evaluation might be because different characteristics of the projects used for protocol analysis and evaluation, for example, the difference between student and commercial design projects, or between individual and collaborative design projects. In addition, the priority-based encoding might also affect the identification of the main links.

The difference found between the results obtained from the research presented in this thesis and the evaluation might be because of different design scenarios. Considering the data sources used for the content and protocol analysis and the evaluation, it could be found that while there was similarity between that of the content and protocol analysis, which was different from the data source of the evaluation. In the content analysis, company documents describing standard product and procedure were analysed. Though they were used within a context of a hypothesised design case, such scenario was based on the documents, hence was directed by the documented standard/idealised practice. In the protocol analysis, a supervised student design project was analysed. With supervisor's supervision, the project was conducted, similarly, in a way that was directed by experienced designer's practice using some standard design methods. However, in the evaluation workshop, the design projects used by the designers for the evaluation were projects in the real world. Hence, though there might be a number of guidance or best practice, they might be neglected by designers because their objectives in these projects were mainly to deliver the required results within limited time. Therefore, more in-depth analysis of industrial design project might reveal the coupling in different design environments.

The evaluation revealed a diversity of designers' views of the coupling links was found from the evolution because most links were identified by only one designer (See Table H-1 and Table H-2 in Appendix H). Though such diversity might be caused by a number of factors, such as different working experience, projects used for the evaluation, or different understanding of the elements and links by the designers, it would suggest that industry still does not have a common view of the coupling of the artefact and design process on the knowledge level.

Overall, the strengths and weaknesses of the coupling identified in the research presented in this thesis are:

Strengths

- ✓ The result of the coupling obtained from both the content analysis of company design documents and protocol analysis of a student design project, which ensured it could be applied to not only individual design conducted by novice designer in academe, but also company high level design practice.
- ✓ The presented coupling model provided an initial insight of the coupling of the artefact and design process knowledge elements.

Weaknesses

- The content analysis was conducted based only on one company, hence the coupling might not apply to other companies.
- The evolved coupling was obtained mainly based on content analysis of eight design documents and protocol analysis of an individual student design project, which is an innovative engineering design of roadside furniture. Hence it might not reflect the coupling of other design types.
- The model lacks in-depth empirical study of industrial design cases, which needs to be evolved through study of more industrial design projects.

In all, the research presented in this thesis provided an initial insight of the nature of the coupling. By no means, the model was not a generalised coupling model of design, because it was obtained by analysing only eight industrial design documents and one single student design project. Hence, it might not apply to other design types. Nevertheless, such initial insight of the nature of the coupling can be used as the basis for further research.

9.2 RESEARCH METHODS

By adopting the triangulation methodology (discussed in Section 9.3), the research methods employed in the research included literature review, content analysis, protocol analysis, and questionnaire workshops.

9.2.1 Content analysis of company design documents

The content analysis (in Chapter 5) of eight design related documents from Company A formed the basis of the research by identifying the knowledge elements and a number of coupling links between them. However, such analysis was still a high level one, because the documents describe company standard product information such as requirements, function, and structure, and standard procedures producing such product. Therefore, to evolve the coupling identified from the content analysis, a detailed study of a design project was required, which resulted in the following protocol analysis of a student design project.

9.2.2 Protocol analysis of a supervised design project

Protocol analysis has been considered as one of the most appropriate method to investigate the cognitive activities carried out by designers (Cross et al. 1996), due to it's capability of providing deep insights into a studied project for researchers. Protocol analysis of a student design project was adopted to analyse the knowledge elements involved in the coupling and coupling model (in Chapter 6 and Chapter 7). However, due to the limitation of protocol analysis, it can only analyse what the designer and the supervisor discussed. Hence, for their internal cognitive activities, this method can not analyse unless they talk about what they think in their mind.

The protocol of **task clarification, conceptual**, and **embodiment design** of the recorded project was analysed. As mentioned in Chapter 1, the reason of analysing these three phases was because most development of the artefact were carried out in these three phases. Therefore, the fundamental changes of the artefact have been almost finished by the end of embodiment design. Hence the relationship between the artefact and design process is relatively stable after the embodiment design. Though it was hypothesised that the coupling might also apply to other design phases, further work can be done to evaluate whether the finding apply to other phases of the design process, such as detail design.

The analysis was conducted in a **cyclic manner**, in that the protocol was checked and analysed a number of times during the analysis. Such cyclic analysis increased the encoder's better understanding of the project, which, in turn, improved the accuracy and objectivity of the encoding. However, subjectivity of the analysis still existed because the identification of the elements and links relied on the inference of the encoder, based upon the available information. Hence different encoder might result in different encoding. The objectivity of the analysis, therefore, can be improved by encoding the protocol by more than one researcher

The **segmentation** of the protocol was based on the protocol semantic topics. The main purpose of segmenting the protocol in the research was to facilitate the counting of the elements and links within each session. Because the main objectives of the analysis were to identify the knowledge elements occurrence trends over the three phases and main links between the elements, how the protocol was segmented, therefore, did not affect the analysis results.

In order to identify the occurrence trends of the knowledge elements and main links of the coupling, the protocol was analysed based on the elements and links' occurrence percentage over the 12 sessions. The analysis was **session-based**, i.e., the percentage of the elements and links over the 12 sessions were analysed. A time-based analysis of three elements DK_{A-G}, WK_{A-Se}, and WK_{P-A} presented in Appendix E showed that the time-based and session-based analysis resulted in the same results of the overall trends of the knowledge elements over the three design phases.

In addition, during the **supervision sessions**, the designer reported the work had been done since last meeting, which included the progress of the artefact and activities carried out in deriving such artefact. The supervisor directed the student of both the artefact and design process. By recording such discussion, it eliminated the effort to interview the designer in order to obtain such information. Moreover, by recording such a supervised design project, not only the artefact being designed, but also how the design process was conducted can be studied. Hence the relationships between them were more explicitly expressed comparing to a non-supervised design project. This contributed better analysis of the protocol considering the research focus, i.e., the coupling of the artefact and design process. However, one weakness of recording such a supervised project was that the recording only included every discussion session between the student and supervisor. Hence, though the student discuss with the supervisor of the activities carried out since the previous supervision, due to the decay of long-term memory (Gero and Tang 2001), details of some activities conducted outside the supervision sessions may not be fully recorded. In addition, due to the time limitation of the supervision session, student might only discuss the main activities and progress of the design. Therefore, not all the information was recorded for such design project. For example, the students presented ten concepts to the supervisor during Session 7. However, the detailed concepts creating process was not fully recorded

The analysis was conducted manually and did not use any software. Though both Clementine and Nvivo (two **qualitative analysis software**) were tried to conduct the protocol analysis, it was found that they could not analyse this design project efficiently. The main reason was that many key words only appear once within the protocol, though many of them represented same elements. Due to the time limitation of this research, protocol was manually analysed. However, analysing the protocol by using one qualitative analysis tool worth to have a try in the future work.

Overall, the strengths and weaknesses of the protocol analysis conducted in the research presented in this thesis are summarised as:

Strengths

- ✓ Protocol analysis has been considered as one of the most appropriate method to investigate the cognitive activities carried out by designers.

- ✓ By recording a supervised individual design project, not only it eliminated the effort to interview the designer in order to obtain the design information, but also both the artefact and design process information were recorded, which resulted in more explicitly relationship between the artefact and design process, comparing to a non-supervised design project. This contributed analysis of the protocol considering the research focus being the coupling of the artefact and design process.

Weaknesses

- ✗ Protocol analysis can only analyse what the designers discussed. Hence, for their internal cognitive activities, this method can not analyse unless the designers talk about what they think in their mind.
- ✗ Due to the research scope being task clarification, conceptual, and embodiment design, only protocol of these three phases of the recorded project was analysed. Further work can be done to evaluate whether the finding apply to other phases of the design process, such as detail design
- ✗ The detailed design activities conducted by the student outside of the supervision session were not analysed, and which might not be completely reported during the supervision session, due to the decay of long-term memory. In addition, the limited supervision length might also constrain the student to only discuss the main activities and progress of the design.
- ✗ No qualitative analysis software was used to conduct the analysis. However, analysing the protocol by using qualitative analysis tools worth to have a try in the future work.
- ✗ The identification of the elements and links relied on the inference of the encoder, based upon the available information. Hence different encoder might result in different encoding. Such subjectivity might be minimised by have other encoder analysing the same protocol.

9.2.3 Evaluation questionnaire

The results obtained from the protocol analysis were evaluated through questionnaire answered by eight engineering designers during two workshops (Chapter 8). Five of them came from BAE Systems Surface Fleet Solutions Limited (SFS), the other three came from Company A, the same company that the content analysis was based on. This ensured that the evaluation was not based on design cases and designers from only one single company. Moreover, except two designers, the other six designers worked with different product types, and they used different projects as the scenario for the evaluation. Such variety ensured that the evaluation results did not limited to one specific type of design. Hence, the evaluation results can be used to evaluate the generality of the research results. Of the eight answered questionnaires, seven results were analysed considering the consistency of the answers.

The evaluation results were affected by designers' understanding of the questionnaire, i.e., their answers were subject to their understanding of the knowledge elements and the coupling link. For example, two main issues were raised during the workshops, which mainly related to the designers' understanding of the knowledge elements and links between the elements. One was the concept of $WK_{A\text{-}CR}$, the causal relationship between basic artefact knowledge elements, and the other was ***link of employment***. It was found during the pilot study that the understanding is subjected to the length of the evaluation.

The duration of both workshops was one and half hour, which might have affected the designers' understanding of the questionnaire, hence limited the accuracy of the evaluation. Though the format of the questionnaire had under through several main changes (see Chapter

8) in order to make it readily understandable by designers, the two issues showed that designers still had difficulty to fully understand the elements and links within this limited one and half hour. Moreover, the duration of the workshop might also have constrained the designers from drawing all the possible links they might used in their work. Hence, a lengthy evaluation session could contribute to designers' better understanding of the elements and coupling link, which would resulted in more accurate evaluation results.

In all, the strengths and weaknesses of the evaluation questionnaire are:

Strengths

- ✓ Two workshops organised in two companies ensured that the evaluation was based on design cases not limited to one single company.
- ✓ Seven designers, with different experiences and product focuses, used different projects for the evaluation. Such variety ensured that the evaluation results did not limited to one specific type of design. Hence the results can be used in evaluate the generality of the research results.

Weaknesses

- ✗ The evaluation results were affected by the designers' understanding of the questionnaire.
- ✗ The understanding of the questionnaire was affected by the duration of the two workshops, one and half hour, which limited the depth of the evaluation.
- ✗ The limited time might also have limited designers from drawing all the possible links they might use during their work. Hence, longer evaluation session could improve the evaluation effectiveness.

9.3 RESEARCH METHODOLOGY

As mentioned in Chapter 2, three principles should be abided while carrying out a research work, i.e., within a framework of a set of philosophies; use valid and reliable procedures, methods and techniques; and the process should be unbiased and objective. In the research presented in this thesis, a post-positivism philosophy was adopted based on the nature of design being human involved in the design activities. Such philosophy resulted in the knowledge-seeking through a triangulation research methodology, which triangulated the research from three aspects, i.e., data sources, methods, and theory building.

The data sources triangulation includes data from literature and industrial design documents, designers' view, and design cases from both academe and industry. Such data triangulation ensures that not only company practice but also empirical design data were used in analysing the research problem.

A "between-methods" triangulation was adopted in the research presented in this thesis, which included literature review, content analysis, protocol analysis, and questionnaire as discussed in the previous section. These methods have been proved to be valid and reliable in a number of research (Holsti 1969; Gero and McNeill 1998; Ridley 2008). Following research focus being identified through the literature review, the coupling model was developed by combining the results obtained from both the content and protocol analysis. Such combination ensured that the coupling not only applies to the scenario of individual design by novice designer, but also collaborative design by experienced designers. Hence, it provided a relatively potent means of assessing the degree of convergence as well as elaborating the divergence between the results obtained from the two methods. In this regard, Table 7-6 and Table 7.7 showed the difference and similarity of the coupling links obtained from the content analysis and protocol analysis.

Finally, the theory triangulation was realised through the generation and evaluation of the coupling model. In doing this, the results obtained from the protocol analysis were compared with the evaluation results given by industrial designers through questionnaire. This ensured the findings being checked against industrial design cases.

Though triangulation methodology provided the aforementioned strengths, it was limited by the time permitted for conducting the research. For example, seven student design projects were recorded and studied. However, due to the limited time, only protocol of one project was transcribed and analysed, which lasted ten design sessions, 283 mins 54 secs. In addition, the length of the research also constrained the research from analysing protocol of the design process of an industrial design case, which normally lasts several or tens of years in a medium-large size design and manufacturing company. This implies that further research could be done by following in industrial design case, and analysing the protocol as the design continues.

Though there is another type of triangulation, i.e., investigator triangulation, was not adopted for the research presented in this thesis. This implies further work could be done by having the same data analysed by other researchers. One advantage of the investigator triangulation is that comparing findings resulted from different investigator could reveal whether the research has been biased and subjective.

The strengths and weaknesses of the research methodology are summarised as follow.

Strengths

- ✓ Post-positivism philosophy matches the design research domain because design is human-involved activity.
- ✓ Data triangulation ensures that the model is based not only company practice, but also empirical project.
- ✓ Methods triangulation provided a relatively potent means of assessing the degree of convergence as well as elaborating the divergence between the results obtained from the content analysis and protocol analysis.
- ✓ The theory triangulation in the research ensured the findings were checked against industrial design cases.

Weaknesses

- ✗ The choosing of different data sources and research methods were subjected to the time permitted for conducting the research presented in this thesis.
- ✗ Only eight company design documents and a student design project was analysed for deriving the coupling model. Without using any empirical industrial design project, the generality of the findings might be affected, i.e., the finding might not apply to all types of design. This has been found through the evaluation, which will be discussed in Section 9.3.

9.4 FUTURE WORK

Through the research carried out in this work, a number of additional insights into the nature of the coupling were obtained. These are briefly presented here as areas for further investigation.

9.4.1 More analysis of empirical industrial design projects

The work analysed in this thesis was mainly based on content analysis of eight industrial design documents and protocol analysis of one student design project under supervision.

Though it provided a good insight into the coupling by providing not only the information of the artefact and design process, but also the relationships between them, the evaluation has shown that there exist differences not only between the results obtained from the protocol analysis and evaluation, but also among views of different designers. Therefore, further analysis of different types of projects conducted in companies will benefit the model elaboration in order to obtain a generalised coupling model, or different coupling models for different types of design. By analysing different types of projects, a set of best practice of knowledge elements occurrence trends over different design phases might be identified that can benefit designers. Moreover, the analysis will improve its accuracy by encoding each chunk of knowledge to all of the identified roles it acts.

9.4.2 Investigator triangulation

To minimize the subjectivity of encoding process, protocol could be analysed by different encoder. In addition, qualitative analysis software could be applied to analyse the protocol. The encoded knowledge elements could also be investigated by different researcher, to see whether the same results could be obtained from the same set of data.

9.4.3 Detailing activity

One potential future work for the research presented in this thesis is to extend the design activity in the coupling model to more specific types of activity. During the analysis of the coupling, all the activities were treated as only one element of the design process, which resulted in a relatively stable occurrence trend of the activity over the three design phases. It is hypothesised here that if the activity was encoded as different types, such as the ontology presented by Sim and Duffy (2003), the trend analysis might show different patterns for different types of design activities. Thereafter, the coupling might also shows different types of activity linking with some specific types of artefact knowledge elements. For example, the B_e, F_e, and S_e might related with analysis and synthesis activities, while B_{it} and F_{it} mainly related with interpretation and evaluation activities.

9.4.4 Coupling of design process and management knowledge

While the research presented in this thesis focused on the coupling of the evolutionary artefact and design process knowledge, another research direction could be to couple the design process and management knowledge. In which case, domain design process knowledge will be included, because it was found that it mainly relates to design management knowledge through the research presented in this thesis.

9.4.5 Knowledge evolution support

Though the work presented in this thesis is coupling of the evolutionary artefact and design process knowledge, which studied the coupling phenomenon in design, knowledge evolution is neither the focus nor supported by this work. Rather, "evolutionary" was described as one characteristic of design knowledge, which related to the coupling. Therefore, as a future research direction, the relationship between the knowledge evolution and coupling can be further investigated.

9.4.6 Change propagation

The research presented in this thesis presented a descriptive model of the coupling, which includes the occurrence trends of the knowledge elements involved in the coupling, and the coupling model per se. It is considered that such descriptive knowledge can be used as a basis for further research on the prescriptive aspects of the relationships between the knowledge elements. That is, how the change of one element affects or propagates to other related knowledge elements. Such research might include the degree and distance of the affection. Hence, the change propagation can be then used for change predictions in design.

9.4.7 System support for design development

While the research presented the model of the coupling phenomenon, further work can be done in how the current research can support design development, for example, through integrating such results into another design development support system. The occurrence trends might provide criteria for checking a current design, by providing some practice information. The coupling model might be used while in the designing, to provide designers with all the possible relationships of the current focused element, which might help designers with concepts brainstorming process.

9.5 SUMMARY

The strengths and weaknesses of the work presented in this thesis are discussed in this chapter, which include the research methodology, methods, and the results. In addition, the future work are identified. Table 9-1 summarises the discussion presented in this chapter.

Table 9-1: Summary of discussion

		Pros	Cons	Recommendations
Analysis /Results	Coupling elements	✓ A set of basic knowledge elements involved in the coupling were identified.	× Priority-based encoding during the protocol analysis affected the analysed proportion of several knowledge elements (CR, G, In, Out, R, and C); × The result of the knowledge elements and their frequency lacks in-depth industrial design cases study.	✓ Carry out a more comprehensive analysis by encoding the knowledge to all possible elements; ✓ Carry out more analysis based on industrial design cases.
	Elements occurrence trends	✓ Element occurrence trends over three design phases were identified, which provided an initial insight of the elements occurrence trends; ✓ Suggestion of potential best practice of occurrence trends for some particular design.	× Priority-based encoding during the protocol analysis affected the occurrence trend of several knowledge elements (CR, G, In, Out, R, and C); × Lacks in-depth industrial design cases study, hence might not generalised for different types of design.	✓ Carry out a more comprehensive analysis by encoding the knowledge to all possible elements; ✓ Carry out more analysis of different types of design to identify possible trends suit generalised design; ✓ Carry out more analysis of different types of design to identify potential best practice of good design.
	Coupling	✓ The presented model provided an initial insight of the coupling; ✓ The model was obtained from both the content and protocol analysis, which ensured that it could be applied to not only individual design conducted by novice designer, but also company general design practice.	× one-company based content analysis might result in that the coupling might not apply to other companies; × Priority-based encoding might affect the identification of the main links; × Lacks in-depth industrial design cases study, hence might not generalised for different types of design.	✓ Carry out a more comprehensive analysis by encoding the knowledge to all possible elements; ✓ Carry out more analysis of different types of design for identifying a generalised coupling model.
Methods	Content analysis	✓ Provided an initial insight of the coupling.	× The analysed documents are description of standard product and procedures.	
	Protocol analysis	✓ Provide deep insight into the analysed project;	× Can not analyse internal cognitive activities, unless designers talk them;	✓ Analysing by using software; ✓ The protocol can be encoded by more

		✓ The recording of a supervised project eliminated the effort of formal interviewing designers; ✓ The recorded supervised project provided both information of the artefact and design process knowledge, hence the relationships between them can be better studied.	✗ Details of activities conducted outside the supervision sessions might not be fully recorded due to the decay of long-term memory and limited duration of the supervision; ✗ The analysis was manual rather than using qualitative analysis software; ✗ Subjectivity of the analysis was unavoidable.	than on researcher to minimize the subjectivity.
	Evaluation questionnaire	✓ Two workshops in two companies avoided the views of designers from only one company; ✓ The variety of designers' experiences, product focuses, and projects used for the evaluation ensured the results did not limit to only one type of design.	✗ Evaluation results were subjective to designers' understanding of the elements and coupling links; ✗ The duration of the workshops limited designers fully understand the elements and coupling links; ✗ The duration of the workshops limited designers from drawing all the coupling links they might use in their work.	✓ Longer evaluation workshops can obtain more accurate results.
Methodology		✓ The post-positivism philosophy suits design research; ✓ Triangulation of the data sources, methods, and theory building ensured that the research was unbiased and objective.	✗ The methods adopted were limited by the scope and time of the research.	
Future work		✓ Analyse different types of industrial design projects; ✓ Accommodate different types of design activities; ✓ Investigate coupling of design process and management knowledge; ✓ Support knowledge evolution; ✓ Investigate change propagation; ✓ Provide system support for design development by using the coupling.		

Chapter 10 CONCLUSION

The overall aim of the research presented in this thesis was to model the nature of the coupling of evolutionary artefact and design process knowledge. It was found that artefact and design process knowledge are coupled through inter-relationships between them. Chapters 5, 6, and 7 presented the main findings of the nature of the coupling. Specifically, the occurrence trends of the coupling knowledge elements were presented in Chapter 6 and the coupling model itself was presented in Chapter 5 and Chapter 7.

The contribution of the research presented in this thesis is made up of a number of elements. Figure 10-1 presents an overall summary of the work, highlighting these elements and their relationships. The remainder of this chapter presents a brief summary of the contributions as they have been presented in this thesis to summarise the results and conclude.

10.1 TRIANGULATION RESEARCH METHODOLOGY

A post-positivism philosophy was adopted based on the research focus and nature of design. Such philosophy resulted in the investigation of knowledge through a triangulation research methodology as presented in Chapter 2, to triangulate the research from three aspects in the research presented in this thesis, i.e., data sources, methods, and theory building.

The data sources triangulation includes data from literature and industrial design documents, designers' views, and design cases from both academe and industry. A "between-methods" triangulation (See Section 2.3) was adopted that included literature review, content analysis, protocol analysis, and questionnaire. Following the research focus being identified through the literature review, the nature of the coupling was analysed by combining both the results obtained from the content analysis of eight design documents from a design company and protocol analysis of a supervised student design project. Finally, the theory triangulation was realised through the generation and evaluation of the coupling model. In doing this, the results obtained from the content and protocol analysis were compared with the evaluation results given by industrial designers through a questionnaire.

10.2 ARTEFACT AND DESIGN PROCESS KNOWLEDGE

Design knowledge is considered to be composed of design artefact, process, management, and supplementary knowledge. Existing research was reviewed in Chapter 3 in terms of the design knowledge, focusing on the artefact and design process knowledge. The review revealed the evolutionary feature of both the artefact and design process knowledge. In addition, the review features the following secondary contributions.

➢ **Knowledge pyramid in design support (Section 3.1)**

A three layered design knowledge pyramid (Wang and Duffy 2007) was created. Within the pyramid, the top application layer is composed of different knowledge-based design support systems, the middle layer includes design knowledge models that build the basis for the application layer, and the bottom ontology layer composes different design knowledge ontologies that provide support for developing design knowledge models.

➢ **Knowledge ontology (Appendix A)**

Due to the complexity and heterogeneity of knowledge involved in design, design knowledge can be categorised to different types of knowledge from different points of view (Wang and Duffy 2007), such as:

- Current working and domain;
- Declarative and procedural;

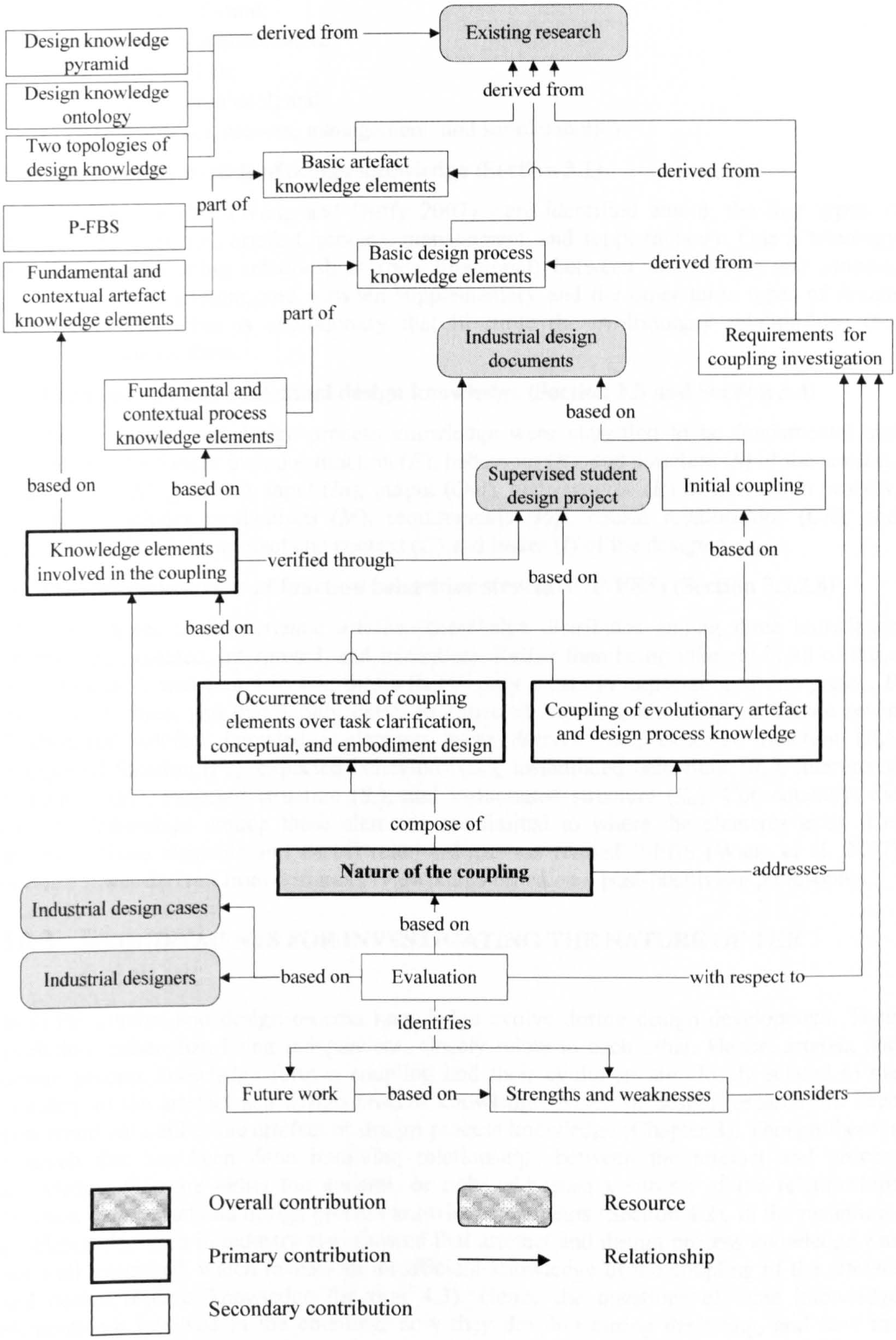


Figure 10-1: Summary of the work

- Descriptive and prescriptive;
- Documented and undocumented;
- Formal and informal;
- Qualitative and quantitative;
- Tacit and explicit;
- Textual and graphical; and
- Design artefact, process, management, and supplementary.

➢ **Two topology models of design knowledge (Section 3.1)**

Two topology models (Wang and Duffy 2007) were identified among the four types of design knowledge, i.e., artefact, process, management, and supplementary. One is teleology that depicts supporting relationships (one-directional) between the artefact and process, process and management, and between supplementary and the other three types of design knowledge. The other is evolutionary that illustrate the evolutionary relationships (bi-directional) among them.

➢ **Fundamental and contextual design knowledge (Section 3.3 and Section 3.4)**

The basic artefact and design process knowledge were classified to be fundamental and contextual. The former includes function (*F*), behaviour (*B*), and structure (*S*) of the artefact, and activity (*A*), goal (*G*), input (*In*), output (*Out*), and resource (*R*) of the design process. The latter includes motivations (*M*), requirements (*Rq*), causal relationships (*CR*), and constraints (*Ct*) of the artefact and context (*C*) and issues (*I*) of the design process.

➢ **Post-positivism view of function behaviour structure (P-FBS) (Section 3.3.2.8)**

The three types of fundamental artefact knowledge distributes among three knowledge spaces, i.e., expected, interpreted, and instantiate. Rather than being inherent in all of these three spaces, it was found in this thesis that *F* only exists in expected and interpreted, *B* exists in all three, and that *S* only exists in expected and instantiated space. Hence seven fundamental artefact knowledge elements were derived, i.e., expected function (F_e), interpreted function (F_{it}), expected behaviour (B_e), instantiated behaviour (B_{is}), interpreted behaviour (B_{it}), expected structure (S_e), and instantiated structure (S_{is}). Consequently, the causal relationships among these elements are limited to where the elements exist. The model of these elements and causal relationships was termed P-FBS (Wang et al. 2007) because it was derived from designers' viewpoints based on a post-positivism philosophy.

10.3 Requirements for Investigating the Nature of the Coupling

Both the artefact and design process knowledge evolve during design development. Their evolution, rather than being independent, closely relate to each other. Hence, artefact and design process knowledge form a coupling and their evolution are closely related to the coupling of the artefact and design process knowledge. Much of design research has been concerned with either the artefact or design process knowledge (Chapter 3). Though there is research that has been done involving relationships between the artefact and process knowledge, they are either too general, or only addressed a sub-set of the relationships between the artefact and design process knowledge elements (Section 4.2). In the meantime, problems identified in industry also showed that artefact and design process knowledge was not well integrated, which reveals an insufficient knowledge of the coupling of the artefact and design process knowledge (Section 4.3). Hence the questions of what knowledge elements are involved in the coupling, how they develop during designing, and how the coupling elements of the artefact and design process are linked were still unanswered. To fill in this knowledge gap, the research was justified to focus on modelling the nature of the coupling of evolutionary artefact and design process knowledge (Section 4.4).

10.4 NATURE OF THE COUPLING

In order to model the nature of the coupling, content analysis (Section 5.1) of eight company design related documents was conducted in order to gain an initial insight of the coupling. The nature of the coupling was further analysed through protocol analysis of a supervised student design project (Section 6.1).

Knowledge elements involved in the coupling

Based on the 18 basic knowledge elements identified from the literature review, i.e. F_e, F_{it}, B_e, B_s, B_{it}, S_e, S_{is}, M, Rq, CR, and Ct of the artefact and A, G, In, Out, R, C, and I of the design process, current working knowledge (*WK*) of these 18 elements, general domain artefact knowledge ($DK_{A\text{-}G}$), and domain artefact knowledge (DK_A) of F_{it}, B_{it}, and S_{is}, were found involved in the coupling through the content and protocol analysis. Hence, 22 knowledge elements were identified to involve in the coupling in this thesis.

Coupling knowledge elements occurrence trends

Knowledge evolution is defined as addition, modification, or deletion of knowledge in this thesis, which can be revealed through discussion of designers. Hence such evolution was revealed through the occurrence trends of the knowledge elements over the design process. The protocol analysis showed that different types of coupling elements exhibited different occurrence trends over task clarification, conceptual, and embodiment design (see Chapter 6). Some elements exhibited more obvious patterns in comparison to some others. Overall, *domain artefact knowledge* has a decreasing trend with its peak in task clarification (Section 6.2.1). *Expected current working artefact knowledge* exhibited an increasing trend with its peak in conceptual design, followed with a slight decrease in embodiment design (Section 6.2.1). *Interpreted* and *instantiated current working artefact knowledge* exhibited an increasing trend with their peak in embodiment design (Section 6.2.1). Finally both *contextual current working artefact knowledge* (Section 6.2.1) and *current working design process knowledge* (Section 6.2.2) exhibited a relatively stable trend.

Coupling of evolutionary artefact and design process knowledge

It was found that design knowledge evolves through two types of link: *link of creation* and *link of employment*. The *link of creation* links two elements where one triggers the creation or occurrence of the other. For example, a chunk of *instantiated domain artefact structural knowledge* ($DK_{A\text{-}Sis}$) triggers creation of an "interpreting" *design activity*. The *link of employment* exists between two elements where one is employed as the other one. For example, a chunk of *expected current working artefact functional knowledge* ($WK_{A\text{-}Fe}$) is employed as an *input* ($WK_{P\text{-}In}$) by a *design activity*. These two types of link constitute the coupling of the evolutionary artefact and design process knowledge.

An initial insight of the coupling was derived from the content analysis, which includes 6 creation and 15 employment links (Chapter 5, Figure 5-7 and Figure 5-8). Through the protocol analysis, the coupling was found to be composed of 18 creation and 15 employment links (Chapter 7, Figure 7-4 and Figure 7-9). Such results were converged by combining the results obtained from the content analysis. The evolved coupling model presented in this thesis is composed of 19 creation and 17 employment links (Table 7-6, Table 7-7, and Figure 7-10). These coupling links reveal the main relationships between the artefact and design process knowledge, which build the basis for the evolution of the artefact and design process knowledge.

10.5 Evaluation

To evaluate the work of the research, a questionnaire was answered by eight practising designers from two companies in two workshops regarding to the main findings presented in this thesis, i.e., the knowledge elements involved in the coupling, elements occurrence trends, and the coupling model. Considering validation of the results, seven were studied for the evaluation.

It was found that all of the 22 knowledge elements were considered to occur and involve in the coupling during design development. Though designers had different views of the frequency of each element, 14 elements were viewed by at least two designers as having the same frequency as that obtained from the protocol analysis.

Designers had a diversity of views of the element occurrence trends, in that there were at least four answers for each element. Therefore, only the trends that were chosen by the three most experienced designers, or by more than two designers, were analysed during the evaluation. The results showed that, of the 22 evaluated elements, 2 were viewed as having the same trend as that obtained from the protocol analysis, while 7 were viewed as similar, and 13 were viewed as different.

Various views of the coupling links existed among the designers, which resulted in 48 creation and 42 employment links. Among them, 9 creation and 12 employment links were also identified from the protocol analysis. However, there were still 12 creation and 7 employment links identified from the protocol analysis that were not identified from the evaluation.

The difference between the results obtained from the content and protocol analysis and evaluation workshops in respect of the elements' occurrence trends and coupling might be explained in terms of limited duration of the evaluation workshops, the difference between student and commercial design projects, as well as the difference between individual and collaborative design projects. In addition, the diversity of views of the knowledge elements occurrence trends and coupling links among designers might be caused by a number of factors, such as designers' different design experiences, different product types that they normally worked on, different projects used by the them for the evaluation, as well as their different understanding of the knowledge elements and links.

10.6 Strengths and Weaknesses and Future Work

The triangulation methodology adopted in this work enabled the coupling model to be based on not only literature and company general practice, but also empirical design project. In addition, it provided a relatively potent means of assessing the degree of convergence as well as elaborating the divergence between the results obtained from the different methods adopted, i.e., literature review, content analysis, and protocol analysis. However, choosing different data sources and research methods was subjected to the time permitted for conducting the research. Hence only eight industrial design documents and one student design project were analysed for developing the coupling model. Without using any empirical industrial design project, the generality of the findings might be affected, i.e., the coupling model might not apply to all types of design.

The coupling was obtained from both the content and protocol analysis, which ensured that it could be applied to not only individual design conducted by novice designer, but also company general design practice. The identification of a set of basic knowledge elements involved in the coupling, their occurrence trends, and the links between the elements provided an initial insight of the nature of the coupling. Moreover, the evaluation enabled the work being checked against industrial design cases. However, the identification of the elements and links during the content and protocol analysis relied on the inference of the encoder. Hence different encoders might result in different encoding. In addition, though the model was evaluated by checking against industrial design cases, the evaluation results were subjected to the designers' understanding of the questionnaire, which was affected by the duration of the workshops. Hence, more empirical study of industrial design cases can enable the coupling model to be further evolved and more accurately reflect the practice in industry.

In view of these weaknesses of the work and other potential research directions (Section 9.4), future work was identified to be:

- To analyse more different types of industrial design projects;
- To have the research checked/done by different researchers;
- To accommodate different types of design activities;
- To investigate coupling of design process and management knowledge;
- To support knowledge evolution;
- To investigate change propagation;
- To provide system support for design development.

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Appendices

Appendix A EXISTING DESIGN KNOWLEDGE ONTOLOGIES

In Chapter 3 of the thesis, a design knowledge pyramid is presented, of which design knowledge ontology build the basic level. This appendix examines the ontology level of the knowledge pyramid in further detail by presenting different design knowledge classifications from different points of view.

Ontology is the branch of philosophy that deals with the nature of existence by clarifying the nature and structure of the world (Sim and Duffy 2003). In artificial intelligence, ontology means a formal system for representing domain concepts and their related linguistic realisations by using basic elements (Chandrasekaran et al. 1998). Uschold and Grundinger (1996) advocated ontology in order to have a shared understanding as a unifying framework for different viewpoints. A review of related literature reveals that there has been a variety of classifications of design knowledge. With regard to different researchers' views of the classifications, there appear to be some inconsistencies among them, which seems to stem from the researchers' different research objectives, approaches, and adopted principles and standards. To this end, this section gives an account of some of the most commonly used classifications in engineering design while taking such differences into consideration. The list is not meant to be exhaustive but more indicative of the engineering design domain. The following nine classifications are examples of the design knowledge ontology:

- Current working and domain knowledge (Zhang 1999);
- Declarative and procedural knowledge (Achten et al. 1998);
- Descriptive and prescriptive knowledge (Roozenburg and Eekels 1995; Aken 2005);
- Documented and undocumented knowledge (Ishino and Jin 2002);
- Formal and informal knowledge (Conklin 1996);
- Qualitative and quantitative knowledge (Gero 1990);
- Tacit and explicit knowledge (Nonaka and Takeuchi 1995);
- Textual and graphical (Al-salka et al. 1998); and
- Design artefact, process, management and supplementary knowledge (Takeda, Veerkamp et al. 1990; Ishino and Jin 2002).

Of these classifications, the first eight could be applied to general knowledge. That is, they are suitable to classifications of knowledge not only in engineering design but also in other disciplines. However, the last one, design artefact, process, management and supplementary knowledge, is dedicated to knowledge classification in the engineering design domain.

Knowledge source – current working and domain

Depending on whether the knowledge being used is generated by the current design project or not, design knowledge can be classified into current working knowledge (CWK) and domain knowledge (DK) (Zhang 1999). This classification is consistent with Aken's "Specific design knowledge" and "General design knowledge" (Aken 2005, p.387).

According to Zhang (1999), current working knowledge refers to the knowledge of the design on which the designer is currently working, and domain knowledge is the knowledge of past designs in a domain. As Zhang pointed out, domain knowledge can consist of generalised knowledge of a design domain that is applicable to different design cases (i.e. general knowledge), and the knowledge of specific past designs (i.e. past cases). Design rules (including design operations and their conditions) are examples of general knowledge (Nomaguchi and Tomiyama 2004). In particular, when creating new designs, to aid the evolution of current design, designers rely on experiences from past design (Maher and

Gomez de Silva Garza 1997). This experiential knowledge from past design also belongs to general knowledge.

Design cases are one of the major types of domain knowledge, which is widely used for complex product design, such as airplanes and ships. A case is normally adopted from an available past design and evolved by including more functions, enhancing the performance, or improving the quality. Cases are also used in analogical reasoning (Duffy 1997b), in which designers learn generalised abstract knowledge from past design to proceed with similar design. As Haffey and Duffy (2000) observed, whether or not cases could be fully used is one difference between novice and expert designers. Where novice designers generally rely on rule-based reasoning or deductive reasoning to solve problems, the experts can base their judgements on higher-level similarities between examples.

Knowledge cognition – declarative and procedural

From cognitive psychologists' view, design knowledge can be considered to contain declarative knowledge and/or procedural knowledge (Achten et al. 1998; Darlington et al. 1998; Berge and Hezewijk 1999; Nickols 2000). Declarative knowledge is knowledge about "know what", and contains a description of objects, events or methods and how they are related to other objects, events and methods. On the other hand, procedural knowledge is knowledge of "know how" that encodes how to perform certain tasks so as to achieve a particular result. This type of knowledge is normally stored in terms of procedures. For an example of these two types of knowledge, consider a modular roadside barrier. It is composed of locktabs, receptacles, panels, posts, brackets, visibility strips, abacus balls, and finials. The panels can be 1.5m, 1m, or 0.5m. These descriptions are together termed the declarative knowledge of a modular roadside barrier, because they present some components or properties of roadside barrier. However, "The receptacle should be sunk into the concrete and concrete left to cure. On return the next day, the posts and locktabs should be inserted, with subsequent attachment of brackets and panels.", is regarded as procedural knowledge because it describes how to install the barrier on the ground.

In engineering design, an artefact might be represented by both declarative and procedural knowledge for different purposes, in order to take benefit of their different advantages. However, the same chunk of knowledge could be viewed as declarative or procedural knowledge in different contexts. As researchers in the AI laboratory of the University of Michigan (Hyun et al. 1994) proposed, whether knowledge is viewed as declarative or procedural, is not an intrinsic property of the knowledge itself, but based on how people read from it. As a result, the distinction between declarative and procedural knowledge is somewhat subjective in that the judgement depends on human being's expectation and interpretation.

Knowledge function – descriptive and prescriptive

In a review of previous research on design models, Finger and Dixon (1989) and Love (1997), among others, delineated two types of design model: one is descriptive and the other is prescriptive. In a similar vein, others (e.g. Roozenburg and Eekels 1995; Aken 2005; Horvath and Duhovnik 2005) talked about the function of design knowledge, which can also be characterised by descriptive design knowledge and prescriptive design knowledge. The former describes what constitutes the design artefact and what typically occurs during a design process. For example, the outer diameter of the receptacle of a modular roadside barrier is 68mm, and the abacus balls will be stamped from a flat steel sheet with 2mm thickness. On the other hand, the latter specifies how something should be or should be done (Aken 2005). Therefore, prescriptive design knowledge is the knowledge which prescribes how the artefact should look, behave and how the design should be undertaken. For example, during the course of designing roadside barrier, designers may prescribe that the "the post should be broken when the barrier is crashed by a car". Put simply, prescriptive knowledge could be used as guidance for designers to make decisions to proceed with the design.

Knowledge availability – documented and undocumented

The fourth knowledge classification is based on its availability, which categorises knowledge in terms of documented knowledge and undocumented knowledge (Ishino and Jin 2002). Documented knowledge, on the one hand, is the knowledge that has been recorded by writing, filming, or taping with some medium. As a result, documented knowledge is available for people to refer to and therefore benefits knowledge re-use. On the other hand, undocumented knowledge refers to the knowledge that has not been documented. It may be either knowledge undiscovered or that has been discovered, however, still in human being's mind.

Knowledge style – formal and informal

According to whether knowledge has an ordered, organised method or style, it can then be categorised into either formal or informal knowledge. Overall, formal knowledge is knowledge that has been expressed in a systematic way or an ordered, organised style. For Conklin (1996), formal knowledge is the knowledge that could be found in books, manuals, and documents, and can be easily shared in training courses. Rules and strategies are examples of formal knowledge. In contrast to formal knowledge, informal knowledge is knowledge that lacks a proper structure or order, and is usually presented in a primary or simpler way. Notes, images or sketches are examples of informal knowledge. Furthermore, informal knowledge can be applied in the process of creating formal knowledge (Conklin 1996). For example, a designer noticed the pedestrian barriers were repeatedly kept on getting struck by vehicles, and it took the local council a long time to replace them. The informal motivation to improve the quality and replacement of pedestrian barriers can be used as input for creating formal requirements description of pedestrian barrier design.

Knowledge accountability – quantitative and qualitative

Quantitative and qualitative have been discussed in Chapter 2 as the two primary classifications of research methodologies. While quantitative research methods collect and analyse data that can be calculated or evaluated by using mathematical methods, qualitative research methods use data describing the quality of the research subject. Similarly, design knowledge can be categorised into quantitative and qualitative according to whether the knowledge is accountable. While the data embedded within quantitative knowledge is accountable and can be manipulated with mathematical methods, those embedded within qualitative knowledge is not accountable and can be analysed by using qualitative methods.

Knowledge accessibility – tacit and explicit

According to whether knowledge can be articulated in a direct way, or it is accessible, design knowledge is categorised into tacit and explicit (Nonaka and Takeuchi 1995; Nickols 2000; Ishino and Jin 2002; Sim and Duffy 2003). Implicit (Haffey and Duffy 2000) and codified (Aken 2005) are other terms that are used for tacit and explicit knowledge respectively.

According to Nonaka and Takeuchi (1995), tacit knowledge is subjective and experience based knowledge that can not be articulated in words, sentences, numbers or formulas, because they are normally context specific. Similarly, Sim and Duffy (2003) pointed out that tacit knowledge is personal and context-specific. Therefore it is hard to formalise and communicate with (Nonaka and Takeuchi 1995). Due to the difficulty of expression, it is relatively difficult to access tacit knowledge. An example of tacit knowledge is design experience possessed by expert designers (Matthews et al. 2002). With this experience, they know why they make a decision in one specific situation. However, sometimes it is difficult for them to express the rationale in a way for others to readily understand. Explicit knowledge, on the other hand, refers to knowledge that is comparatively objective, rational and is transmittable in formal, systematic expression (Nonaka and Takeuchi 1995; Sim and Duffy 2003). Compared to tacit knowledge, generally, it is therefore more readily to be accessed and utilised. Examples of explicit knowledge are knowledge captured in diagrams, tables, and documents.

Knowledge representation – textual and graphical

Design knowledge can be represented in different ways, such as text, symbol, graphic and table. In general, texts and graphics are considered as the main representation formats of design knowledge (Al-salka et al. 1998).

Textual knowledge is knowledge that is represented with, among others, words and numbers, which may be in the format of documents, audio, and video. It is largely used to represent design specifications, design functions, components, design activities, or design rules in engineering design.

Graphics is a type of symbolical representation of design knowledge, which is used prevalently in engineering design. Drawings, pictures, sketches, and diagrams, are examples of graphical knowledge used in engineering design. As an aid for short term memory and long term memory, graphics provides a method to present information and knowledge in a direct way (Achten et al. 1998).

Knowledge content – design artefact, process, management, and supplementary

Because the research presented in this thesis is about artefact and process knowledge, the discussion of classifying design knowledge to artefact, process, management and supplementary according to its content is presented in detail in Section 3.2.

Summary

For clarity, Table A-1 summarises the design knowledge classifications discussed in this appendix. It should be noted that, a chunk of knowledge could belong to different knowledge types within different classification at the same time. That is to say, it could be both declarative and prescriptive knowledge, or be documented, explicit, symbolic, and domain knowledge. For example, when designers prescribe the length of barrier's panel, this chunk of knowledge is prescriptive according to its function. At the same time, it is also declarative knowledge of the barrier. Similarly, a chunk of undocumented knowledge can contain tacit knowledge as well as explicit knowledge.

Table A-1: Classifications of engineering design knowledge

Classification viewpoints	Knowledge types	Examples
Source	Current working knowledge	Functions of the current working design
	Domain knowledge	Functions of a past design case
Cognition	Declarative knowledge	Artefact functions
	Procedural knowledge	Artefact behaviour and consequent functional results
Function	Descriptive knowledge	Components of a finished design
	Prescriptive knowledge	Description of what components should a design has
Availability	Documented knowledge	Company procedures
	Undocumented knowledge	Designers' intuition of a design

Classification viewpoints	Knowledge types	Examples
Style	Formal knowledge	Company procedures
	Informal knowledge	Design concept sketches
Accountability	Quantitative knowledge	Dimension of the structure components
	Qualitative knowledge	Rationale used in decision making
Accessibility	Tacit knowledge	Design experience
	Explicit knowledge	Physical laws
Representation	Textual knowledge	Paragraphs describing design specification
	Graphical knowledge	3D drawing of a design
Content	Design artefact knowledge	Functions, behaviours, structures, causal relationships, constraints
	Design process knowledge	Design goals, activities, resources, inputs, outputs, contexts, issues
	Design management knowledge	Process planning knowledge
	Design supplementary knowledge	Enterprise cultures, national policy strategies.

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Appendix B CONTENT ANALYSIS

Eight design related documents from Company A were analysed, which were mainly description of standard company artefact knowledge that was accumulated from past designs and process that describes standard company working procedure. The analysis focused on artefact and design process knowledge elements as well as the links between them in order to obtain an initial finding of the nature of the coupling. All the documents and reference to the company are classified confidential. Consequently, the documents title and product name have been substituted with general words in this appendix.

The analysis result of the knowledge elements and links between them are presented in the following two sections, i.e., "Knowledge elements" and "Coupling links".

B.1 KNOWLEDGE ELEMENTS

The following eight tables list the key words identified for each knowledge element from the eight documents. N/A indicates such element was not identified in the document.

Document 1 Artefact structure

Knowledge elements	Key words
$WK_{A\text{-}Be}$	N/A
$WK_{A\text{-}Bis}$	N/A
$WK_{A\text{-}Bit}$	N/A
$WK_{A\text{-}Fe}$	Business catalogues, Standard specification, Functions, Elementary function, Contract
$WK_{A\text{-}Fit}$	Functional diagram, Performing functions
$WK_{A\text{-}Se}$	Contractual configuration, Constituent assembly, Configuration component, Business catalogues, Standard specification, Conception solutions, Design principles
$WK_{A\text{-}Sis}$	Configuration, 3D Models, 2D Drawings, Design solution, Mock-up, Chosen design principle, Parts
$WK_{A\text{-}CR}$	Category, Standard specification
$WK_{A\text{-}Ct}$	Constraints
$WK_{A\text{-}M}$	Company requirements, Customer needs
$WK_{A\text{-}Rq}$	Contract, Requirement program, Market requirement
$WK_{P\text{-}A}$	Way of working, Update/Creation of data, Build contract, Create specification, Means, Change, Evaluation
$WK_{P\text{-}G}$	Objective
$WK_{P\text{-}In}$	In
$WK_{P\text{-}Out}$	Out
$WK_{P\text{-}R}$	Catalogues, Standard specification, Department, Tools, Literature, Who
$WK_{P\text{-}C}$	Status, Interactions, Scenario, State of design, All functions/solutions
$WK_{P\text{-}I}$	N/A
DK_{A}	Standard specification, Business catalogue, Literature, Standards

Document 2 Artefact design phase

Knowledge elements	Key words
$WK_{A\text{-}Be}$	Performance, Given characteristics
$WK_{A\text{-}Bis}$	N/A
$WK_{A\text{-}Bit}$	Functional simulation
$WK_{A\text{-}Fe}$	Artefact requirements
$WK_{A\text{-}Fit}$	Artefact specification
$WK_{A\text{-}Se}$	Alternative concepts
$WK_{A\text{-}Sis}$	Physical definition, Baseline concept, Baseline configuration, Detailed concept, Specification, Sized components
$WK_{A\text{-}CR}$	Category, Standard specification
$WK_{A\text{-}Ct}$	Constraints
$WK_{A\text{-}M}$	External triggering events (customers, competition, suppliers), Internal development of new product ideas, Market situation, Opportunities
$WK_{A\text{-}Rq}$	Design requirements, Standards
$WK_{P\text{-}A}$	Activities (definition, comparison, analysis, optimisation, integration)
$WK_{P\text{-}G}$	Content of phase
$WK_{P\text{-}In}$	In
$WK_{P\text{-}Out}$	Out, Result output, Deliverables
$WK_{P\text{-}R}$	Resources, budget, Design standard, Requirements
$WK_{P\text{-}C}$	Environment, Marketing, Production, Program status
$WK_{P\text{-}I}$	N/A
DK_{A}	Literature

Document 3 Artefact information object

Knowledge elements	Key words
$WK_{A\text{-}Be}$	N/A
$WK_{A\text{-}Bis}$	N/A
$WK_{A\text{-}Bit}$	Structure analysis, Performance, Systems ability
$WK_{A\text{-}Fe}$	Configuration, Functions, Defined functions
$WK_{A\text{-}Fit}$	Functional architecture, Performance
$WK_{A\text{-}Se}$	Configuration, Possible solutions, Possible combinations
$WK_{A\text{-}Sis}$	Systems architecture, Geometry
$WK_{A\text{-}CR}$	Design principles, Design evolution, Design rationale
$WK_{A\text{-}Ct}$	Design principles
$WK_{A\text{-}M}$	Market analysis and opportunities

$WK_{A\text{-}Rq}$	Requirements, Design principles
$WK_{P\text{-}A}$	Propose (solutions), Customise, Capture
$WK_{P\text{-}G}$	Targets, Purpose
$WK_{P\text{-}In}$	Input information objects (architecture, configuration, performance...)
$WK_{P\text{-}Out}$	Output information objects
$WK_{P\text{-}R}$	Resources, Budget, Documents, Standard specification, Catalogues
$WK_{P\text{-}C}$	N/A
$WK_{P\text{-}I}$	N/A
DK_{A}	Rules, Methods

Document 4 System specification

Knowledge elements	Key words
$WK_{A\text{-}Be}$	Performances to be achieved
$WK_{A\text{-}Bis}$	N/A
$WK_{A\text{-}Bit}$	Implementation of the functions performed by the system
$WK_{A\text{-}Fe}$	System specification, System description, Function requirements document, function description document
$WK_{A\text{-}Fit}$	Functions
$WK_{A\text{-}Se}$	System physical architecture, System description document, System interface
$WK_{A\text{-}Sis}$	Chosen system design (Electronic, Electric, Fluid, Mechanical, Man machine interface, Optical...), Equipment, Items, Parts
$WK_{A\text{-}CR}$	System description document, Function requirements document, Function description document, Design rationale
$WK_{A\text{-}Ct}$	Technologies availability, Business and marketing constraints, Environmental constraints
$WK_{A\text{-}M}$	User's needs
$WK_{A\text{-}Rq}$	System requirements, Equipment requirements, Safety requirements, Operational requirements
$WK_{P\text{-}A}$	Activities (allocate, determine, design, ...)
$WK_{P\text{-}G}$	Objectives, Purpose
$WK_{P\text{-}In}$	Input (documents of requirements, function...)
$WK_{P\text{-}Out}$	Output (documents of requirements, structure...)
$WK_{P\text{-}R}$	Standards documents, Department, Tools, Lessons learned, Technologies availability
$WK_{P\text{-}C}$	Availability of input data
$WK_{P\text{-}I}$	N/A
DK_{A}	Product standard specification, Lessons learned from previous programs

Document 5 System design process

Knowledge elements	Key words
WK_{A-Be}	Artefact performance
WK_{A-Bis}	N/A
WK_{A-Bit}	Artefact performance
WK_{A-Fe}	Artefact functions
WK_{A-Fit}	Artefact performance
WK_{A-Se}	System concept, Equipment specification, Structure and installation
WK_{A-Sis}	Design solutions, Structure and installation, Equipment
WK_{A-CR}	N/A
WK_{A-Ct}	System constraints
WK_{A-M}	Customer and market needs
WK_{A-Rq}	System requirements, Components requirements
WK_{P-A}	Activities (specify, analyse, verify, define, monitor, verify...)
WK_{P-G}	N/A
WK_{P-In}	Input (Deliverable of system requirements, function, structure...)
WK_{P-Out}	Output (Deliverable of system requirements, function, structure...)
WK_{P-R}	Departments
WK_{P-C}	N/A
WK_{P-I}	N/A
DK_{A}	N/A

Document 6 Requirements management

Knowledge elements	Key words
WK_{A-Be}	N/A
WK_{A-Bis}	N/A
WK_{A-Bit}	N/A
WK_{A-Fe}	Validated requirements
WK_{A-Fit}	Designed requirements
WK_{A-Se}	Alternative physical solutions, Structure, System and sub-system, Equipment, Abstract solution definition
WK_{A-Sis}	Preferred solution, drawings, models
WK_{A-CR}	Solution definition (S-F, F-R)
WK_{A-Ct}	Constraints
WK_{A-M}	Customer and stakeholder's needs
WK_{A-Rq}	System requirements, component requirements, External requirements, Internal requirements,
WK_{P-A}	Activities, Steps (Capture, analysis, validation, allocation, verification, change)

$WK_{P\text{-}G}$	Aims, objectives,
$WK_{P\text{-}In}$	Inputs (needs, requirements)
$WK_{P\text{-}Out}$	Outputs (Requirements)
$WK_{P\text{-}R}$	Tools, Documents, Means, Techniques, People
$WK_{P\text{-}C}$	Status (maturity level), Source, Stakeholder
$WK_{P\text{-}I}$	N/A
DK_{A}	Standard procedures

Document 7 Function definition process

Knowledge elements	Key words
$WK_{A\text{-}Be}$	Functional requirements
$WK_{A\text{-}Bis}$	N/A
$WK_{A\text{-}Bit}$	N/A
$WK_{A\text{-}Fe}$	Functional requirements, Function description
$WK_{A\text{-}Fit}$	Functions identified in functional analysis
$WK_{A\text{-}Se}$	Physical components that are necessary to implement artefact functions, System architecture, Equipment
$WK_{A\text{-}Sis}$	Structure
$WK_{A\text{-}CR}$	Rq-F, F-S, System breakdown, , Function decomposition
$WK_{A\text{-}Ct}$	Non-functional requirements
$WK_{A\text{-}M}$	Customer/User need, certification/safety requirements, costs
$WK_{A\text{-}Rq}$	Top level requirements, Certification/safety requirements
$WK_{P\text{-}A}$	Activities (decompose, identify, allocate, specify...)
$WK_{P\text{-}G}$	Objectives, Purpose
$WK_{P\text{-}In}$	Input (function at different status)
$WK_{P\text{-}Out}$	Output (function at different status)
$WK_{P\text{-}R}$	Tools, Documents, Database
$WK_{P\text{-}C}$	N/A
$WK_{P\text{-}I}$	N/A
DK_{A}	N/A

Document 8 Component level design process

Knowledge elements	Key words
$WK_{A\text{-}Be}$	Feasibility study, Performance
$WK_{A\text{-}Bis}$	N/A
$WK_{A\text{-}Bit}$	Simulations, Performance, Operations, Function analysis

$WK_{A\text{-}Fe}$	General functions, Feasibility study
$WK_{A\text{-}Fit}$	Main new features, Functionalities, System description, Function analysis
$WK_{A\text{-}Se}$	Previous model, Proposed structure, Possibility of system design, arrangement
$WK_{A\text{-}Sis}$	Selected system, System concept description, Geometric definitions, Product structure, 3D models
$WK_{A\text{-}CR}$	Feasibility study, Experience of engineers
$WK_{A\text{-}Ct}$	Restrictions, Construction regulations, Standards
$WK_{A\text{-}M}$	N/A
$WK_{A\text{-}Rq}$	Requirements, System description
$WK_{P\text{-}A}$	Activity A, B...
$WK_{P\text{-}G}$	To...
$WK_{P\text{-}In}$	Requirements, Predefined systems, Functions, Expected structures
$WK_{P\text{-}Out}$	Deliverables, Structure, Function, Requirements
$WK_{P\text{-}R}$	Reference documents
$WK_{P\text{-}C}$	N/A
$WK_{P\text{-}I}$	N/A
DK_{A}	N/A

B.2 COUPLING LINKS

Two types of links, i.e., *cause-effect link of creation* and *link of employment* were analysed within each document. The identified links in each document are indicated in the following tables. In the upper "Cause-effect link of creation" part of each table, the elements listed in the second column represent the causing elements, and those in the second row represent caused elements. In the lower "Link of employment" part, the elements listed in the second column represent the employing elements, and those in the second row represent employed elements.

Document 1 Artefact structure

Cause-effect link of creation

Causing elements \ Caused elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}																			
	WK_{A-Bit}																			
	WK_{A-Bis}																			
	WK_{A-Fe}													√						
	WK_{A-Fit}													√						
	WK_{A-Se}													√						
	WK_{A-Sis}																			
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}													√						
	WK_{A-Rq}													√						
Design process	WK_{P-A}	√				√	√	√	√				√							
	WK_{P-G}																			
	WK_{P-In}																			
	WK_{P-Out}																			
	WK_{P-R}																			
	WK_{P-C}																			
	WK_{P-I}																			

Link of employment

Employing elements \ Employed elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}																			
	WK_{A-Bit}																			
	WK_{A-Bis}																			
	WK_{A-Fe}																			
	WK_{A-Fit}																			
	WK_{A-Se}																			
	WK_{A-Sis}																			
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}																			
	WK_{A-Rq}																			
Design process	WK_{P-A}																			
	WK_{P-G}					√		√	√				√							
	WK_{P-In}	√				√	√	√	√			√	√							
	WK_{P-Out}	√				√	√	√	√			√	√							
	WK_{P-R}	√								√										
	WK_{P-C}					√		√	√											
	WK_{P-I}																			

Document 2 Artefact design phase

Cause-effect link of creation

Causing elements \ Caused elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}													√						
	WK_{A-Bit}													√						
	WK_{A-Bis}																			
	WK_{A-Fe}													√						
	WK_{A-Fit}													√						
	WK_{A-Se}													√						
	WK_{A-Sis}													√						
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}													√						
	WK_{A-Rq}													√						
Design process	WK_{P-A}		√	√		√	√	√	√			√	√							
	WK_{P-G}																			
	WK_{P-In}																			
	WK_{P-Out}																			
	WK_{P-R}																			
	WK_{P-C}																			
	WK_{P-I}																			

Link of employment

Employing elements \ Employed elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}																			
	WK_{A-Bit}																			
	WK_{A-Bis}																			
	WK_{A-Fe}																			
	WK_{A-Fit}																			
	WK_{A-Se}																			
	WK_{A-Sis}																			
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}																			
	WK_{A-Rq}																			
Design process	WK_{P-A}																			
	WK_{P-G}											√	√							
	WK_{P-In}	√						√	√			√	√							
	WK_{P-Out}					√	√	√	√				√							
	WK_{P-R}																			
	WK_{P-C}																			
	WK_{P-I}																			

Document 3 Artefact information object

Cause-effect link of creation

Caused elements / Causing elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}																			
	WK_{A-Bit}													√						
	WK_{A-Bis}																			
	WK_{A-Fe}													√						
	WK_{A-Fit}													√						
	WK_{A-Se}													√						
	WK_{A-Sis}													√						
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}													√						
	WK_{A-Rq}													√						
Design process	WK_{P-A}			√		√	√	√	√				√							
	WK_{P-G}																			
	WK_{P-In}																			
	WK_{P-Out}																			
	WK_{P-R}																			
	WK_{P-C}																			
	WK_{P-I}																			

Link of employment

Employed elements / Employing elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}																			
	WK_{A-Bit}																			
	WK_{A-Bis}																			
	WK_{A-Fe}																			
	WK_{A-Fit}																			
	WK_{A-Se}																			
	WK_{A-Sis}																			
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}																			
	WK_{A-Rq}																			
Design process	WK_{P-A}																			
	WK_{P-G}																			
	WK_{P-In}			√		√	√	√	√				√							
	WK_{P-Out}			√		√	√	√	√				√							
	WK_{P-R}	√								√	√									
	WK_{P-C}																			
	WK_{P-I}																			

Document 4 System specification

Cause-effect link of creation

Causing elements \ Caused elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}													√						
	WK_{A-Bit}													√						
	WK_{A-Bis}																			
	WK_{A-Fe}													√						
	WK_{A-Fit}													√						
	WK_{A-Se}													√						
	WK_{A-Sis}													√						
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}																			
	WK_{A-Rq}													√						
Design process	WK_{P-A}		√	√		√	√	√	√				√							
	WK_{P-G}																			
	WK_{P-In}																			
	WK_{P-Out}																			
	WK_{P-R}																			
	WK_{P-C}																			
	WK_{P-I}																			

Link of employment

Employing elements \ Employed elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}																			
	WK_{A-Bit}																			
	WK_{A-Bis}																			
	WK_{A-Fe}																			
	WK_{A-Fit}																			
	WK_{A-Se}																			
	WK_{A-Sis}																			
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}																			
	WK_{A-Rq}																			
Design process	WK_{P-A}																			
	WK_{P-G}																			
	WK_{P-In}		√	√		√	√	√	√				√							
	WK_{P-Out}		√	√		√	√	√	√				√							
	WK_{P-R}	√								√										
	WK_{P-C}																			

Document 5 System design process

Cause-effect link of creation

Caused elements / Causing elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}													√						
	WK_{A-Bit}													√						
	WK_{A-Bis}																			
	WK_{A-Fe}													√						
	WK_{A-Fit}													√						
	WK_{A-Se}													√						
	WK_{A-Sis}													√						
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}													√						
	WK_{A-Rq}													√						
Design process	WK_{P-A}		√	√		√	√	√	√		√	√	√							
	WK_{P-G}																			
	WK_{P-In}																			
	WK_{P-Out}																			
	WK_{P-R}																			
	WK_{P-C}																			
	WK_{P-I}																			

Link of employment

Employed elements / Employing elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}																			
	WK_{A-Bit}																			
	WK_{A-Bis}																			
	WK_{A-Fe}																			
	WK_{A-Fit}																			
	WK_{A-Se}																			
	WK_{A-Sis}																			
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}																			
	WK_{A-Rq}																			
Design process	WK_{P-A}																			
	WK_{P-G}		√	√				√	√											
	WK_{P-In}		√	√		√	√	√	√			√	√							
	WK_{P-Out}		√	√		√	√	√	√		√	√	√							
	WK_{P-R}																			
	WK_{P-C}																			
	WK_{P-I}																			

Document 6 Requirements management

Cause-effect link of creation

Causing elements \ Caused elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}																			
	WK_{A-Bit}																			
	WK_{A-Bis}																			
	WK_{A-Fe}													√						
	WK_{A-Fit}													√						
	WK_{A-Se}													√						
	WK_{A-Sis}													√						
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}													√						
	WK_{A-Rq}													√						
Design process	WK_{P-A}		√	√				√	√			√	√							
	WK_{P-G}																			
	WK_{P-In}																			
	WK_{P-Out}																			
	WK_{P-R}																			
	WK_{P-C}																			
	WK_{P-I}																			

Link of employment

Employing elements \ Employed elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}																			
	WK_{A-Bit}																			
	WK_{A-Bis}																			
	WK_{A-Fe}																			
	WK_{A-Fit}																			
	WK_{A-Se}																			
	WK_{A-Sis}																			
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}																			
	WK_{A-Rq}																			
Design process	WK_{P-A}																			
	WK_{P-G}											√	√							
	WK_{P-In}					√	√	√	√			√	√							
	WK_{P-Out}					√	√	√	√				√							
	WK_{P-R}	√								√	√									
	WK_{P-C}																			
	WK_{P-I}																			

Document 7 Function definition process

Cause-effect link of creation

Causing elements \ Caused elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}													√						
	WK_{A-Bit}																			
	WK_{A-Bis}																			
	WK_{A-Fe}													√						
	WK_{A-Fit}													√						
	WK_{A-Se}													√						
	WK_{A-Sis}													√						
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}													√						
	WK_{A-Rq}													√						
Design process	WK_{P-A}		√			√	√	√	√	√	√	√	√							
	WK_{P-G}																			
	WK_{P-In}																			
	WK_{P-Out}																			
	WK_{P-R}																			
	WK_{P-C}																			
	WK_{P-I}																			

Link of employment

Employing elements \ Employed elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}																			
	WK_{A-Bit}																			
	WK_{A-Bis}																			
	WK_{A-Fe}																			
	WK_{A-Fit}																			
	WK_{A-Se}																			
	WK_{A-Sis}																			
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}																			
	WK_{A-Rq}																			
Design process	WK_{P-A}																			
	WK_{P-G}					√	√						√							
	WK_{P-In}		√			√	√	√	√			√	√							
	WK_{P-Out}		√			√	√	√	√	√		√	√							
	WK_{P-R}	√								√										
	WK_{P-C}										√	√	√							
	WK_{P-I}																			

Document 8 Component level design process

Cause-effect link of creation

Causing elements \ Caused elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}													√						
	WK_{A-Bit}													√						
	WK_{A-Bis}																			
	WK_{A-Fe}													√						
	WK_{A-Fit}													√						
	WK_{A-Se}													√						
	WK_{A-Sis}													√						
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}																			
	WK_{A-Rq}													√						
Design process	WK_{P-A}		√	√		√	√	√	√	√	√		√							
	WK_{P-G}																			
	WK_{P-In}																			
	WK_{P-Out}																			
	WK_{P-R}																			
	WK_{P-C}																			
	WK_{P-I}																			

Link of employment

Employing elements \ Employed elements		Artefact												Design process						
		DK_A	WK_{A-Be}	WK_{A-Bit}	WK_{A-Bis}	WK_{A-Fe}	WK_{A-Fit}	WK_{A-Se}	WK_{A-Sis}	WK_{A-CR}	WK_{A-Ct}	WK_{A-M}	WK_{A-Rq}	WK_{P-A}	WK_{P-G}	WK_{P-In}	WK_{P-Out}	WK_{P-R}	WK_{P-C}	WK_{P-I}
Artefact	DK_A																			
	WK_{A-Be}																			
	WK_{A-Bit}																			
	WK_{A-Bis}																			
	WK_{A-Fe}																			
	WK_{A-Fit}																			
	WK_{A-Se}																			
	WK_{A-Sis}																			
	WK_{A-CR}																			
	WK_{A-Ct}																			
	WK_{A-M}																			
	WK_{A-Rq}																			
Design process	WK_{P-A}																			
	WK_{P-G}		√	√				√	√				√							
	WK_{P-In}		√	√		√	√	√	√				√							
	WK_{P-Out}		√	√		√	√	√	√				√							
	WK_{P-R}	√								√										
	WK_{P-C}	√	√	√		√	√	√	√	√	√		√							
	WK_{P-I}																			

Appendix C CONSENT FORM AND ETHLIC CHECK

To record the seven students' design projects, a consent form was signed by the supervisor and students.

Consent form

Project Title	Recording and analysing student projects for design knowledge evolution model development
Participants	Staff: Norman McNally Students: 4th and 5th year design students in DMEM
Project Background	The co-evolutionary phenomenon of design process knowledge and design product knowledge coupling exists during design development. This PhD research is going to build an elaborated model for this knowledge coupling to increase the understanding of design. As one of the requirements of the research, empirical design process data by students need to be recorded for the model analysis, building and evaluation.
Project Introduction	The recording will follow three 4th and 5th year undergraduate students' project work in DMEM, which includes ▪ Recording the meeting between supervisor and students; ▪ Taking photographs of the design work during the students project work; ▪ And, interviewing students and supervisor to clarify the design work.

The code of practice on investigations on human beings by University of Strathclyde including two checklists, which are "supervisor and student ethics checklist" and "checklist for department approved investigations" have been shown to the supervisor and students. This work will be done with the agreement from the supervisor and students.

Supervisor Signature .... Date 300905.

Students Signatures .... Date

30/9/05
30/09/05
30/9/05
30/09/05
30/09/05
30.09.05
6/10/05

Because the study involves 'investigation on human beings', two checklists regarding to "Ethics Committee - Code of Practice on Investigations on Human Beings", and "Department Approved Investigations" were signed by the author and her supervisor to ensure that the recording and analysis abide the rules of such investigation.

Ethics Committee -
Code of Practice on Investigations on Human Beings

When implementing a staff or student project which involves 'investigation on human beings' it is important to note that the university has a code of practice governing the implementation and conduct of such investigations. This 'code of practice was developed by the 'Ethics Advisory Committee' and approved by the university court on 5th May 2000. The code governs all investigations on human beings including class teaching experiments and demonstrations, student projects and research investigations which fall within the scope of the code. The 'Departmental Research Committee' will act as the 'Departmental Ethics Committee', and can approve most routine, non-invasive investigations.

It is the responsibility of the supervisor to make the student aware of relevant guidelines and ensure that they are observed. The supervisor is also responsible for submitting details of proposed investigations for approval where necessary.

The following contains 2 checklists to aid the implementation of this practice:

(I) The first is to identify cases which require to be approved by the University Ethics Advisory Committee. If any of the boxes are marked in checklist (i) the investigation must be submitted to the university committee for approval.

(ii) The second is to ensure correct procedure is adhered to in any 'routine or non-invasive' investigation i.e. those which are readily approved by the 'Department Ethics Committee' (in essence the checklist represents a summary of Section 6 of the Code of Practice on Investigations on Human Beings.)

These checklists should not be viewed as a substitute for the original document and thus all supervisors should be familiar with the code before utilising these in staff/student research projects. The checklists are designed to ensure that the staff/students are immediately aware of the implications of the guidelines to their investigation. Furthermore, they act as departmental records of staff/student conduct in investigations on humans.

As 'Ethics Advisory Committee' approval of a protocol can take up to 4 weeks (longer for very specific requests), where research is likely to include an element of 'investigations on humans', an analysis of expected procedures should be carried out at as early a stage as possible.

In addition to the university regulations, investigations of a Physiological, Sociological and Biological nature must conform to additional 'codes of practice' set out by relevant professional bodies - in such cases the secretary of the ethics advisory board can supply copies of these statements.

(i) Supervisor and Student Ethics Checklist

Project Title: Recording and Analysis of student project for knowledge evolution model development

Participants (staff/students carrying out investigation): Staff: Norman MacNally; Student: 4th and 5th design students

Investigation Content:
1. Recording the supervision meetings (audio)
2. Taking photographs of work during design development.
3. Interview with students and supervisors.

Does the investigation involve, any of the following (mark as appropriate):

1)	Harm, discomfort, physical or psychological risk (esp. pregnant women, elderly, the young).	yes ☐	no ☑
2)	Participants whose ability to give voluntary consent is limited (cognitively impaired, prisoners, persons with chronic physical or mental conditions).	yes ☐	no ☑
3)	Invasive techniques (DNA testing, collection of body fluids/tissue).	yes ☐	no ☑
4)	Extensive degree or duration of exercise or physical exertion.	yes ☐	no ☑
5)	Manipulation of human responses (cognitive or affective) which may involve stress or anxiety.	yes ☐	no ☑
6)	Administration of drugs, liquid/food additives.	yes ☐	no ☑
7)	Deception of the participants which might cause distress or effect their willingness to participate in the research.	yes ☐	no ☑
8)	The collection of highly personal, intimate, private or confidential information.	yes ☐	no ☑
9)	Payment to the participants (other than travel/time costs).	yes ☐	no ☑

If the answer to any of the above questions is yes you must submit a protocol to the 'Ethics Advisory Committee' unless previous consent has been granted for practising the 'generic' procedure involved. The protocol for such submissions to the 'Ethics Advisory Committee' can be found in Appendix A of the 'Code of Practice on Investigations of Humans Beings'.

Supervisors Signature(s)

........[signature]........ Date 29/9/05

.... Date ....

Students/Researchers Signature(s)

.....Wong Wei...... Date 29/09/05

.... Date ....

.... Date ....

.... Date ....

(ii) Checklist for Department Approved Investigations

Mark all boxes when you have read, understand and, where appropriate, will adhere to the guidelines - also note the documentation required relative to your investigation:

N.B Investigators must acknowledge, understand and adhere to all of the points on this checklist.

Project Title:

Participants (staff/students carrying out investigation):

Investigation Content:

It is the supervisors responsibility to make students aware of these guidelines and the students to provide the supervisor with the required documentation from affected investigation components. Signed copies should be maintained by the supervisor and student(s) for departmental records.

- ☐ **Consent.** Obtain informed consent of all volunteers. A consent form <u>must</u> be signed by all volunteers.
- ☐ **Protection.** Protect all volunteers from possible harm and preserve their rights. <u>No</u> investigation should involve significant risks to mental or physical well-being of its participants.
- ☐ **Inducement.** Provide no financial inducement nor other coercion (actual or implied) to persuade people to take part in the investigation.
- ☐ **Withdrawal.** Volunteers must be free to withdraw at any stage, without giving reason.
- ☐ **Termination.** The investigation should stop <u>immediately</u> if volunteers report any problems (physical, mental or otherwise) during it. The problems must be reported to the appropriate ethics committee.
- ☐ **Recruitment.** Volunteer recruitment should wherever possible be via letter, notice (or orally - if through a group approach). However, random street or doorstep surveys are acceptable.
- ☐ **Staff Participation.** The motives for staff/students to participate as a volunteer in an investigation should be taken into special consideration i.e. neither declining nor agreeing to participate in an investigation should affect academic assessment in anyway.
- ☐ **Special Consideration.** Special consideration should be given to the young, adults with any cognitive disabilities or learning difficulties and to all persons who live in or are connected to an institutional environment (in such cases the investigator should refer to Appendix C of the 'code of practice on investigations on human beings').
- ☐ **Pregnancy.** Women of child bearing age must not be recruited for any investigation which could be harmful to fertility/pregnancy (in such cases the investigator should refer to Appendix C of the 'code of practice on investigations on human beings').
- ☐ **Selection.** Submissions based on the investigation should include details of the basis for volunteer selection i.e. questionnaires and/or other measures in the selection process.
- ☐ **Justification.** Investigators must justify the number/type of subjects chosen for each study.

- **Confidentiality.** Confidentiality and privacy must be maintained. Any waiver of confidentiality should be justified and consent must be given, in writing, by the volunteer(s). In addition, the investigator must comply with Data Protection Legislation.
- **Informing Volunteers.** Each volunteer must be provided with an information sheet providing full relevant details of the nature, object and duration of the proposed investigation and a contact for further queries (whom is independent of the investigation normally the secretary of the ethics advisory committee).
- **Deception.** There shall be no deception that might affect a person's willingness to participate in an investigation nor about the risks involved.
- **Unusual Symptoms.** Volunteers will be encouraged to note any unusual or unexpected symptoms arising during the investigation. These should be reported to the appropriate ethics committee
- **Location.** Places where investigations take place should be appropriate to the type and risk factor of study undertaken. Further, the ethics committee are entitled to carry out spot checks.
- **Records.** Full records of all procedures carried out should be maintained in an appropriate form. A register of all volunteers should be taken and a note of the population/sample from which they were drawn.
- **Queries.** Post investigation queries from a participant should be directed to an appropriate professional (supervisor, head of department etc.).
- **Insurance.** It is the responsibility for the applicant to seek extended insurance if the investigation scope falls out-with the University's Public Liability Policy (in such cases the investigator should refer to **Appendix B** of the original 'code of practice' document).

Additional general guidelines exist for biological, psychological and sociological investigations - in such cases refer to **Sections 6.2 and 6.3** of the original 'code of practice' document.

Supervisors Signature(s)

........[signature]........ Date ..29\9\05...

.... Date ....

Students/Researchers Signature(s)

........[signature]........ Date ..29/09/05

.... Date ....

.... Date ....

.... Date ....

Appendix D DESCRIPTIVE DATA OF LINKS – PROTOCOL ANALYSIS

Table D-1: Cause effect link of creation

	Causing element	**DK_A**									**WK_A**	
	Creating links	$DK_{A-G} \rightarrow WK_{P-A}$	$DK_{A-G} \rightarrow WK_{P-G}$	$DK_{A-G} \rightarrow WK_{P-I}$	$DK_{A-Bit} \rightarrow WK_{P-A}$	$DK_{A-Fit} \rightarrow WK_{P-A}$	$DK_{A-Fit} \rightarrow WK_{P-G}$	$DK_{A-Fit} \rightarrow WK_{P-I}$	$DK_{A-Sit} \rightarrow WK_{P-A}$	$DK_{A-Sa} \rightarrow WK_{P-G}$	$WK_{A-Be} \rightarrow WK_{P-A}$	$WK_{A-Bit} \rightarrow WK_{P-A}$
Occurrence times	Session 1	1	1	1					1			
	Session 2	6										
	Session 3	7		4		1	1	1	2			
	Session 4	18	1	3		2			1			
	Session 5	7		4								
	Session 6	7		1								
	Session 7	1				1			2			
	Session 8	4	1						1	1	1	
	Session 9		1						1			
	Session 10			1								2
	Session 11								1		1	
	Session 12	1	1		1				1		1	3
	Sum	**52**	**5**	**14**	**1**	**4**	**1**	**1**	**10**	**1**	**3**	**5**
	Overall %	**7.11%**	**0.68%**	**1.92%**	**0.14%**	**0.55%**	**0.14%**	**0.14%**	**1.37%**	**0.14%**	**0.41%**	**0.68%**
Percentage within each session	Session 1	3.13%	3.13%	3.13%	0.00%	0.00%	0.00%	0.00%	3.13%	0.00%	0.00%	0.00%
	Session 2	33.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Session 3	15.91%	0.00%	9.09%	0.00%	2.27%	2.27%	2.27%	4.55%	0.00%	0.00%	0.00%
	Session 4	40.00%	2.22%	6.67%	0.00%	4.44%	0.00%	0.00%	2.22%	0.00%	0.00%	0.00%
	Session 5	33.33%	0.00%	19.05%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Session 6	28.00%	0.00%	4.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Session 7	2.13%	0.00%	0.00%	0.00%	2.13%	0.00%	0.00%	4.26%	0.00%	0.00%	0.00%
	Session 8	16.67%	4.17%	0.00%	0.00%	0.00%	0.00%	0.00%	4.17%	4.17%	4.17%	0.00%
	Session 9	0.00%	3.03%	0.00%	0.00%	0.00%	0.00%	0.00%	3.03%	0.00%	0.00%	0.00%
	Session 10	0.00%	0.00%	0.79%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.57%
	Session 11	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.63%	0.00%	0.63%	0.00%
	Session 12	0.64%	0.64%	0.00%	0.64%	0.00%	0.00%	0.00%	0.64%	0.00%	0.64%	1.91%
	Average %	**14.43%**	**1.10%**	**3.56%**	**0.05%**	**0.74%**	**0.19%**	**0.19%**	**1.88%**	**0.35%**	**0.45%**	**0.29%**

	Causing element	**WK_A**										
	Creating links	$WK_{A-Bit} \rightarrow WK_{P-I}$	$WK_{A-Fe} \rightarrow WK_{P-A}$	$WK_{A-Fe} \rightarrow WK_{P-I}$	$WK_{A-Fit} \rightarrow WK_{P-A}$	$WK_{A-Fit} \rightarrow WK_{P-I}$	$WK_{A-Se} \rightarrow WK_{P-A}$	$WK_{A-Se} \rightarrow WK_{P-G}$	$WK_{A-Se} \rightarrow WK_{P-I}$	$WK_{A-Sit} \rightarrow WK_{P-A}$	$WK_{A-Sit} \rightarrow WK_{P-G}$	$WK_{A-Sit} \rightarrow WK_{P-I}$
Occurrence times	Session 1							1				
	Session 2						1	1				
	Session 3								1			
	Session 4						1					
	Session 5											
	Session 6			1			2	1				
	Session 7		1				7	1				
	Session 8		1				4	2				
	Session 9		1		1		1			1		
	Session 10						10	4	6	1		4
	Session 11	1			1		22	1	12	11	4	11
	Session 12	1				1	15		8	12	3	15
	Sum	**2**	**3**	**1**	**2**	**1**	**63**	**11**	**27**	**25**	**7**	**30**
	Overall %	**0.27%**	**0.41%**	**0.14%**	**0.27%**	**0.14%**	**8.62%**	**1.50%**	**3.69%**	**3.42%**	**0.96%**	**4.10%**
Percentage within each session	Session 1	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	3.13%	0.00%	0.00%	0.00%	0.00%
	Session 2	0.00%	0.00%	0.00%	0.00%	0.00%	5.56%	5.56%	0.00%	0.00%	0.00%	0.00%
	Session 3	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	2.27%	0.00%	0.00%	0.00%
	Session 4	0.00%	0.00%	0.00%	0.00%	0.00%	2.22%	0.00%	0.00%	0.00%	0.00%	0.00%
	Session 5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Session 6	0.00%	0.00%	4.00%	0.00%	0.00%	8.00%	4.00%	0.00%	0.00%	0.00%	0.00%
	Session 7	0.00%	2.13%	0.00%	0.00%	0.00%	14.89%	2.13%	0.00%	0.00%	0.00%	0.00%
	Session 8	0.00%	4.17%	0.00%	0.00%	0.00%	16.67%	8.33%	0.00%	0.00%	0.00%	0.00%
	Session 9	0.00%	3.03%	0.00%	3.03%	0.00%	3.03%	0.00%	0.00%	3.03%	0.00%	0.00%
	Session 10	0.00%	0.00%	0.00%	0.00%	0.00%	7.87%	3.15%	4.72%	0.79%	0.00%	3.15%
	Session 11	0.63%	0.00%	0.00%	0.63%	0.00%	13.92%	0.63%	7.59%	6.96%	2.53%	6.96%
	Session 12	0.64%	0.00%	0.00%	0.00%	0.64%	9.55%	0.00%	5.10%	7.64%	1.91%	9.55%
	Average %	**0.11%**	**0.78%**	**0.33%**	**0.31%**	**0.05%**	**6.81%**	**2.24%**	**1.64%**	**1.54%**	**0.37%**	**1.64%**

Table D-1: Cause effect link of creation (Continue)

	Causing element	**WK_A**						**WK_P**				
	Creating links	$WK_{A-Ct} \rightarrow WK_{P-A}$	$WK_{A-Ct} \rightarrow WK_{P-I}$	$WK_{A-M} \rightarrow WK_{P-A}$	$WK_{A-M} \rightarrow WK_{P-G}$	$WK_{A-Rq} \rightarrow WK_{P-G}$	$WK_{A-Rq} \rightarrow WK_{P-I}$	$WK_{P-A} \rightarrow DK_{A-G}$	$WK_{P-A} \rightarrow DK_{A-Bd}$	$WK_{P-A} \rightarrow DK_{A-Fu}$	$WK_{P-A} \rightarrow WK_{A-Be}$	$WK_{P-A} \rightarrow WK_{A-Bd}$
Occurrence times	Session 1			1			1			2	1	
	Session 2					1						
	Session 3									8		
	Session 4							1	2	11		
	Session 5											
	Session 6								2	1		
	Session 7					1		1		1		4
	Session 8									2		
	Session 9	1			1	2		1		1		1
	Session 10								3			4
	Session 11											2
	Session 12		1							1		7
	Sum	**1**	**1**	**1**	**1**	**4**	**1**	**3**	**7**	**27**	**1**	**18**
	Overall %	**0.14%**	**0.14%**	**0.14%**	**0.14%**	**0.55%**	**0.14%**	**0.41%**	**0.96%**	**3.69%**	**0.14%**	**2.46%**
Percentage within each session	Session 1	0.00%	0.00%	3.13%	0.00%	0.00%	3.13%	0.00%	0.00%	6.25%	3.13%	0.00%
	Session 2	0.00%	0.00%	0.00%	0.00%	5.56%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Session 3	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	18.18%	0.00%	0.00%
	Session 4	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	2.22%	4.44%	24.44%	0.00%	0.00%
	Session 5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Session 6	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	8.00%	4.00%	0.00%	0.00%
	Session 7	0.00%	0.00%	0.00%	0.00%	2.13%	0.00%	2.13%	0.00%	2.13%	0.00%	8.51%
	Session 8	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	8.33%	0.00%	0.00%
	Session 9	3.03%	0.00%	0.00%	3.03%	6.06%	0.00%	3.03%	0.00%	3.03%	0.00%	3.03%
	Session 10	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	2.36%	0.00%	0.00%	3.15%
	Session 11	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.27%
	Session 12	0.00%	0.64%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.64%	0.00%	4.46%
	Average %	**0.25%**	**0.05%**	**0.26%**	**0.25%**	**1.15%**	**0.26%**	**0.62%**	**1.23%**	**5.58%**	**0.26%**	**1.70%**

	Causing element	**WK_P**										
	Creating links	$WK_{P-A} \rightarrow WK_{A-Fe}$	$WK_{P-A} \rightarrow WK_{A-Fit}$	$WK_{P-A} \rightarrow WK_{A-Sa}$	$WK_{P-A} \rightarrow WK_{A-Sis}$	$WK_{P-A} \rightarrow WK_{A-Ct}$	$WK_{P-A} \rightarrow WK_{A-Rq}$	$WK_{P-A} \rightarrow WK_{P-A}$	$WK_{P-A} \rightarrow WK_{P-G}$	$WK_{P-A} \rightarrow WK_{P-Out}$	$WK_{P-G} \rightarrow WK_{P-A}$	$WK_{P-G} \rightarrow WK_{P-G}$
Occurrence times	Session 1	2		2			1			2		
	Session 2			4						1		
	Session 3								1		4	
	Session 4											
	Session 5	1										
	Session 6	1		2							1	
	Session 7			11							8	
	Session 8			5								
	Session 9	1	2	1			2		3		4	2
	Session 10	1	3	36	6	2					21	1
	Session 11	1	4	45	4				1		9	1
	Session 12		2	35	7			1	1	2	10	
	Sum	**7**	**11**	**141**	**17**	**2**	**3**	**1**	**6**	**5**	**57**	**4**
	Overall %	**0.96%**	**1.50%**	**19.29%**	**2.33%**	**0.27%**	**0.41%**	**0.14%**	**0.82%**	**0.68%**	**7.80%**	**0.55%**
Percentage within each session	Session 1	6.25%	0.00%	6.25%	0.00%	0.00%	3.13%	0.00%	0.00%	6.25%	0.00%	0.00%
	Session 2	0.00%	0.00%	22.22%	0.00%	0.00%	0.00%	0.00%	0.00%	5.56%	0.00%	0.00%
	Session 3	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	2.27%	0.00%	9.09%	0.00%
	Session 4	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Session 5	4.76%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Session 6	4.00%	0.00%	8.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	4.00%	0.00%
	Session 7	0.00%	0.00%	23.40%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	17.02%	0.00%
	Session 8	0.00%	0.00%	20.83%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Session 9	3.03%	6.06%	3.03%	0.00%	0.00%	6.06%	0.00%	9.09%	0.00%	12.12%	6.06%
	Session 10	0.79%	2.36%	28.35%	4.72%	1.57%	0.00%	0.00%	0.00%	0.00%	16.54%	0.79%
	Session 11	0.63%	2.53%	28.48%	2.53%	0.00%	0.00%	0.00%	0.63%	0.00%	5.70%	0.63%
	Session 12	0.00%	1.27%	22.29%	4.46%	0.00%	0.00%	0.64%	0.64%	1.27%	6.37%	0.00%
	Average %	**1.62%**	**1.02%**	**13.57%**	**0.98%**	**0.13%**	**0.77%**	**0.05%**	**1.05%**	**1.09%**	**5.90%**	**0.62%**

Table D-1: Cause effect link of creation (Continue)

	Causing element	WK_P							Sum
	Creating links	$WK_{P-G} \rightarrow WK_{P-I}$	$WK_{P-C} \rightarrow WK_{P-A}$	$WK_{P-C} \rightarrow WK_{P-G}$	$WK_{P-C} \rightarrow WK_{P-I}$	$WK_{P-I} \rightarrow WK_{P-A}$	$WK_{P-I} \rightarrow WK_{P-G}$	$WK_{P-I} \rightarrow WK_{P-I}$	
Occurrence times	Session 1		1		5	8	1		**32**
	Session 2		2		1	1			**18**
	Session 3		1	1		12			**44**
	Session 4					4	1		**45**
	Session 5				4	5			**21**
	Session 6				2	4			**25**
	Session 7		2		2	4			**47**
	Session 8	1				1			**24**
	Session 9		2		1	2			**33**
	Session 10	1	2	1	1	16	1		**127**
	Session 11		2			19	3	2	**158**
	Session 12					24	3		**157**
	Sum	**2**	**12**	**2**	**16**	**100**	**9**	**2**	731
	Overall %	**0.27%**	**1.64%**	**0.27%**	**2.19%**	**13.68%**	**1.23%**	**0.27%**	
Percentage within each session	Session 1	0.00%	3.13%	0.00%	15.63%	25.00%	3.13%	0.00%	
	Session 2	0.00%	11.11%	0.00%	5.56%	5.56%	0.00%	0.00%	
	Session 3	0.00%	2.27%	2.27%	0.00%	27.27%	0.00%	0.00%	
	Session 4	0.00%	0.00%	0.00%	0.00%	8.89%	2.22%	0.00%	
	Session 5	0.00%	0.00%	0.00%	19.05%	23.81%	0.00%	0.00%	
	Session 6	0.00%	0.00%	0.00%	8.00%	16.00%	0.00%	0.00%	
	Session 7	0.00%	4.26%	0.00%	4.26%	8.51%	0.00%	0.00%	
	Session 8	4.17%	0.00%	0.00%	0.00%	4.17%	0.00%	0.00%	
	Session 9	0.00%	6.06%	0.00%	3.03%	6.06%	0.00%	0.00%	
	Session 10	0.79%	1.57%	0.79%	0.79%	12.60%	0.79%	0.00%	
	Session 11	0.00%	1.27%	0.00%	0.00%	12.03%	1.90%	1.27%	
	Session 12	0.00%	0.00%	0.00%	0.00%	15.29%	1.91%	0.00%	
	Average %	**0.41%**	**2.47%**	**0.26%**	**4.69%**	**13.76%**	**0.83%**	**0.11%**	

Table D-2: Link of referral

	Referring element	WK_A		WK_P							
	Referral links	$WK_{A-Se} \rightarrow WK_{P-G}$	$WK_{A-Se} \rightarrow WK_{P-C}$	$WK_{P-A} \rightarrow DK_{A-G}$	$WK_{P-A} \rightarrow DK_{A-Sis}$	$WK_{P-A} \rightarrow WK_{A-Be}$	$WK_{P-A} \rightarrow WK_{A-Fe}$	$WK_{P-A} \rightarrow WK_{A-Se}$	$WK_{P-A} \rightarrow WK_{A-Sis}$	$WK_{P-A} \rightarrow WK_{A-Ct}$	$WK_{P-A} \rightarrow WK_{A-Rq}$
Occurrence times	Session 1			4	1			1			
	Session 2			4							
	Session 3			12	3						
	Session 4			10	13					1	
	Session 5			17						1	
	Session 6			7						1	
	Session 7		1	1	2		4				
	Session 8			4	1	3					
	Session 9			1	1	2					
	Session 10			8	4	3	1			1	
	Session 11				7	2	2		3		1
	Session 12	1		6	2	8	1		6	5	
	Sum	**1**	**1**	**74**	**34**	**18**	**8**	**1**	**9**	**9**	**1**
	Overall %	**0.57%**	**0.57%**	**42.29%**	**19.43%**	**10.29%**	**4.57%**	**0.57%**	**5.14%**	**5.14%**	**0.57%**
Percentage within each session	Session 1	0.00%	0.00%	57.14%	14.29%	0.00%	0.00%	14.29%	0.00%	0.00%	0.00%
	Session 2	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Session 3	0.00%	0.00%	80.00%	20.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Session 4	0.00%	0.00%	41.67%	54.17%	0.00%	0.00%	0.00%	0.00%	4.17%	0.00%
	Session 5	0.00%	0.00%	94.44%	0.00%	0.00%	0.00%	0.00%	0.00%	5.56%	0.00%
	Session 6	0.00%	0.00%	77.78%	0.00%	0.00%	0.00%	0.00%	0.00%	11.11%	0.00%
	Session 7	0.00%	11.11%	11.11%	22.22%	0.00%	44.44%	0.00%	0.00%	0.00%	0.00%
	Session 8	0.00%	0.00%	50.00%	12.50%	37.50%	0.00%	0.00%	0.00%	0.00%	0.00%
	Session 9	0.00%	0.00%	11.11%	11.11%	22.22%	0.00%	0.00%	0.00%	0.00%	0.00%
	Session 10	0.00%	0.00%	38.10%	19.05%	14.29%	4.76%	0.00%	0.00%	4.76%	0.00%
	Session 11	0.00%	0.00%	0.00%	35.00%	10.00%	10.00%	0.00%	15.00%	0.00%	5.00%
	Session 12	3.23%	0.00%	19.35%	6.45%	25.81%	3.23%	0.00%	19.35%	16.13%	0.00%
	Average %	**0.27%**	**0.93%**	**48.39%**	**16.23%**	**9.15%**	**5.20%**	**1.19%**	**2.86%**	**3.48%**	**0.42%**

	Referring element	WK_P							Sum
	Referral links	$WK_{P-A} \rightarrow WK_{P-C}$	$WK_{P-G} \rightarrow WK_{A-Ct}$	$WK_{P-G} \rightarrow WK_{A-M}$	$WK_{P-I} \rightarrow WK_{A-Se}$	$WK_{P-I} \rightarrow WK_{A-Sis}$	$WK_{P-I} \rightarrow WK_{A-Ct}$	$WK_{P-I} \rightarrow WK_{P-R}$	
Occurrence times	Session 1	1							**7**
	Session 2								**4**
	Session 3								**15**
	Session 4								**24**
	Session 5								**18**
	Session 6	1							**9**
	Session 7	1							**9**
	Session 8								**8**
	Session 9	3	1	1					**9**
	Session 10	2	1				1		**21**
	Session 11		1		1	2		1	**20**
	Session 12					1	1		**31**
	Sum	**8**	**3**	**1**	**1**	**3**	**2**	**1**	175
	Overall %	**4.57%**	**1.71%**	**0.57%**	**0.57%**	**1.71%**	**1.14%**	**0.57%**	
Percentage within each session	Session 1	14.29%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
	Session 2	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
	Session 3	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
	Session 4	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
	Session 5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
	Session 6	11.11%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
	Session 7	11.11%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
	Session 8	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
	Session 9	33.33%	11.11%	11.11%	0.00%	0.00%	0.00%	0.00%	
	Session 10	9.52%	4.76%	0.00%	0.00%	0.00%	4.76%	0.00%	
	Session 11	0.00%	5.00%	0.00%	5.00%	10.00%	0.00%	5.00%	
	Session 12	0.00%	0.00%	0.00%	0.00%	3.23%	3.23%	0.00%	
	Average %	**6.61%**	**1.74%**	**0.93%**	**0.42%**	**1.10%**	**0.67%**	**0.42%**	

Table D-3: Link of usage

Used element	DK$_A$				WK$_A$						WK$_P$	Sum
Using links	$WK_{P-A} \rightarrow DK_{A-G}$	$WK_{P-A} \rightarrow DK_{A-Bit}$	$WK_{P-A} \rightarrow DK_{A-Fit}$	$WK_{P-A} \rightarrow DK_{A-Sis}$	$WK_{P-A} \rightarrow WK_{A-Be}$	$WK_{P-A} \rightarrow WK_{A-Bit}$	$WK_{P-A} \rightarrow WK_{A-Fe}$	$WK_{P-A} \rightarrow WK_{A-Se}$	$WK_{P-A} \rightarrow WK_{A-Sis}$	$WK_{P-A} \rightarrow WK_{A-Ct}$	$WK_{P-A} \rightarrow WK_{P-R}$	
Occurrence times												
Session 1					1		1				1	**3**
Session 2	1										2	**3**
Session 3	3											**3**
Session 4	1										1	**2**
Session 5	4										1	**5**
Session 6	1	1					1				1	**4**
Session 7												**0**
Session 8												**0**
Session 9	1		1									**2**
Session 10	5			5	8	2	4	1	5	3	3	**36**
Session 11				1				2			3	**6**
Session 12	2			2							2	**6**
Sum	**18**	**1**	**1**	**8**	**9**	**2**	**6**	**3**	**5**	**3**	**14**	70
Overall %	**25.71%**	**1.43%**	**1.43%**	**11.43%**	**12.86%**	**2.86%**	**8.57%**	**4.29%**	**7.14%**	**4.29%**	**20.00%**	
Percentage within each session												
Session 1	0.00%	0.00%	0.00%	0.00%	33.33%	0.00%	33.33%	0.00%	0.00%	0.00%	33.33%	
Session 2	33.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	66.67%	
Session 3	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Session 4	50.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	50.00%	
Session 5	80.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	20.00%	
Session 6	25.00%	25.00%	0.00%	0.00%	0.00%	0.00%	25.00%	0.00%	0.00%	0.00%	25.00%	
Session 7												
Session 8												
Session 9	50.00%	0.00%	50.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Session 10	13.89%	0.00%	0.00%	13.89%	22.22%	5.56%	11.11%	2.78%	13.89%	8.33%	8.33%	
Session 11	0.00%	0.00%	0.00%	16.67%	0.00%	0.00%	0.00%	33.33%	0.00%	0.00%	50.00%	
Session 12	33.33%	0.00%	0.00%	33.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	33.33%	
Average %	**38.56%**	**2.50%**	**5.00%**	**6.39%**	**5.56%**	0.56%	**6.94%**	**3.61%**	**1.39%**	**0.83%**	**28.67%**	

Table D-4: Link of containment

Containing links	$WK_{P-G} \rightarrow DK_{A-G}$	$WK_{P-G} \rightarrow WK_{A-Be}$	$WK_{P-G} \rightarrow WK_{A-Fe}$	$WK_{P-G} \rightarrow WK_{A-Se}$	$WK_{P-R} \rightarrow DK_{A-G}$	$WK_{P-C} \rightarrow DK_{A-G}$	$WK_{P-C} \rightarrow WK_{A-Se}$	Sum
Occurrence times								
Session 1	3			2			1	**6**
Session 2				1	1	1	1	**4**
Session 3	3							**3**
Session 4	2							**2**
Session 5								**0**
Session 6				1				**1**
Session 7				1			1	**2**
Session 8				3				**3**
Session 9	1		1	4				**6**
Session 10				1				**1**
Session 11		1						**1**
Session 12		1		1				**2**
Sum	**9**	**2**	**1**	**14**	**1**	**1**	**3**	**31**
Overall %	**29.03%**	**6.45%**	**3.23%**	**45.16%**	**3.23%**	**3.23%**	**9.68%**	
Percentage within each session								
Session 1	50.00%	0.00%	0.00%	33.33%	0.00%	0.00%	16.67%	
Session 2	0.00%	0.00%	0.00%	25.00%	25.00%	25.00%	25.00%	
Session 3	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Session 4								
Session 5								
Session 6	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	
Session 7	0.00%	0.00%	0.00%	50.00%	0.00%	0.00%	50.00%	
Session 8	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	
Session 9	16.67%	0.00%	16.67%	66.67%	0.00%	0.00%	0.00%	
Session 10								
Session 11	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Session 12	0.00%	50.00%	0.00%	50.00%	0.00%	0.00%	0.00%	
Average %	**23.81%**	**21.43%**	**2.38%**	**60.71%**	**3.57%**	**3.57%**	**13.10%**	

Appendix E TIME-BASED PROTOCL ANALYSIS

The protocol analysis carried out in chapters 6 and 7 were based on session. The percentages of knowledge elements and links within each session were analysed over the 12 sessions in order to find the occurrence trend of the knowledge elements over task clarification, conceptual and embodiment design, and the main coupling links among these knowledge elements. It was considered that the results of session-based and time-based analysis would be similar considering the objectives of the research presented in this thesis. Though, this appendix presents a time-based analysis of the occurrence trend of three knowledge elements over the three design phases. They are $DK_{A\text{-}G}$, $WK_{A\text{-}Se}$, and $WK_{P\text{-}A}$, belonging to domain artefact knowledge, current working artefact and design process knowledge respectively.

The 12 sessions are of variant lengths from 10 minutes to 60 minutes. Following calculations, the length of each design phase is 95 mins 29 secs, 27 mins 41 secs, and 160 mins 46 secs respectively. Table E-1 lists the three phases' covering sessions, lengths, and percentages. It can be found that task clarification and embodiment design took over 90% of the protocol and conceptual design took only 9.75% of the protocol. However, because the analysis is to find the occurrence trend of different knowledge elements over the three phases, the variant lengths will not affect so much of the trend result.

Table E-1: Design phases length

Design phase	Sessions	Length	Percentage
Task clarification	1-6	95 mins 29 secs	33.62%
Conceptual design	7-9	27 mins 41 secs	9.75%
Embodiment design	10-11	160 mins 46 secs	56.63%

To analyse the occurrence trend based on time, the protocol of each phase was segmented by every 10 minutes. Hence 29 segments were derived for the overall 283 mins 54 secs with 10 in task clarification, three in conceptual design, and 16 in embodiment design. However, two segments at the end of task clarification and conceptual design were 5 mins 27 secs and 7 mins 41 secs respectively. The occurrences of each element per minute were calculated for each segment in order to identify the trend. Table E-2 lists the three elements' occurrence times and frequency over the 29 segments. The design phases are shown in the first column of the table, and the protocol time is shown in the second column.

Table E-2: Occurrence of $DK_{A\text{-}G}$, $WK_{A\text{-}Se}$, and $WK_{P\text{-}A}$ – time-based analysis

Design phase	Time	Occurrence numer			Occurrence/minute		
		$DK_{A\text{-}G}$	$WK_{A\text{-}Se}$	$WK_{P\text{-}A}$	$DK_{A\text{-}G}$	$WK_{A\text{-}Se}$	$WK_{P\text{-}A}$
Task clarification	00'-10'	5	1	16	0.5	0.1	1.6
	11'-20'	2	3	2	0.2	0.3	0.2
	21'-30'	5	5	12	0.5	0.5	1.2
	31'-40'	11	0	17	1.1	0	1.7
	41'-50'	12	0	35	1.2	0	3.5
	51'-60'	8	0	8	0.8	0	0.8
	61'-70'	3	0	6	0.3	0	0.6
	71'-80'	13	0	13	1.3	0	1.3
	81'-90'	13	0	17	1.3	0	1.7
	91'-95'27"	0	3	4	0.0	0.5	0.7
Conceptual design	00'-10'	2	12	25	0.2	1.2	2.5
	11'-20'	5	9	20	0.5	0.9	2.0
	21'-27'41"	3	4	12	0.4	0.5	1.6
Embodiment design	00'-10'	4	7	18	0.4	0.7	1.8
	11'-20'	0	5	16	0	0.5	1.6
	21'-30'	3	10	15	0.3	1	1.5
	31'-40'	0	9	8	0	0.9	0.8
	41'-50'	1	9	10	0.1	0.9	1
	51-'60'	0	10	19	0	1	1.9
	61'-70'	0	8	14	0	0.8	1.4
	71'-80'	0	6	10	0	0.6	1
	81'-90'	0	12	15	0	1.2	1.5
	91'-100'	0	15	13	0	1.5	1.3
	101'-110'	1	13	11	0.1	1.3	1.1
	111'-120'	0	2	11	0	0.2	1.1
	121'-130'	1	8	17	0.1	0.8	1.7
	131'-140'	5	6	15	0.5	0.6	1.5
	141'-150'	0	4	10	0	0.4	1
	151'-160'46"	0	4	9	0	0.4	0.9

Based on Table E-2, the occurrence frequencies of $DK_{A\text{-}G}$, $WK_{A\text{-}Se}$, and $WK_{P\text{-}A}$ over the 29 segments are depicted in Figure E-1. It can be found that though their frequencies fluctuate over these segments, there exist overall trend for each of them over task clarification, conceptual and embodiment design, which are shown in figures E-2 to E-4.

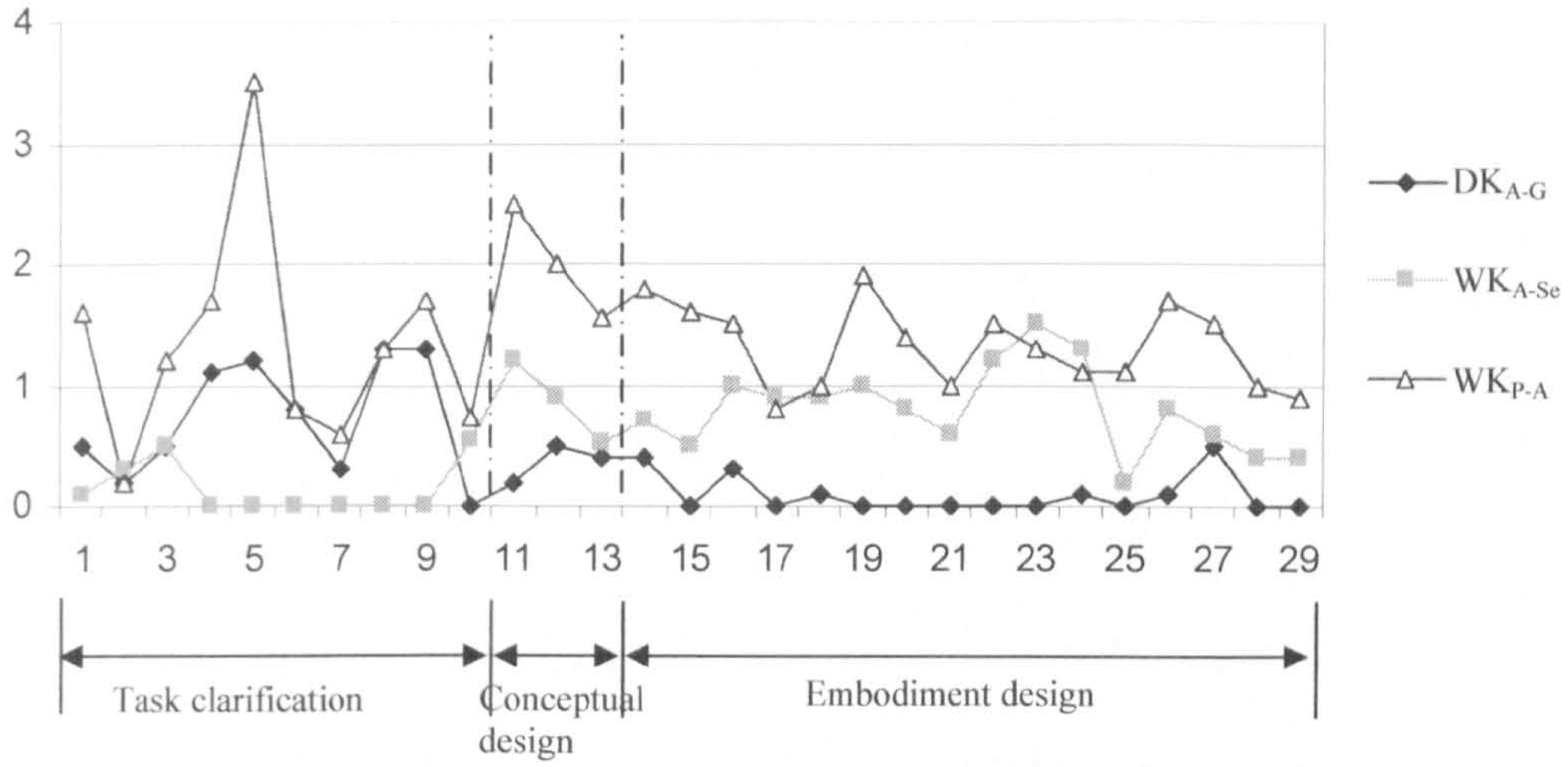

Figure E-1: Occurrence trends of DK_{A-G}, WK_{A-Se}, and WK_{P-A} with 10 mins segments

Figure E-2 illustrates how DK_{A-G}'s frequency changed over time. The two dash dotted lines indicate the division between task clarification, conceptual and embodiment design. Though it fluctuate over some of the 29 segments, its moving average (of 3 period) and logarithmic trendline shows it has **an overall decreasing trend** over task clarification, conceptual and embodiment design. This result is the same as that obtained from the session-based analysis in Chapter 6.

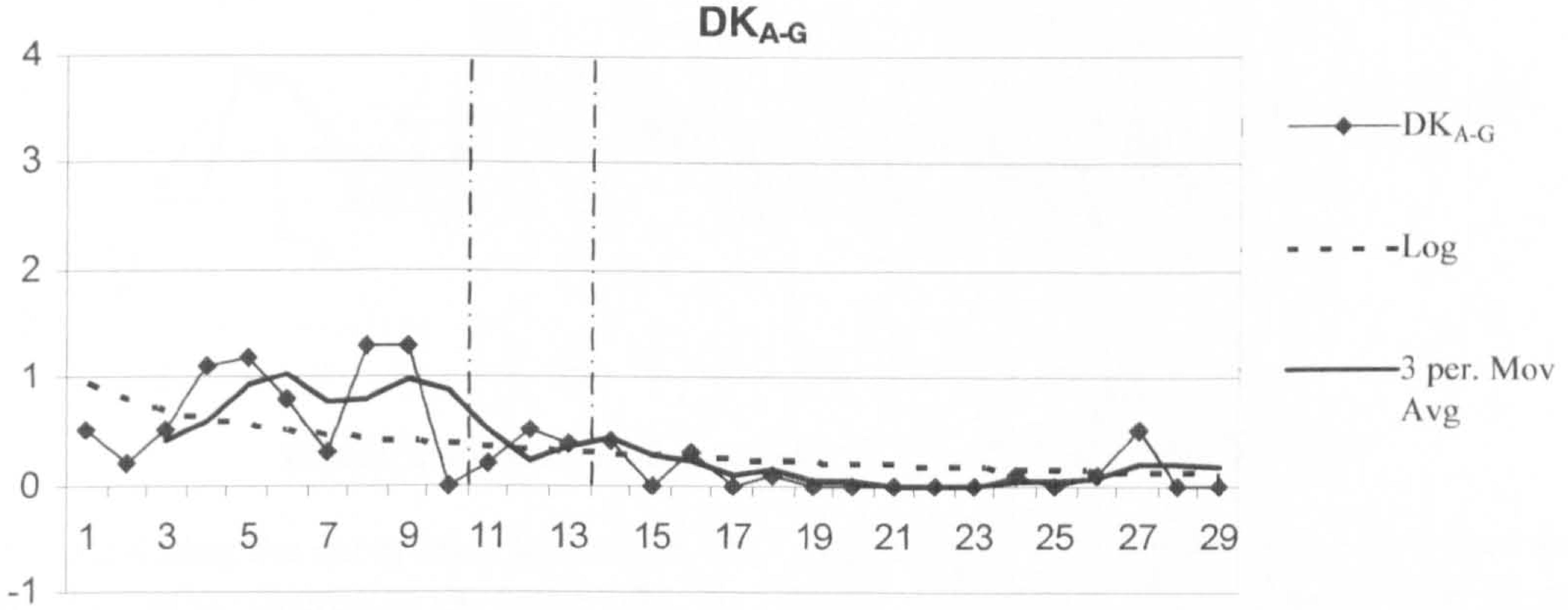

Figure E-2: Occurrence trend of DK_{A-G} – time-based analysis

Figure E-3 shows how WK_{A-Se}'s frequency changed over time. Though it fluctuate over some of the 29 segments, its moving average (of 3 period) and logarithmic trendline shows it has **an overall increasing trend** over task clarification, conceptual and embodiment design. This result is the same as that obtained from the session-based analysis in Chapter 6.

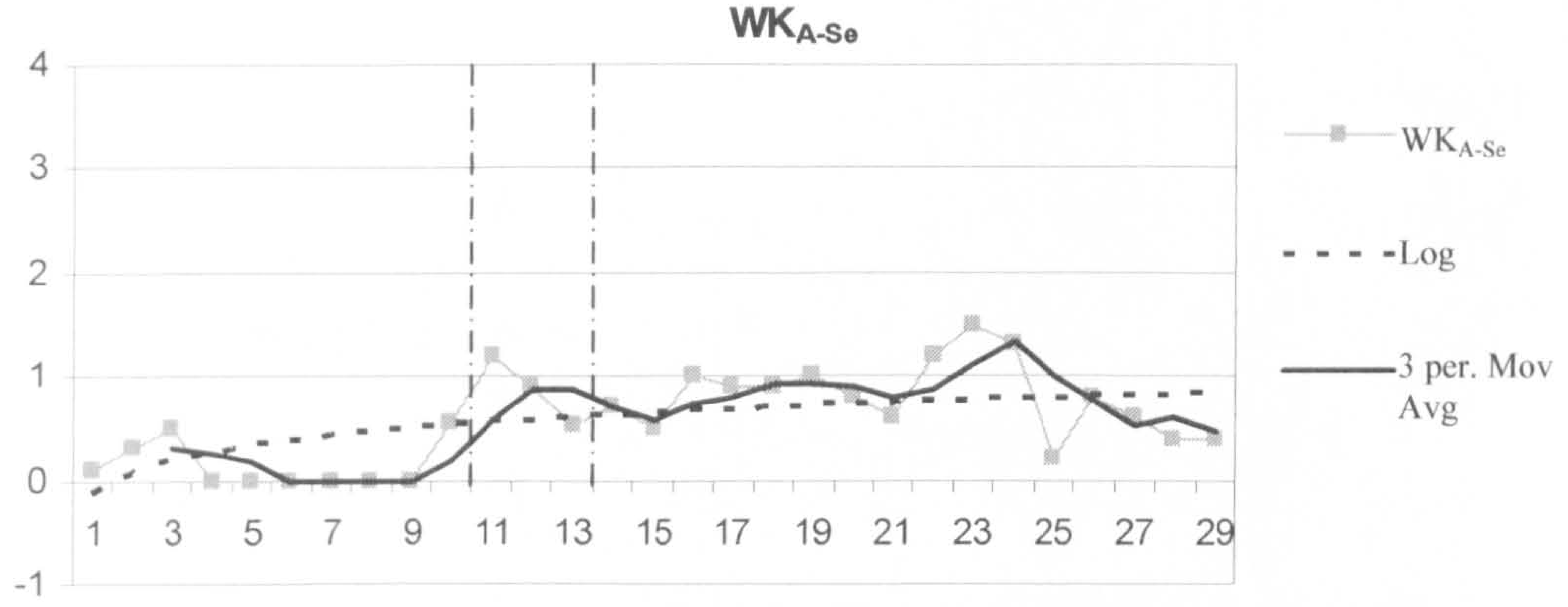

Figure E-3: Occurrence trend of $WK_{A\text{-}Se}$ – time-based analysis

Figure E-4 depicts how $WK_{P\text{-}A}$'s frequency changed over time. Though it fluctuate over most of the 29 segments, its moving average (of 3 period) and logarithmic trendline shows it has **an overall stable trend** over task clarification, conceptual and embodiment design. This result is the same as that obtained from the session-based analysis in Chapter 6.

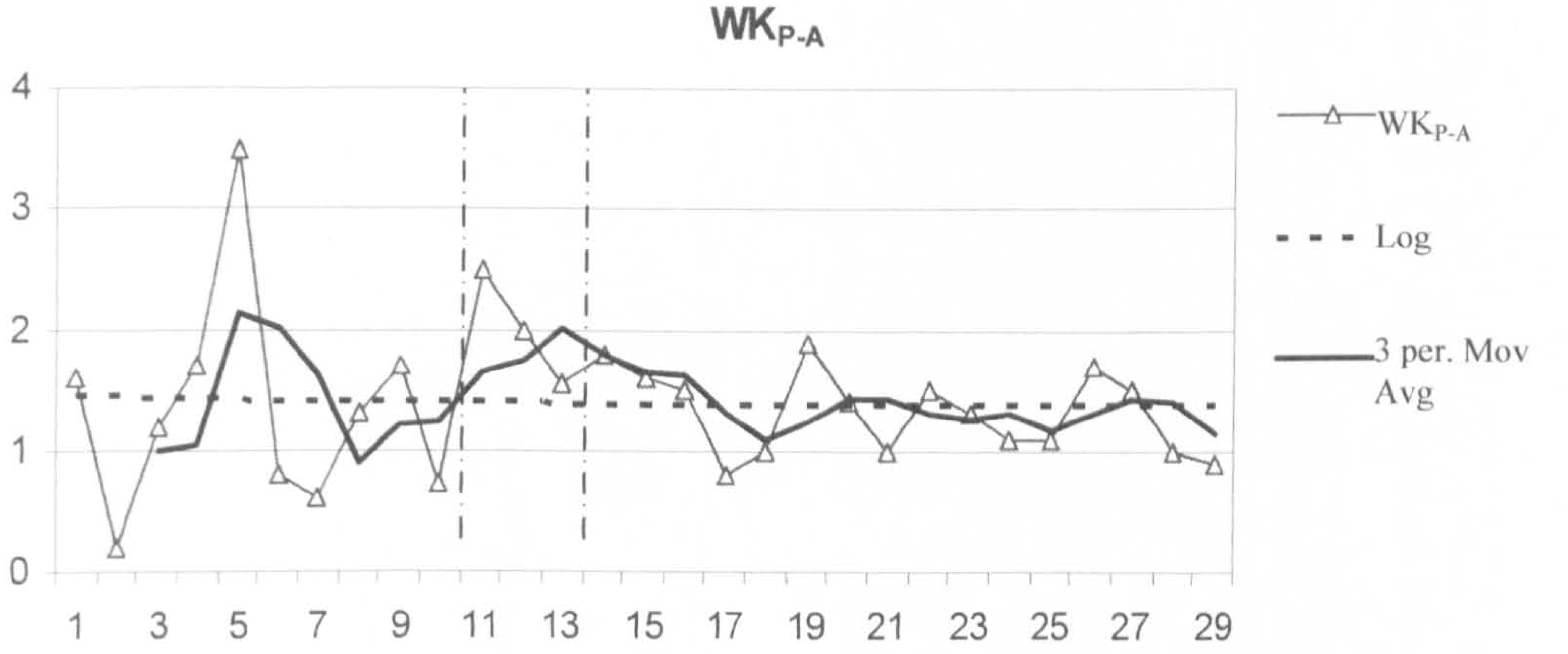

Figure E-4: Occurrence trend of $WK_{P\text{-}A}$ – time-based analysis

By calculating the occurrence times of each segment over the 29 segments, it was found that the fluctuation degree of the knowledge elements is affected by the segment length. Figure E-5 shows the occurrence frequency of the above analysed three elements by segmenting the protocols by 20 minutes long. It can be found, the fluctuation degree of the elements in this chart is lower compare to that in Figure E-1.

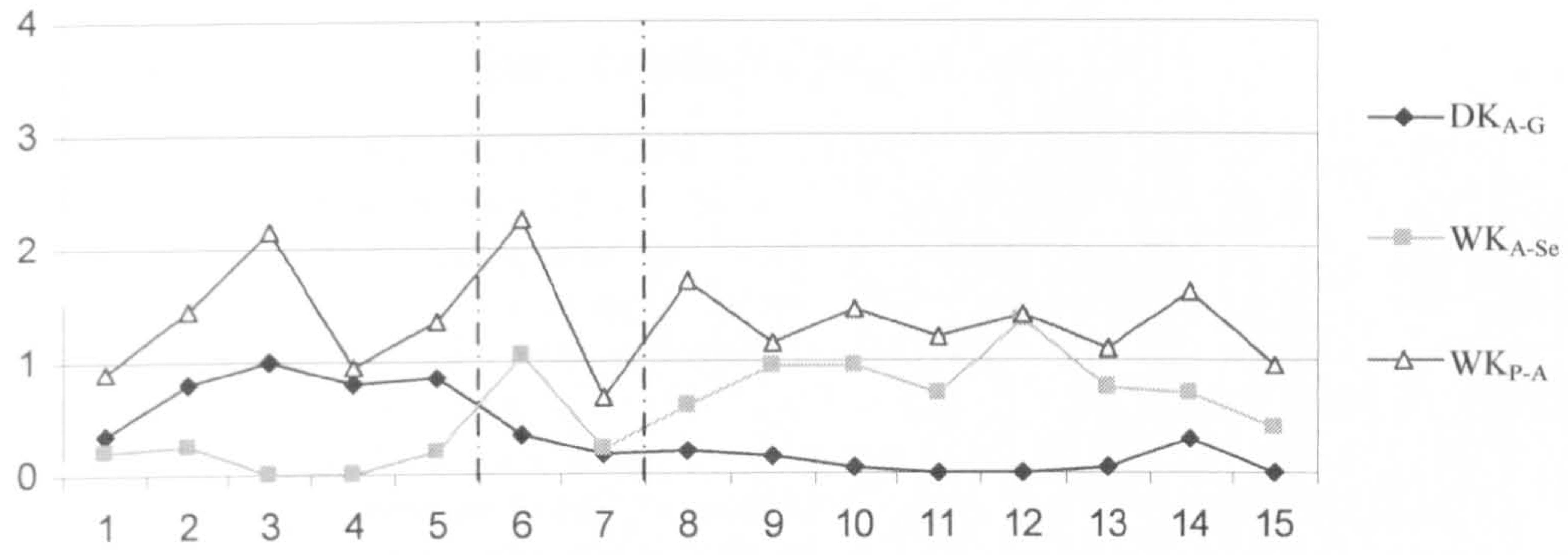

Figure E-5: Occurrence trends of $DK_{A\text{-}G}$, $WK_{A\text{-}Se}$, and $WK_{P\text{-}A}$ with 20 mins segments

Overall, the above conducted analysis revealed that, in order to explore the occurrence trend of the knowledge elements over task clarification, conceptual and embodiment design, the results obtained from both the session-based and time-based analysis are the same.

Appendix F LINK TREND ANALYSIS

Different from the analysis conducted in Chapter 6, which included both the coupling elements and their occurrence trends, the analysis conducted in Chapter 7 focused only on identifying the main coupling links due to the aim of the research was being to identify the coupling. Though, a roughly analysis of the links' trends is presented in this appendix, which shows that the links with sufficient occurrences had similar trends to the artefact elements of the links, most of which connect artefact and design process knowledge elements. However, the links with fewer occurrences did not seem to have an obvious trend. Because the *link of creation* had the most occurrences (731) and the *link of containment* had the least (31), these two types of links are analysed in this appendix to indicate link trend over task clarification, conceptual, and embodiment design.

Similar with the elements trend analysis, the links trend analysis was based on each link's occurrence percentages over the 12 design session, which is listed in Appendix D.

Link of creation

Among the four types of links, *link of creation* turned to have the highest frequency over the 12 sessions both in terms of the number of links (51) and the number of occurrences (731). The analysis of the creation links' trends showed that they had similar trends with the artefact knowledge elements compose the links. Figure F-1 to Figure F-4 illustrate four groups of creation links with different types of design knowledge as the causing and caused elements. The dash dotted lines are the division between design phases.

The trend result of the first group of links is shown in Figure F-1, with domain artefact knowledge as causing elements and design process elements as caused elements. It can be found that these links have a decreasing trend over the three design phases, which is the same as the trend of domain artefact knowledge identified in Chapter 6.

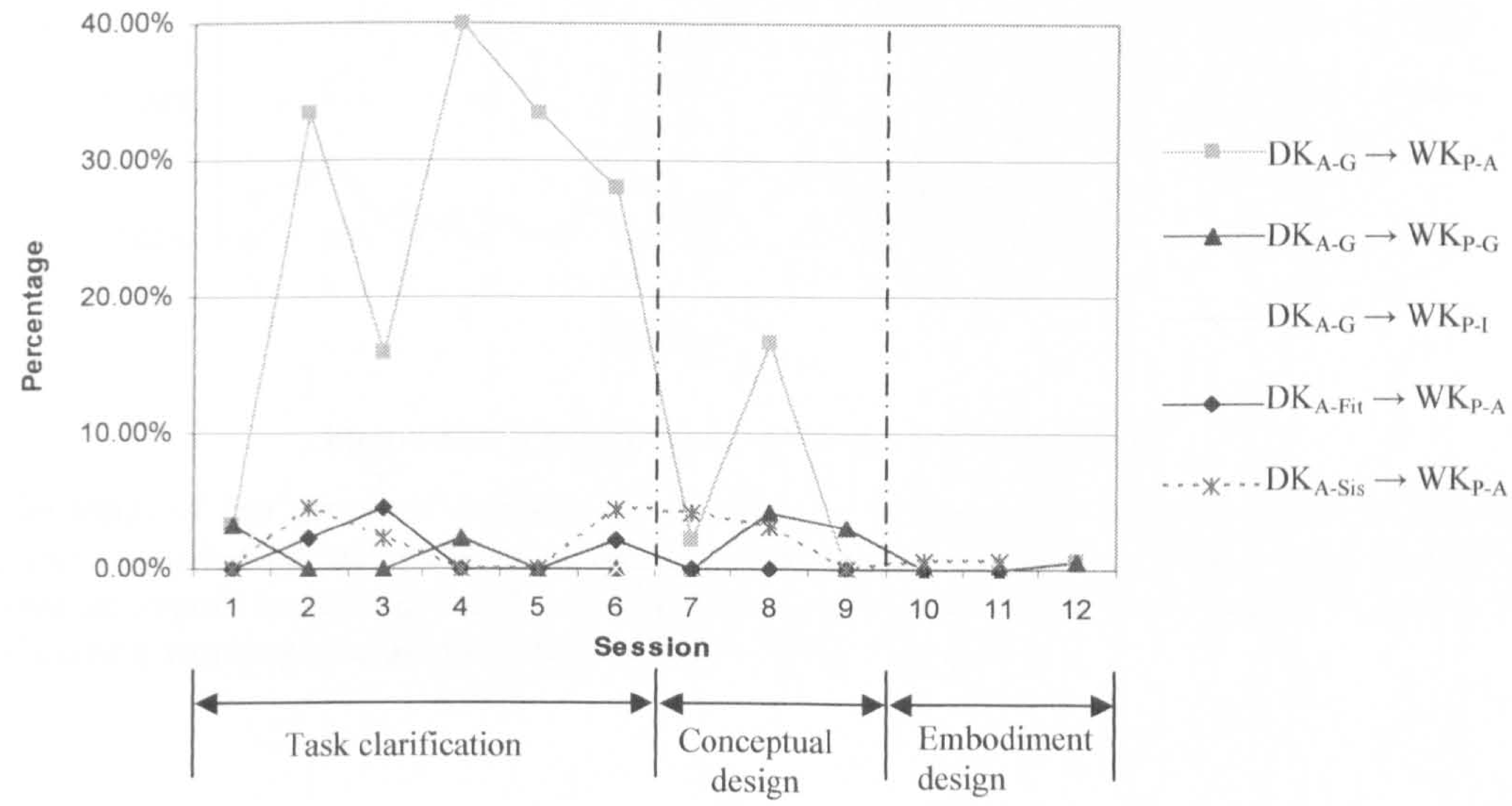

Figure F-1: Trend of creation links – DK_A causing WK_P

The second group of creation links represent design activity causing domain artefact knowledge. It can be found from Figure F-2 that these links have an overall decreasing trend over the three design phases, which is the same as the trend of domain artefact knowledge identified in Chapter 6.

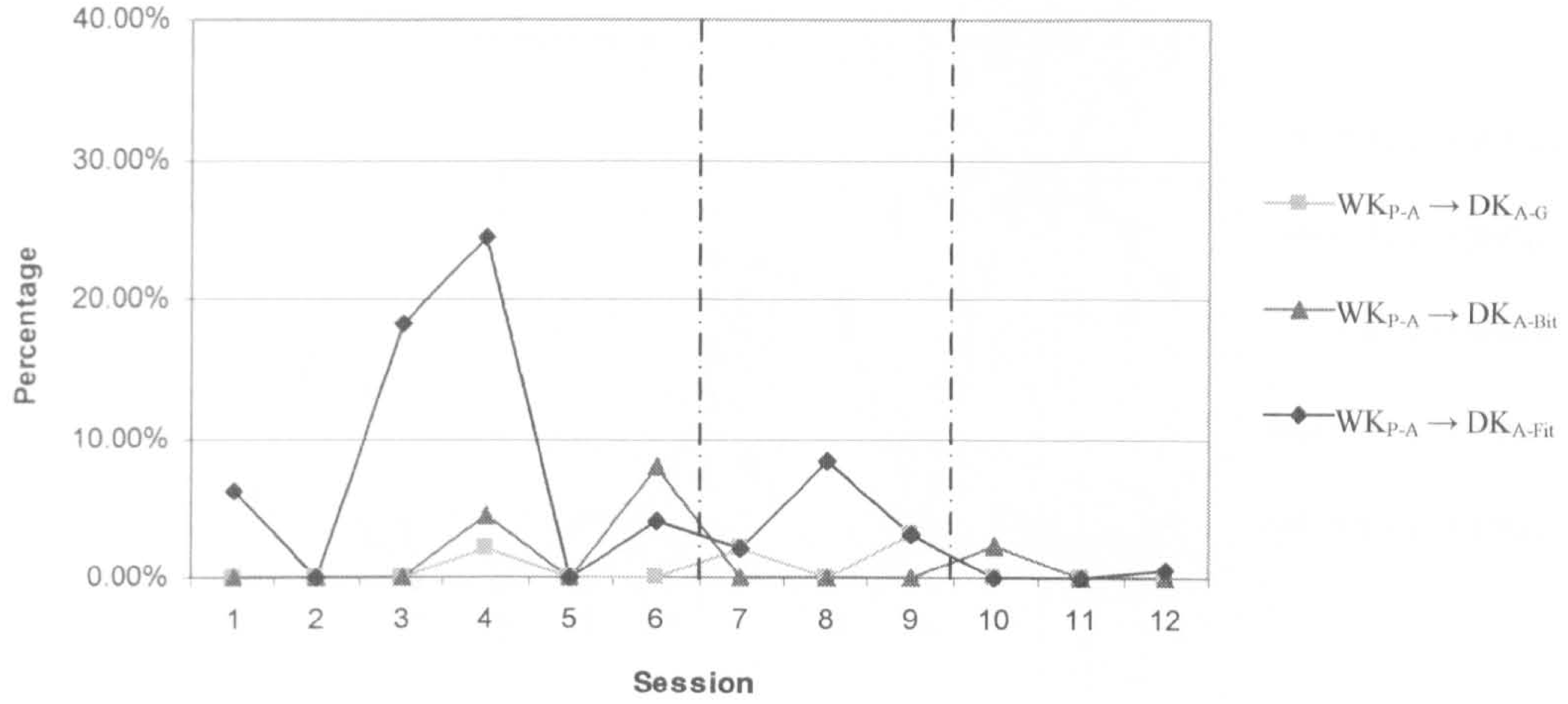

Figure F-2: Trend of creation links – $WK_{P\text{-}A}$ causing DK_A

Figure F-3 shows the trend of the third group of creation links, of which current working artefact knowledge causes current working design process knowledge. It can be found that these links have an overall increasing trend over the three design phases, which is the same as the trend of current working artefact knowledge identified in Chapter 6.

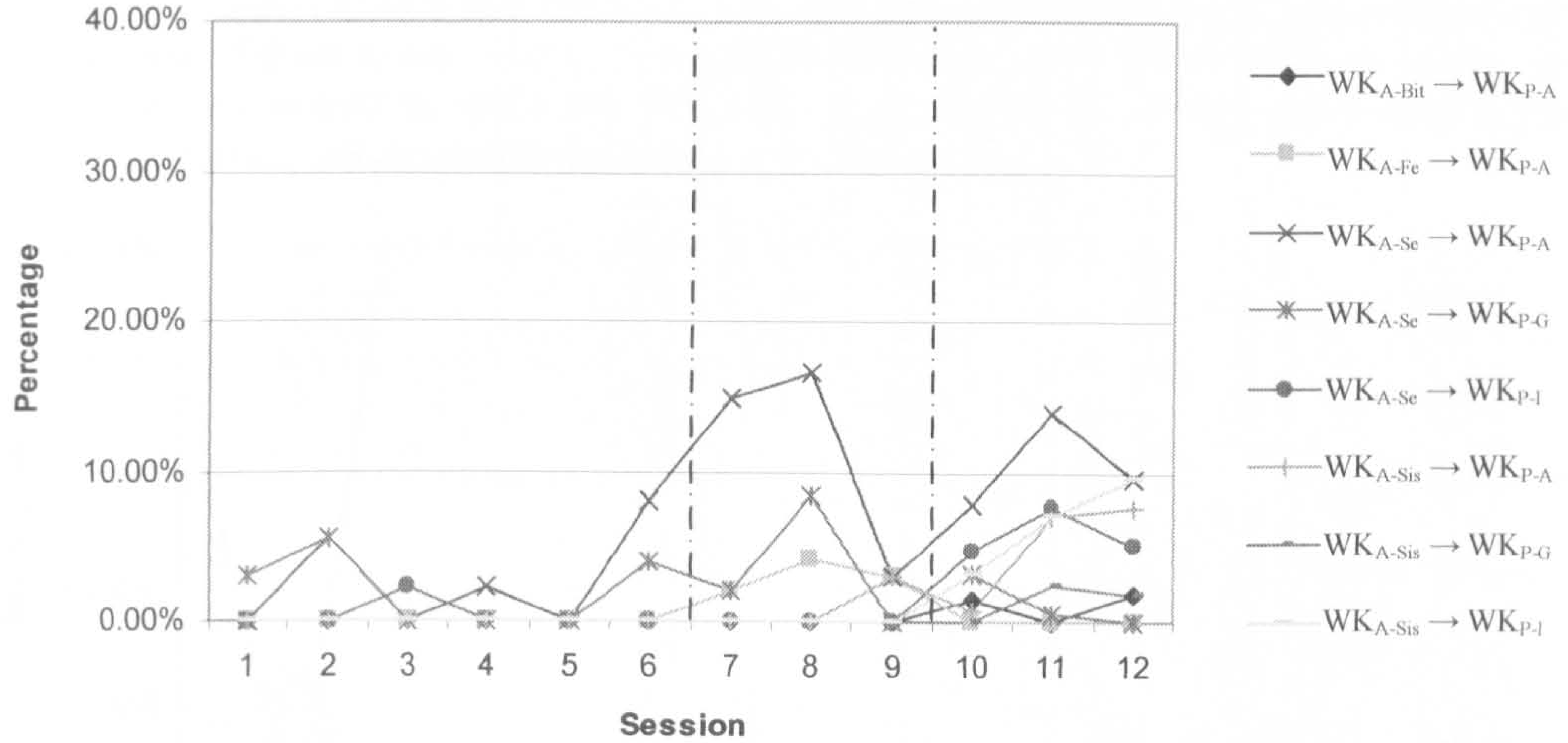

Figure F-3: Trend of creation link – WK_A causing WK_P

The trend of last group of creation links is shown in Figure F-4, which represents design activity causing current working artefact knowledge. The trend chart shows that these links have an overall increasing trend over the three design phases, which is the same as the trend of current working artefact knowledge identified in Chapter 6.

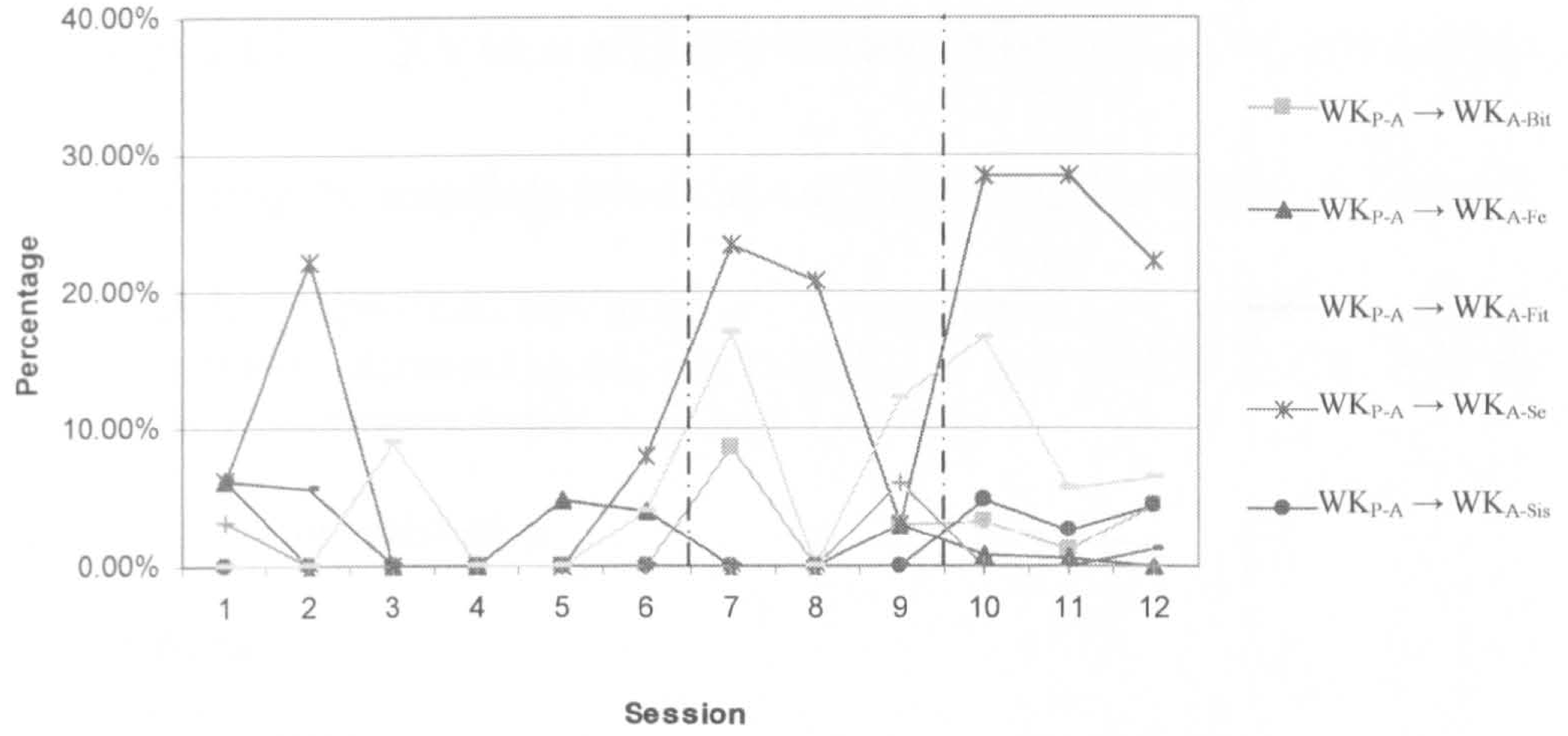

Figure F-4: Trend of creation links – $WK_{P\text{-}A}$ causing WK_A

Link of containment

Figure F-5 depicts the seven containment links' trend over the three design phases. Because there were only 31 occurrences, it was found that this type of like did not exhibit an obvious pattern. The main reason is that the trend was analysed by using the links' percentage within each session. If there is only one or two containment links were identified in a session, then their percentage would be 100% and 50%. Moreover, there were three sessions without any containment links, which caused the break of the link trend.

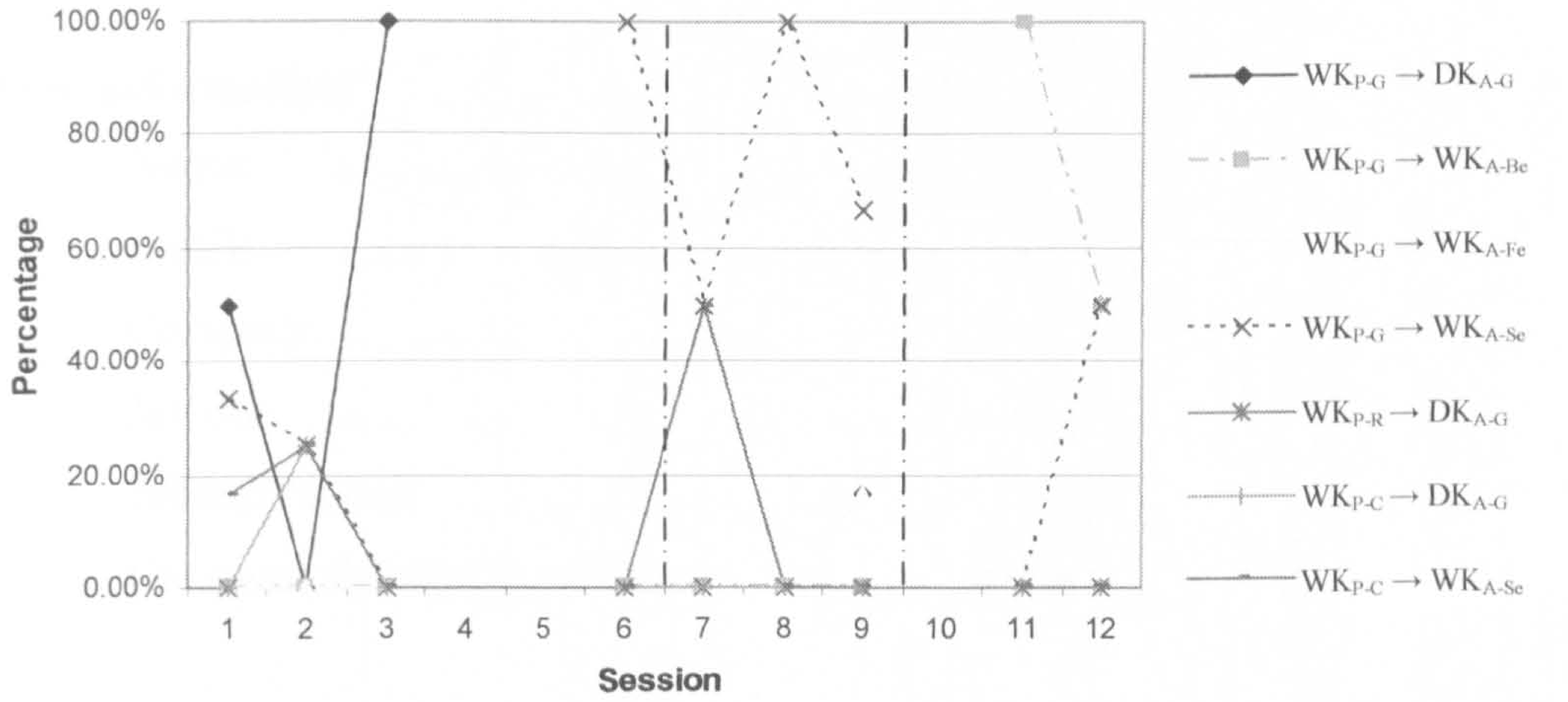

Figure F-5: Trend of containment links – WK_P containing WK_A

Overall, the links trend analysis shows that for the links with sufficient occurrences, they had similar trends to the artefact elements of the links. However, the links with fewer occurrences seemed to have no obvious trends.

Appendix G EVALUATION WORKSHOP QUESTIONNAIRE

Evaluating "Coupling product and design process knowledge"

Product and design process knowledge are often considered to be closely coupled. This questionnaire addresses specific aspects of this relationship, namely the main elements, their occurrence trends, and their coupling.

Thank you for your assistance!

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wenjuan.wang@strath.ac.uk

Your information:

Name: ______________________________

Email: ______________________________

Company: ______________________________

Job title: ______________________________

Products focus: __________________________

Duration of design experience: _____ years

Name:

Part I Design knowledge elements exploration

Category		Design knowledge elements	Frequency: Never	Frequency: Occasionally	Frequency: Often	Frequency: Very often	Trend pattern (Choose A-L from Appendix, if no pattern match, please draw here): A-L	Trend pattern: Draw	Example - "Pen design"	My design project (Note down some examples for your mapping convenience) Project duration: ....hour(s) / day(s) / month(s) / year(s)
General knowledge and past design		General knowledge (General)							Types of pens: Ballpoint, Fountain, Gel, Marker...	
General knowledge and past design		Function (F)							Writing, marking, ...	
General knowledge and past design		Behaviour (B)							Ink (liquid) flow of a fountain pen	
General knowledge and past design		Structure (S)							Clip, Cap, Nib, Body of a fountain pen	
Design case – Product		Need/Motivation (M)							"Slipping", "Difficult to hold"	
Design case – Product		Requirement (Rq)							"Easy to hold"	
Design case – Product	Expected/Intended/planned /Required (E)	Function (Fe)							"Easy to be hold"	
Design case – Product	Expected/Intended/planned /Required (E)	Behaviour (Be)							"There should be friction between pen and finger"	
Design case – Product	Expected/Intended/planned /Required (E)	Structure (Se)							"Rubber grip"	
Design case – Product	Actual/Working (W)	Structure (Sw)							"3D computer model" "Prototype"	
Design case – Product	Actual/Working (W)	Behaviour (Bw)							"Friction between rubber and finger " "Stretch and elastic"	
Design case – Product	Interpreted (I)	Behaviour (Bi)							"The selected material provide the friction" "Attach to the pen body"	
Design case – Product	Interpreted (I)	Function (Fi)							"Non-slip, easy hold"	
Design case – Product		F-B-S mapping, Inter-connections (Cn)							Non-slip — (Rubber) material — (Rib) texture	
Design case – Product		Constraint (Ctr)							"The diameter of the rubber grip is bigger than the pen body"	
Design case – Design process		Activity (A)							"Choose material" "Evaluate the pen"	
Design case – Design process		Goal (G)							"To find a material" "To formulate the function"	
Design case – Design process		Input (In)							"Material solution"	
Design case – Design process		Output (Out)							"Rubber grip"	
Design case – Design process		Resource (Rs)							"Designer", "CAD tools", "Computer" "Available materials"	
Design case – Design process		Context (C)							"Decided the material solution"	
Design case – Design process		Issue (I)							"Find the proper material"	

Please indicate any other elements, which were not listed in this table but can be recognised in your work. (You can write at the back of this page)

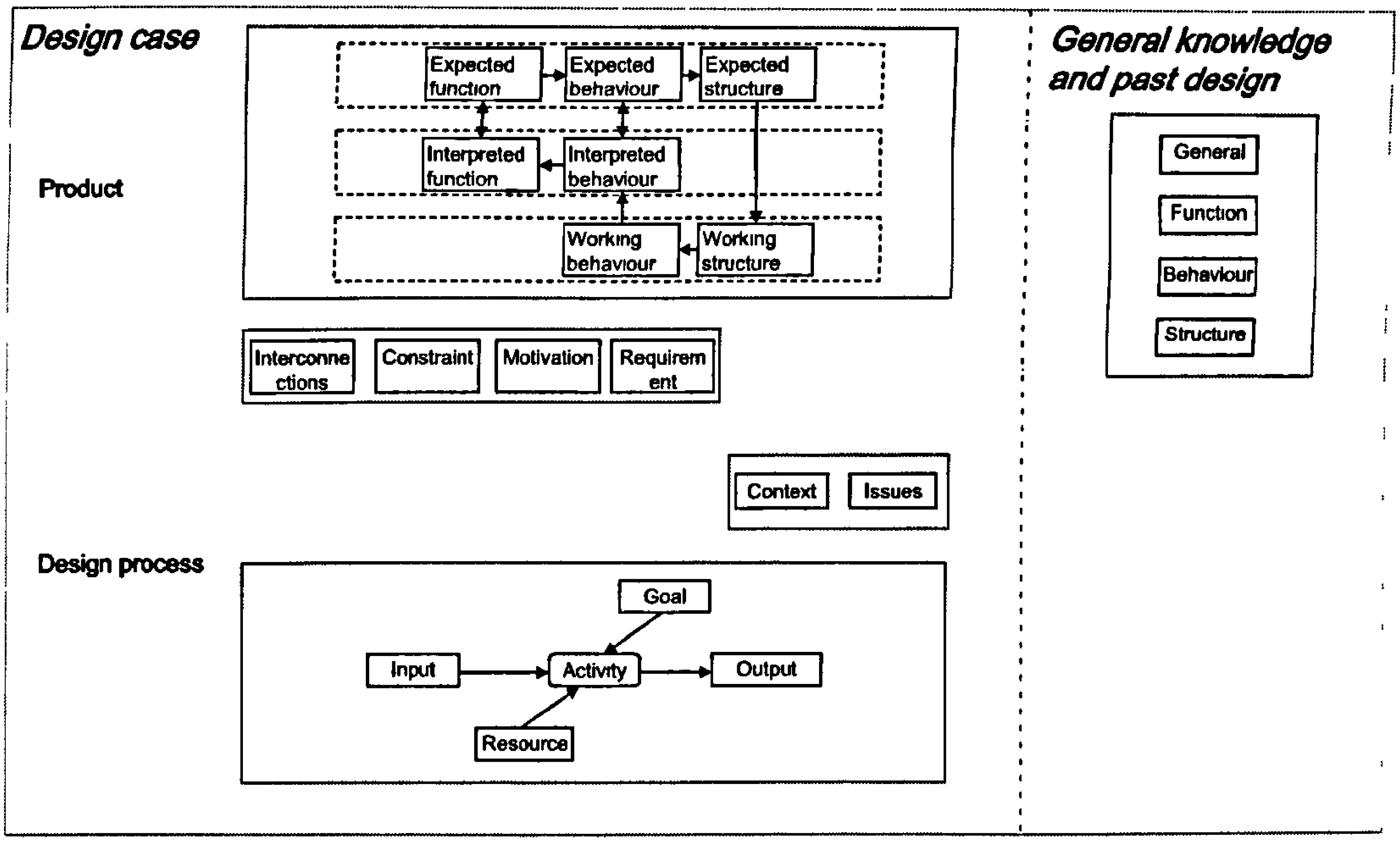
Figure G-1: Knowledge elements exploration – Evaluation Part I

Part II Link product with design process

Please indicate in the following two figures of the two types of links among these elements.

In the Figure 1, please indicate where does the "Cause-effect link of creation" exist among these elements (A→B indicates A causes the creation of B).

Figure 1 Creation links



In the Figure 2, please indicate where does the "Containment link" exist among these elements (A—●B indicates A contains B).

Figure 2 Containment links

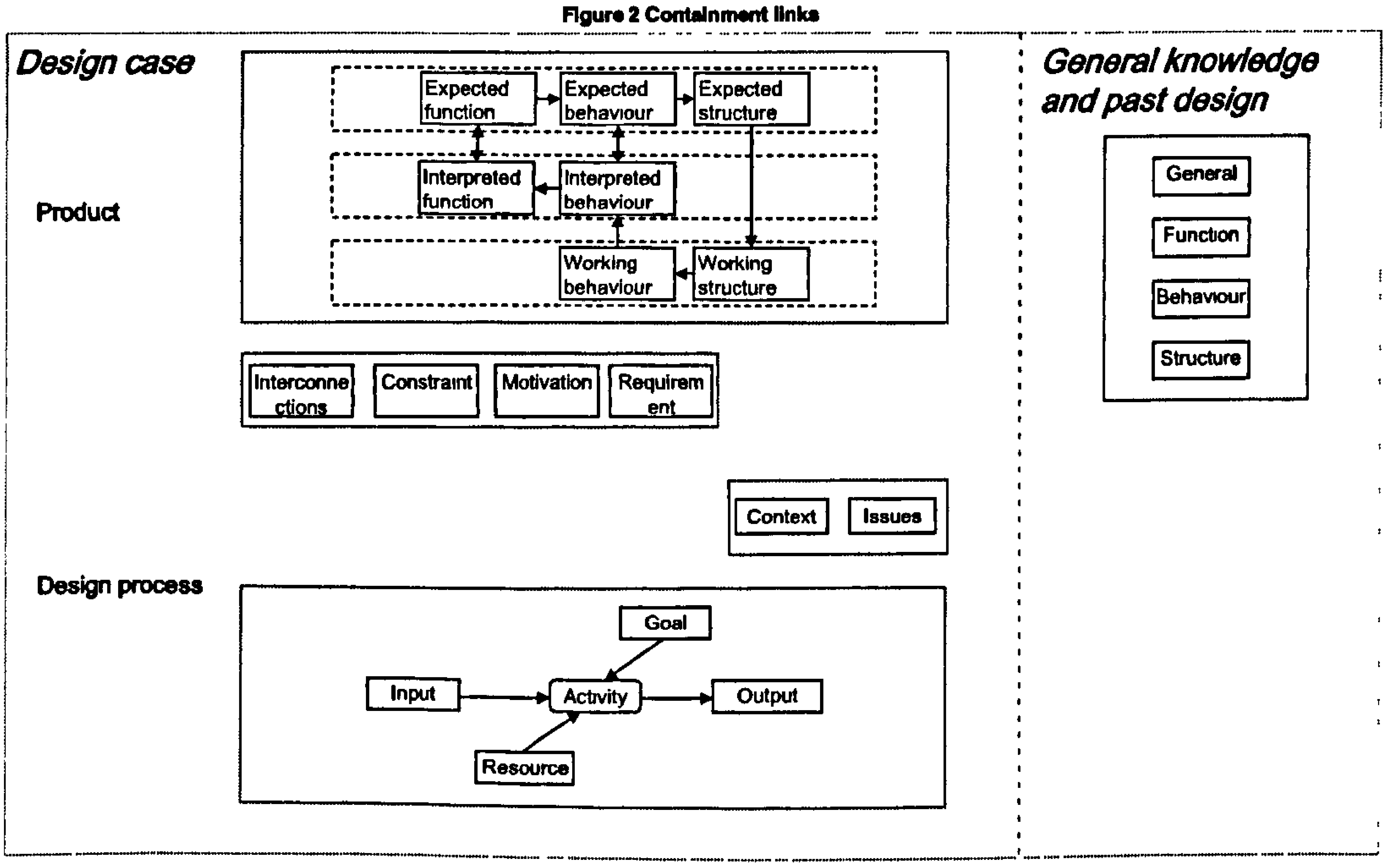
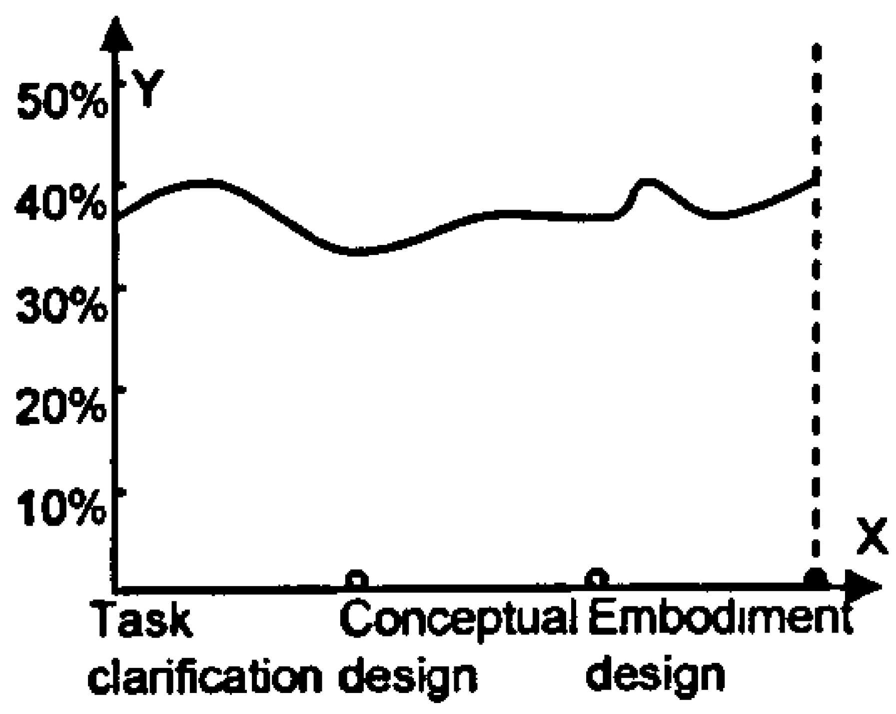


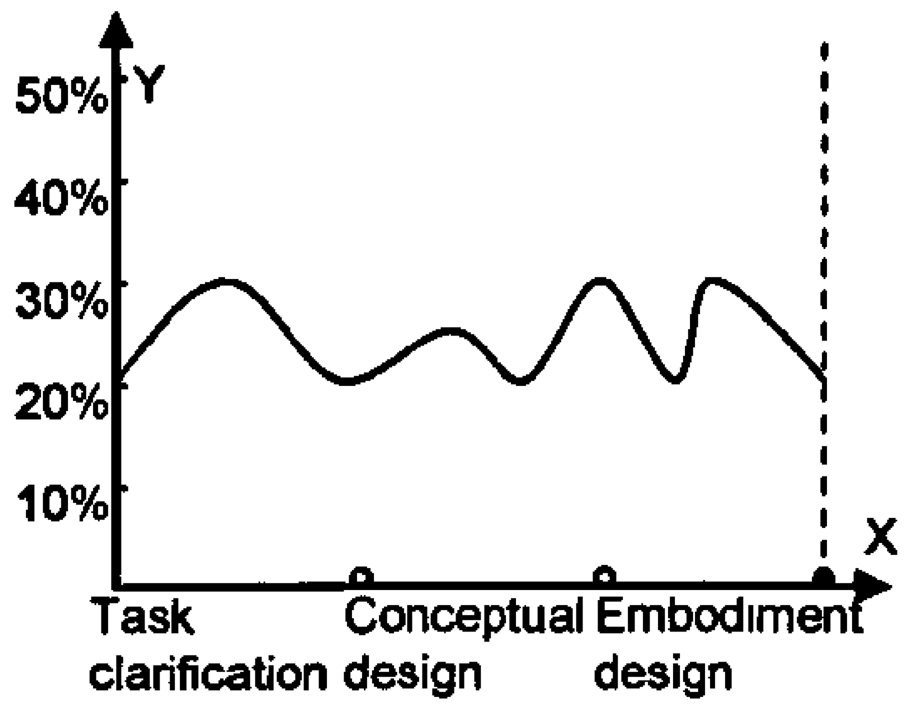
Figure G-2: Coupling exploration – Evaluation Part II

Appendix G-1: Trend charts

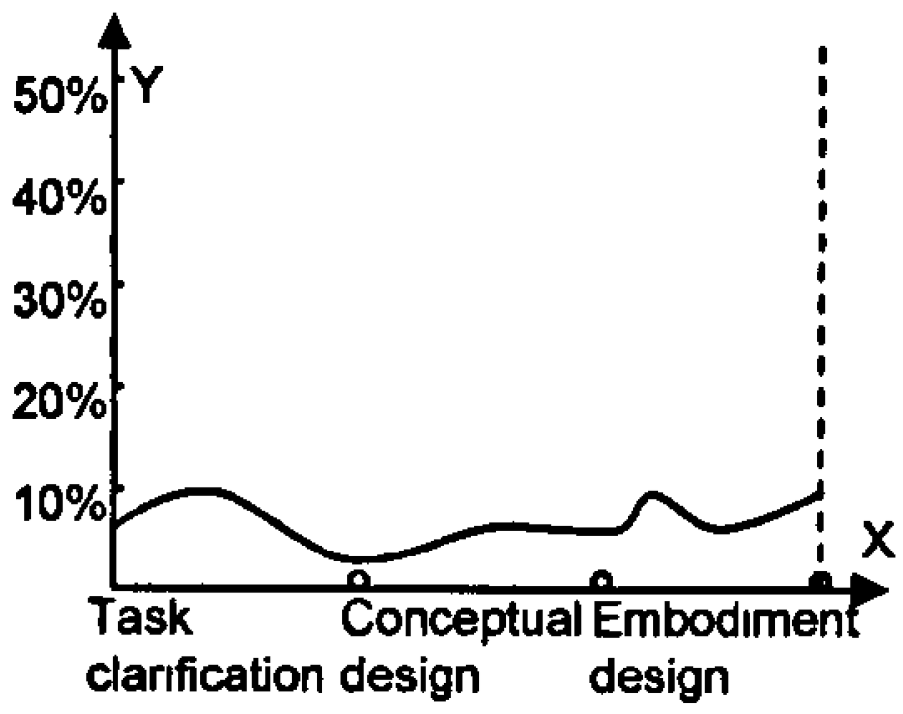
A



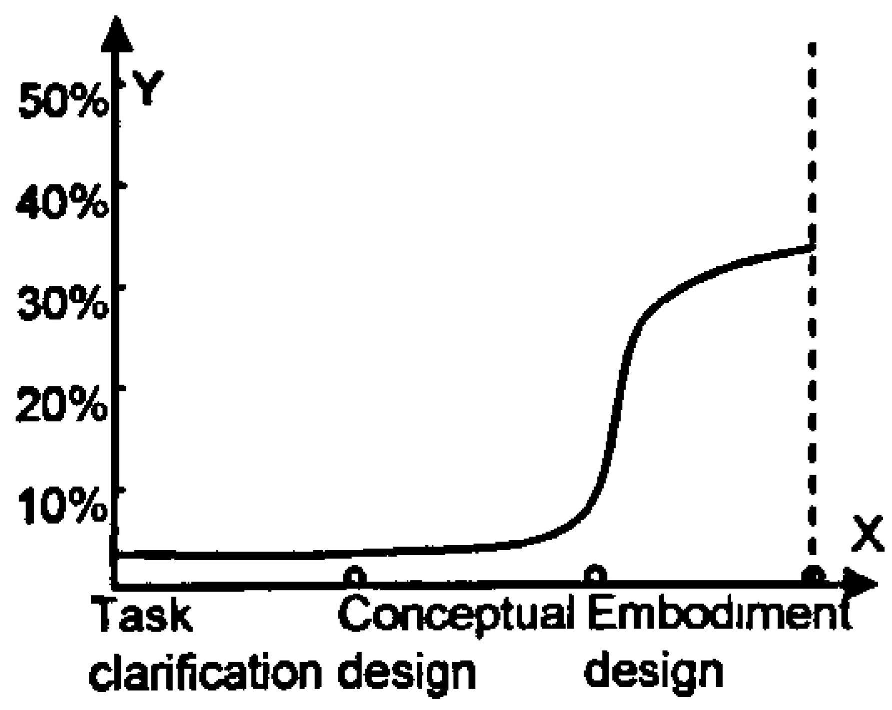
B



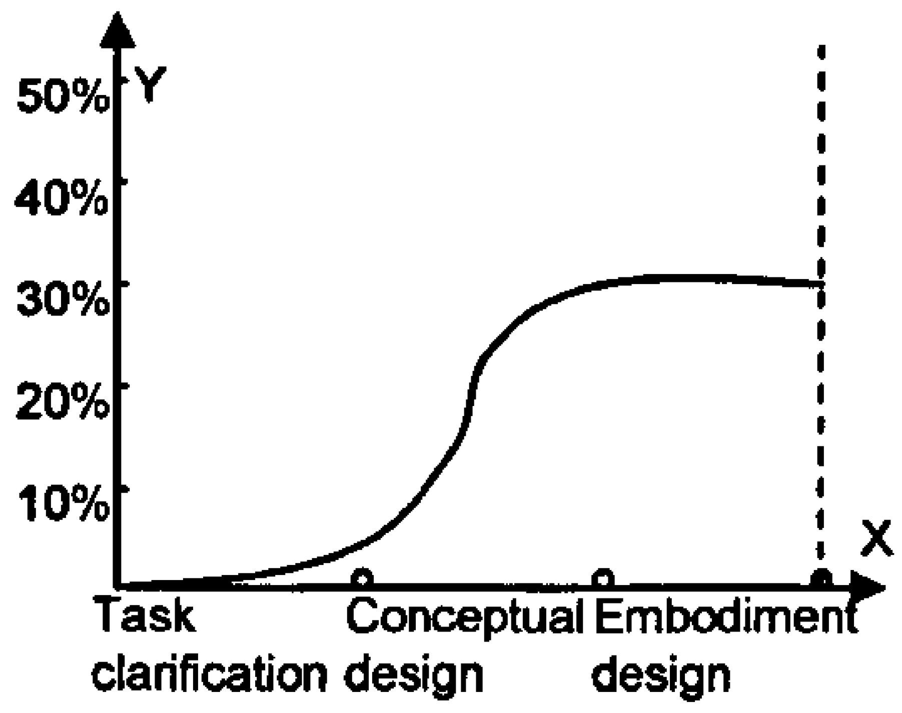
C



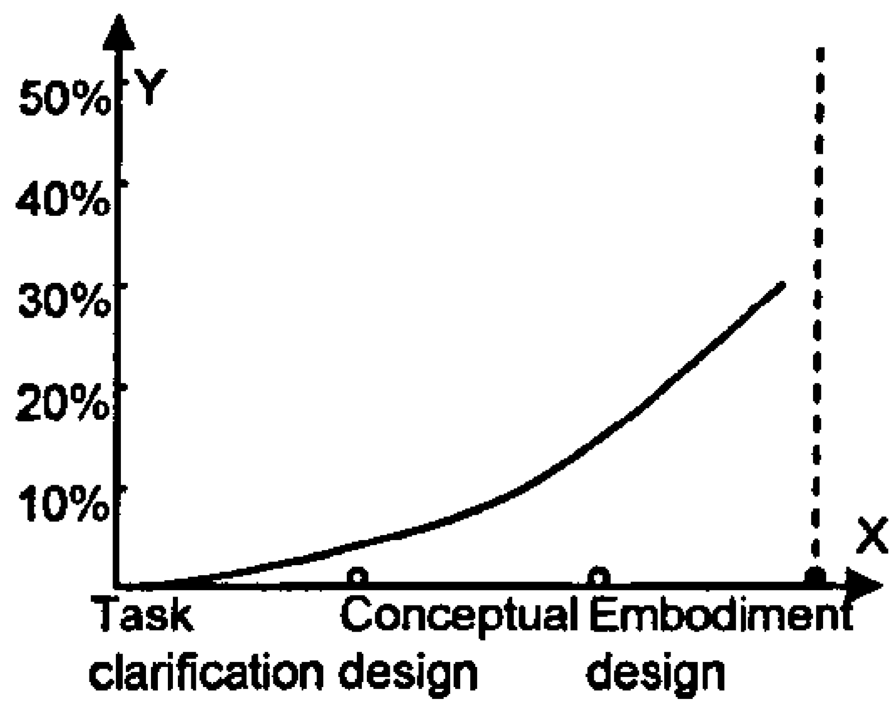
D



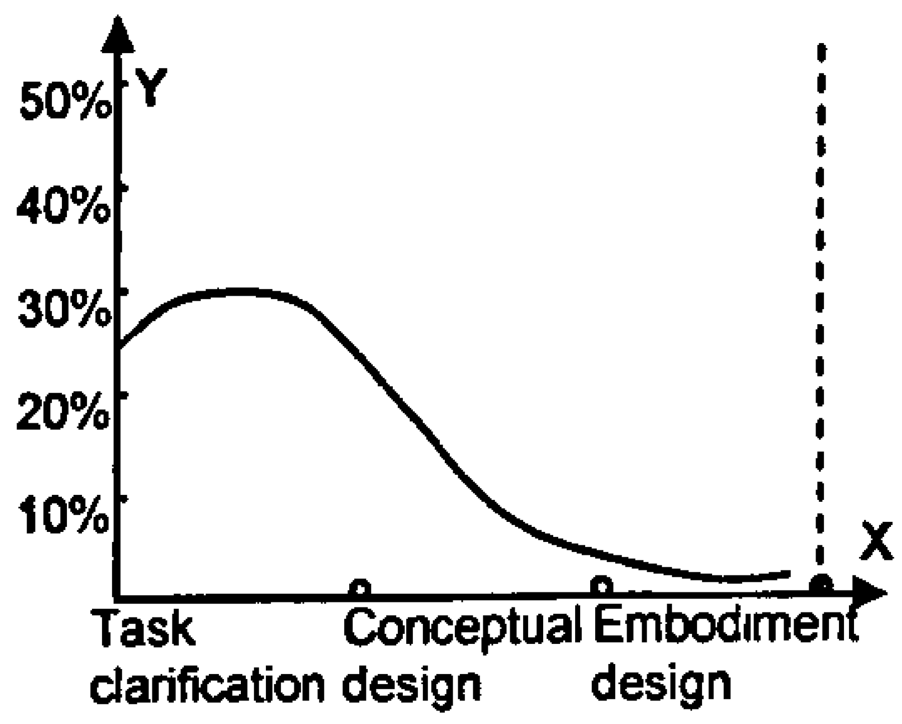
E



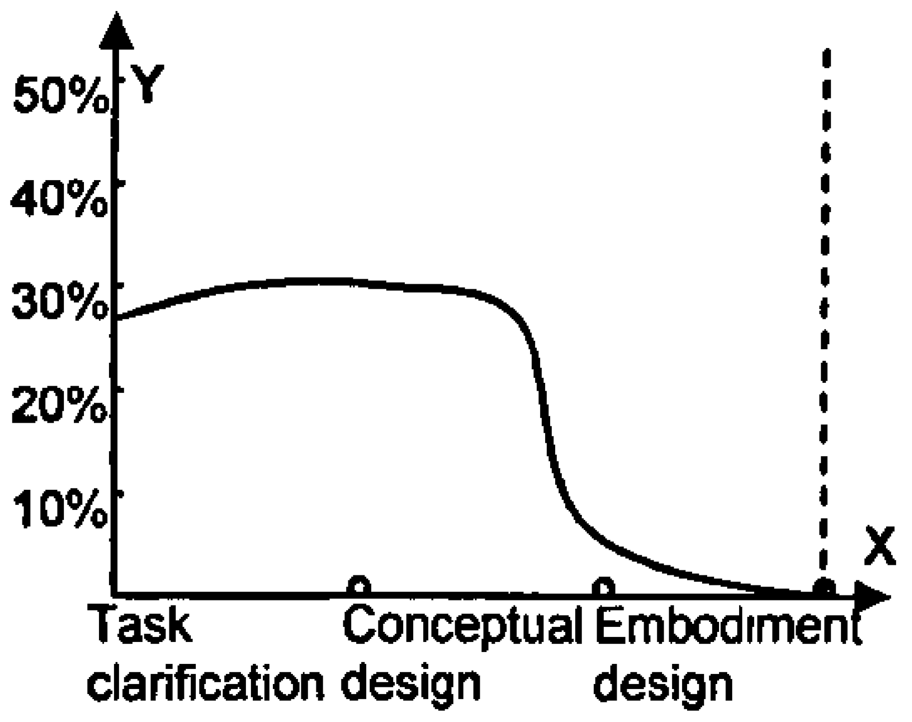
F



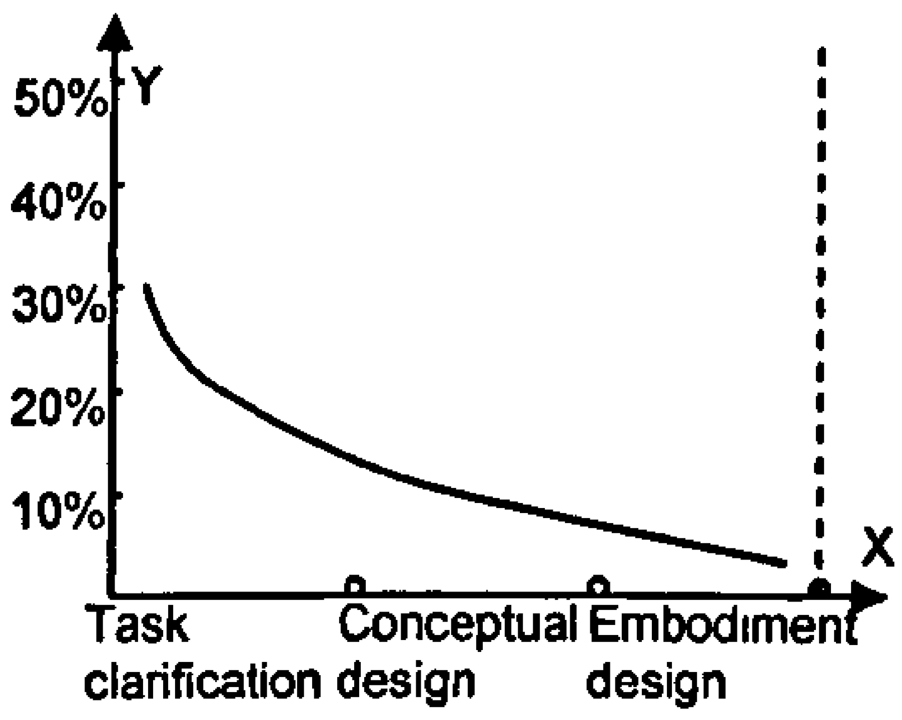
G



H



I



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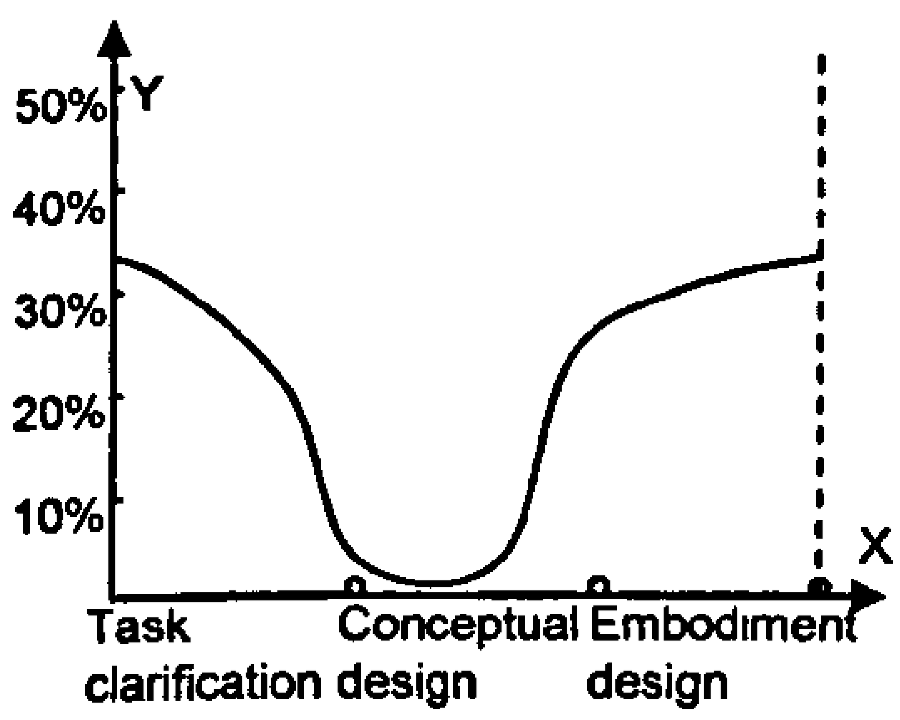
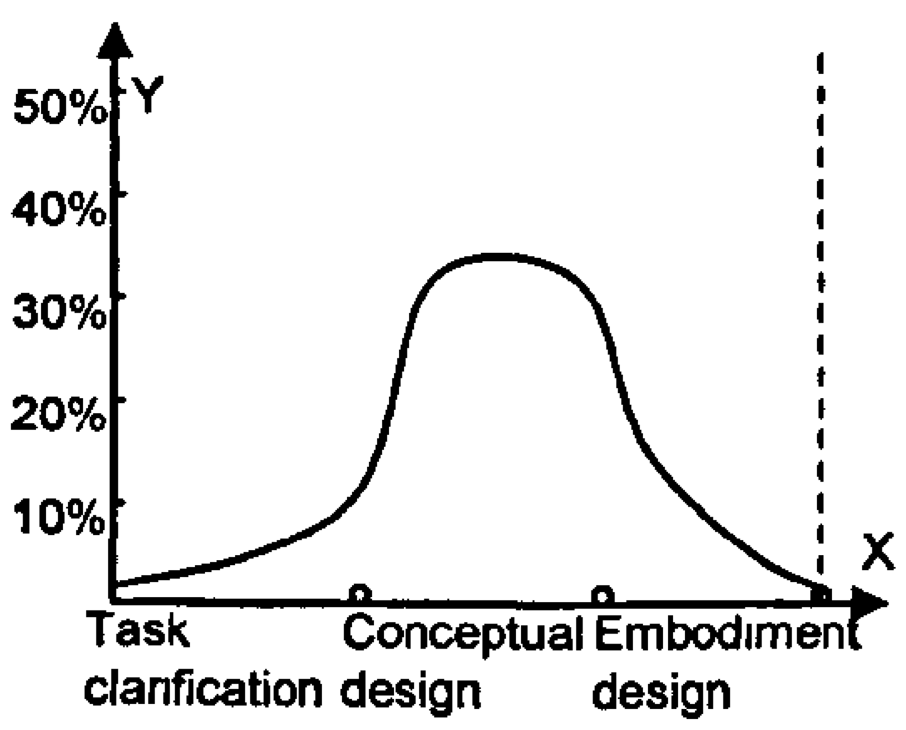
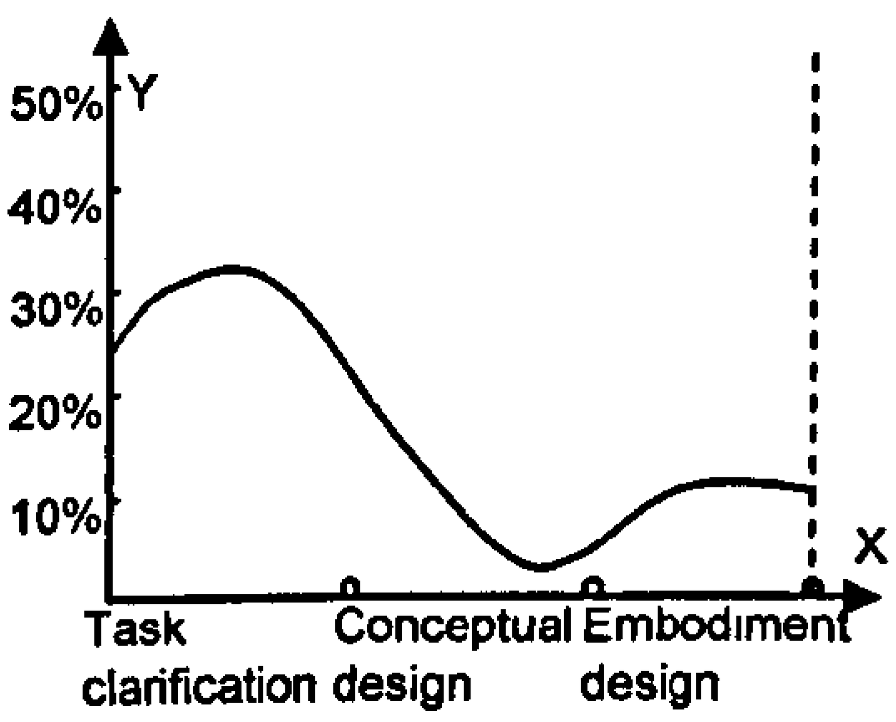


K



L



Appendix G-2: Product elements explanation/definition

Expected (E)
Designers' expectation towards a product

Interpreted (I)
Designers' interpretation of a product

Actual, Working (W)
Instantiation of a product

Function (F)
The useful thing the product will do. The intention and purpose of the product

Behaviour (B)
What the product do

Structure (S)
What the product is composed of, and their interactions.

Motivation (M)
Human being's desires or needs (From customers, stakeholders)

Requirement (Rq)
Characteristics expected to be fulfilled through the design

FBS mappings, Interconnections (Cn)
Cause-effect links among F, B, S, M, Rq

Constraint (C)
Restrictions on an accepted product (Not include the requirements)

Activity (A)
Action takes place during a design process

Goal (G)
Objective of an activity

Input (In)
Knowledge present prior to a design activity

Output (Out)
Knowledge present as a result of carrying out a design activity

Resource (Rs)
Utilised by design activities, such as people, hardware, software

Context (C)
Factors affect design

Issues (I)
Problems to be solved by designers

Appendix H EVALUATION RESULTS

Eight designers from two companies participated two workshops organised in their companies. These designers were identified as designer 1 to designer 8 in this thesis. Designers 1 to 5 come from BAE Systems Surface Fleet Solutions Limited (SFS), and designers 6 to 8 come from Company A. Seven of the finished questionnaires were used as basis for evaluation (except designer 8 from Company A). The two main parts of the evaluation questionnaire finished by each designer are listed in this appendix. They are Part I: Knowledge elements exploration, and Part II: Link product with design process.

Due to confidentiality, the project part of two questionnaires from Company A was cut out, because description of specific product and process were included in this part.

Designer 1, SFS

Name: Ref 1

Part I Design knowledge elements exploration

Category		Design knowledge elements	Frequency: Never	Frequency: Occasionally	Frequency: Often	Frequency: Very often	Trend pattern (Choose A-L from Appendix, if no pattern match, please draw here): A-L	Trend pattern: Draw	Example "Pen design"	My design project (Note down some examples for your mapping convenience) Project duration 7 hour(s) / day(s) / month(s) / year(s)
General knowledge and past design		General knowledge (General)				✓	I		Types of pen: Ballpoint, Fountain, Gel, Marker…	
General knowledge and past design		Function (F)			✓		A		Writing, marking…	
General knowledge and past design		Behaviour (B)			✓		A		Ink (liquid) flow of a fountain pen	
General knowledge and past design		Structure (S)				✓	A		Clip, Cap, Nib, Body of a fountain pen	
Design case – Product		Need/Motivation (M)			✓		L		"Slipping", "Difficult to hold"	
Design case – Product		Requirement (Rq)				✓	H		"Easy to hold"	
Design case – Product	Expected/Intended/planned /Required (E)	Function (Fe)			✓		H		"Easy to be held"	
Design case – Product	Expected/Intended/planned /Required (E)	Behaviour (Be)			✓		I		"There should be friction between pen and finger"	
Design case – Product	Expected/Intended/planned /Required (E)	Structure (Se)			✓		B		"Rubber grip"	
Design case – Product	Actual/Working (W)	Structure (Sw)		✓			E		"3D computer model" "Prototype"	
Design case – Product	Actual/Working (W)	Behaviour (Bw)		✓			L		"Friction between rubber and finger" "Stretch and elastic"	
Design case – Product	Interpreted (I)	Behaviour (Bi)			✓		D		"The selected material provide the friction" "Attach to the pen body"	
Design case – Product	Interpreted (I)	Function (Fi)			✓		A		"Non-slip, easy hold"	
Design case – Product		F-B-S mapping, Inter-connections (Cn)		✓			D		Non-slip — (Rubber) material — (Rib) texture	
Design case – Product		Constraint (Ctr)		✓			D		"The diameter of the rubber grip is bigger than the pen body"	
Design case – Design process		Activity (A)			✓		C		"Choose material" "Evaluate the pen"	
Design case – Design process		Goal (G)		✓			K		"To find a material" "To formulate the function"	
Design case – Design process		Input (In)				✓	A		"Material solution"	
Design case – Design process		Output (Out)			✓		F		"Rubber grip"	
Design case – Design process		Resource (Rs)				✓	A		"Designer", "CAD tools", "Computer" "Available materials"	
Design case – Design process		Context (C)			✓		A		"The material solution that has been decided"	
Design case – Design process		Issues (I)			✓		F		"Find the proper material"	

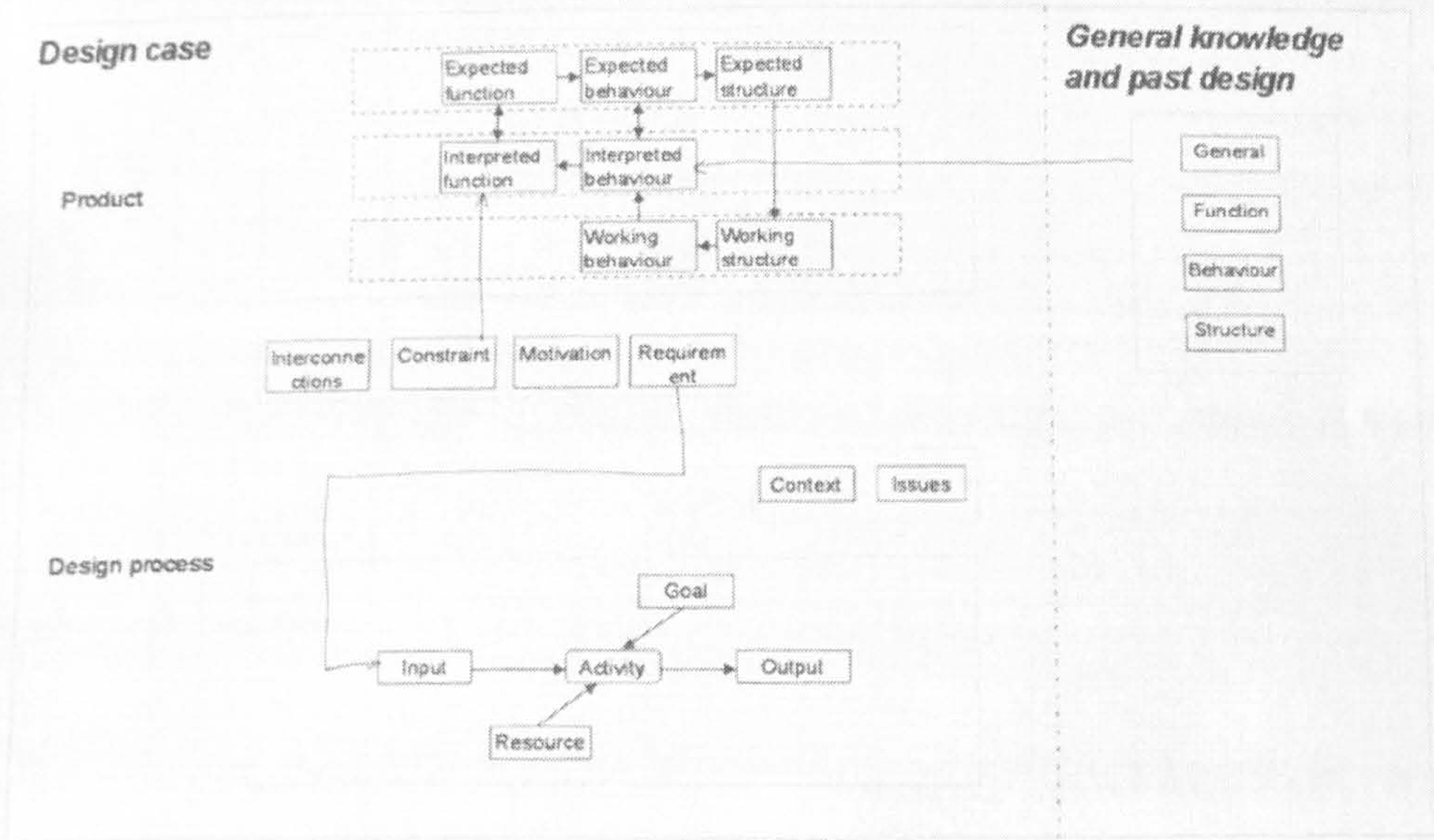
…ease indicate any other elements which were not listed here but can be…

Part II Link product with design process

Please indicate in the following two figures of the two types of links among these elements.

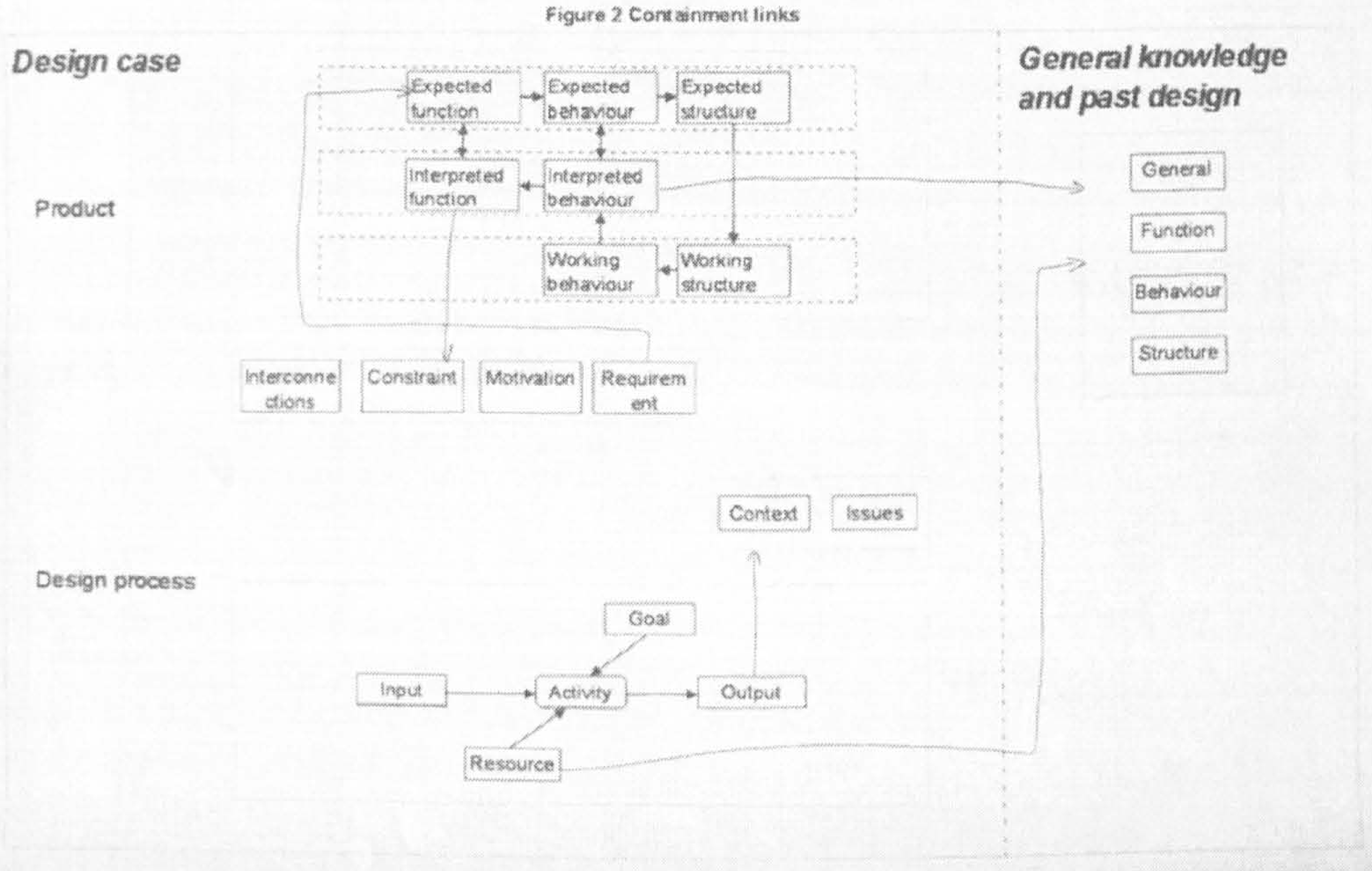
In the Figure 1, please indicate where does the 'Cause-effect link of creation' exist among these elements (A → B indicates A causes the creation of B)

Figure 1 Creation links



In the Figure 2, please indicate where does the 'Containment link' exist among these elements (A → B indicates A contains B)

Figure 2 Containment links



Designer 2, SFS

Ref 2

Part I Design knowledge elements exploration

Name:

Category		Design knowledge elements	Frequency: Never	Occasionally	Often	Very often	Trend pattern (Choose A-L from Appendix, if no pattern match, please draw here): A-L	Draw	Example – "Pen design"	My design project (Note down some examples for your [illegible] mapping convenience) COMBATANT. Project duration: 3 hour(s)/day(s)/month(s)/year(s)
General knowledge and past design		General knowledge (General)			✓		B		Types of pen: Ballpoint, Fountain, Gel, Marker	
		Function (F)				✓	H		Writing, marking	
		Behaviour (B)				✓	E		ink (liquid) flow of a fountain pen	BEHAVIOR + CAPABILITIES OF EQUIPMENT (AVAILABLE).
		Structure (S)			✓		E		Clip, Cap, Nib, Body of a fountain pen	
Design case – Product		Need/Motivation (M)		✓			B		"Slipping", "Difficult to hold"	
		Requirement (Rq)				✓	B		"Easy to hold"	
	Expected/Intended/Desired/Required (E)	Function (Fe)		✓			C		"Easy to be held"	
		Behaviour (Be)		✓			C		"There should be friction between pen and finger"	
		Structure (Se)			✓		C		"Rubber grip"	
	Actual/Working (W)	Structure (Sw)				✓	F		"3D computer model" "Prototype"	3D CAD, 2D CAD, SIMULATION RESULTS,
		Behaviour (Bw)				✓	E		"Friction between rubber and finger" "Stretch and elastic"	
	Interpreted (I)	Behaviour (Bi)				✓	E		"The selected material provide the friction" "Attach to the pen body"	
		Function (Fi)			✓		F		"Non-slip, easy hold"	
		F-B-S mapping, inter-connections (Cn)				✓	K		Non-slip — (Rubber) material — (Rib) texture	
		Constraint (Ctr)		✓			J		"The diameter of the rubber grip is bigger than the pen body"	CONSTRUCTION FACILITIES, TIMESCALES, PLANNING LINES,
Design case – Design process		Activity (A)				✓	E		"Choose material" "Evaluate the pen"	
		Goal (G)		✓			G		"To find a material" "To formulate the function"	
		Input (In)			✓		H		"Material solution"	LIMITS DEPENDENT ON AVAILABILITY?
		Output (Out)				✓	E		"Rubber grip"	
		Resource (Rs)				✓	A		"Designer", "CAD tools", "Computer" "Available materials"	
		Context (C)			✓		B		"The material solution that has been decided"	
		Issues (I)				✓	I		"Find the proper material"	

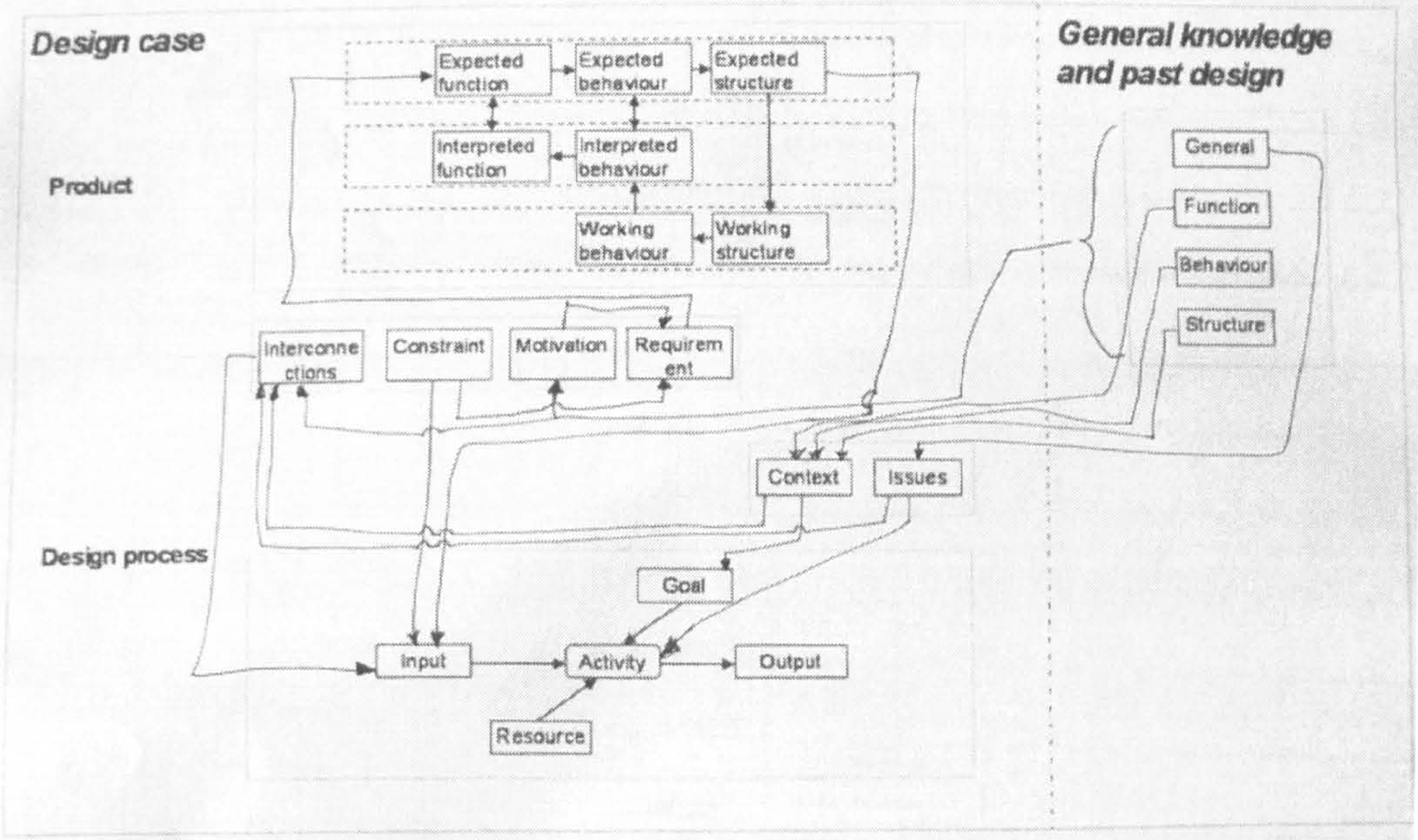
Please indicate any other elements, which were not listed here but can be recognised in your work

Part II Link product with design process

Please indicate in the following two figures of the two types of links among these elements.

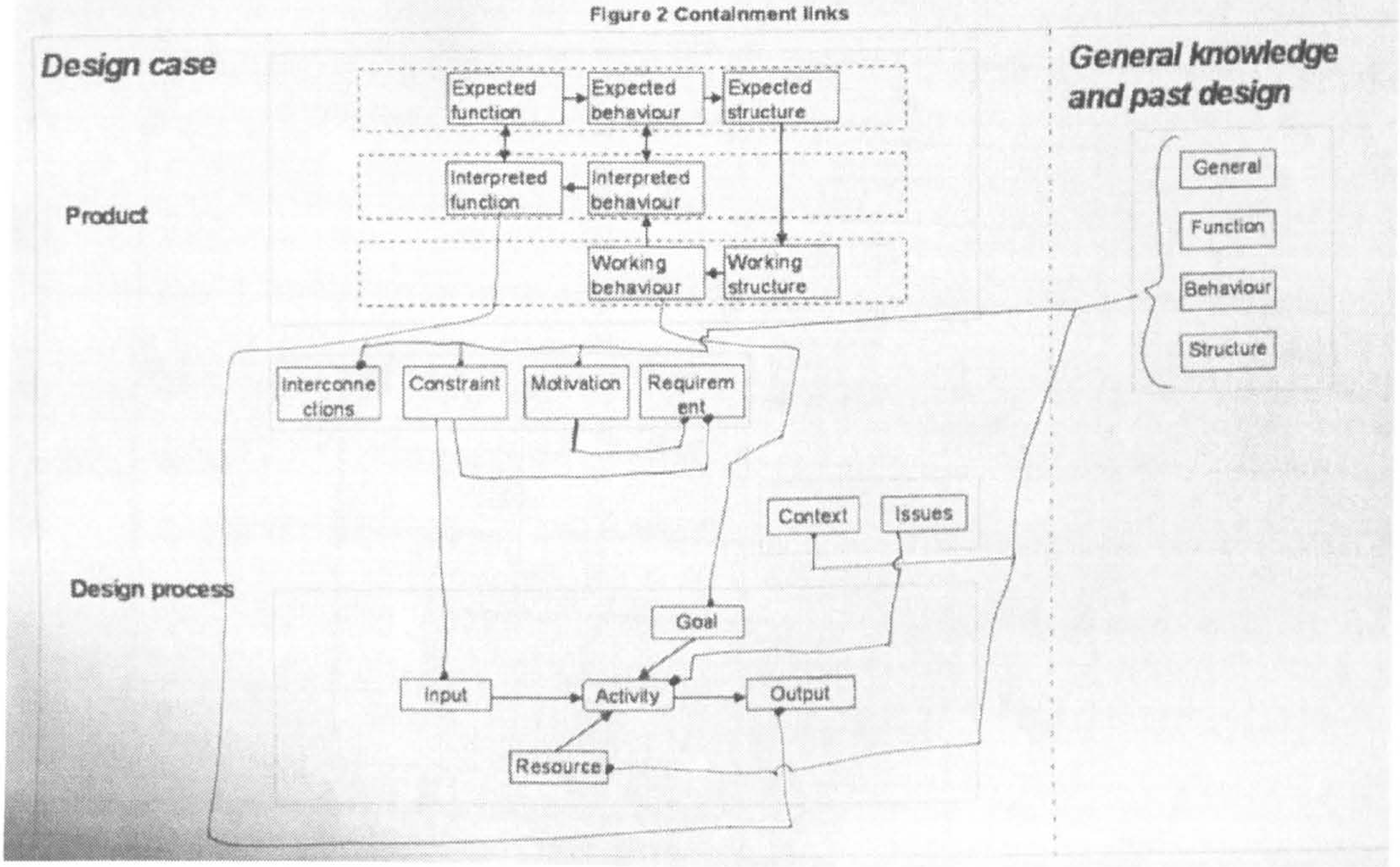
In the Figure 1, please indicate where does the "Cause-effect link of creation" exist among these elements ([A]→[B] indicates A causes the creation of B).

Figure 1 Creation links



In the Figure 2, please indicate where does the "Containment link" exist among these elements ([A]→[B] indicates A contains B).

Figure 2 Containment links



Designer 3, SFS

Name: Ref 3

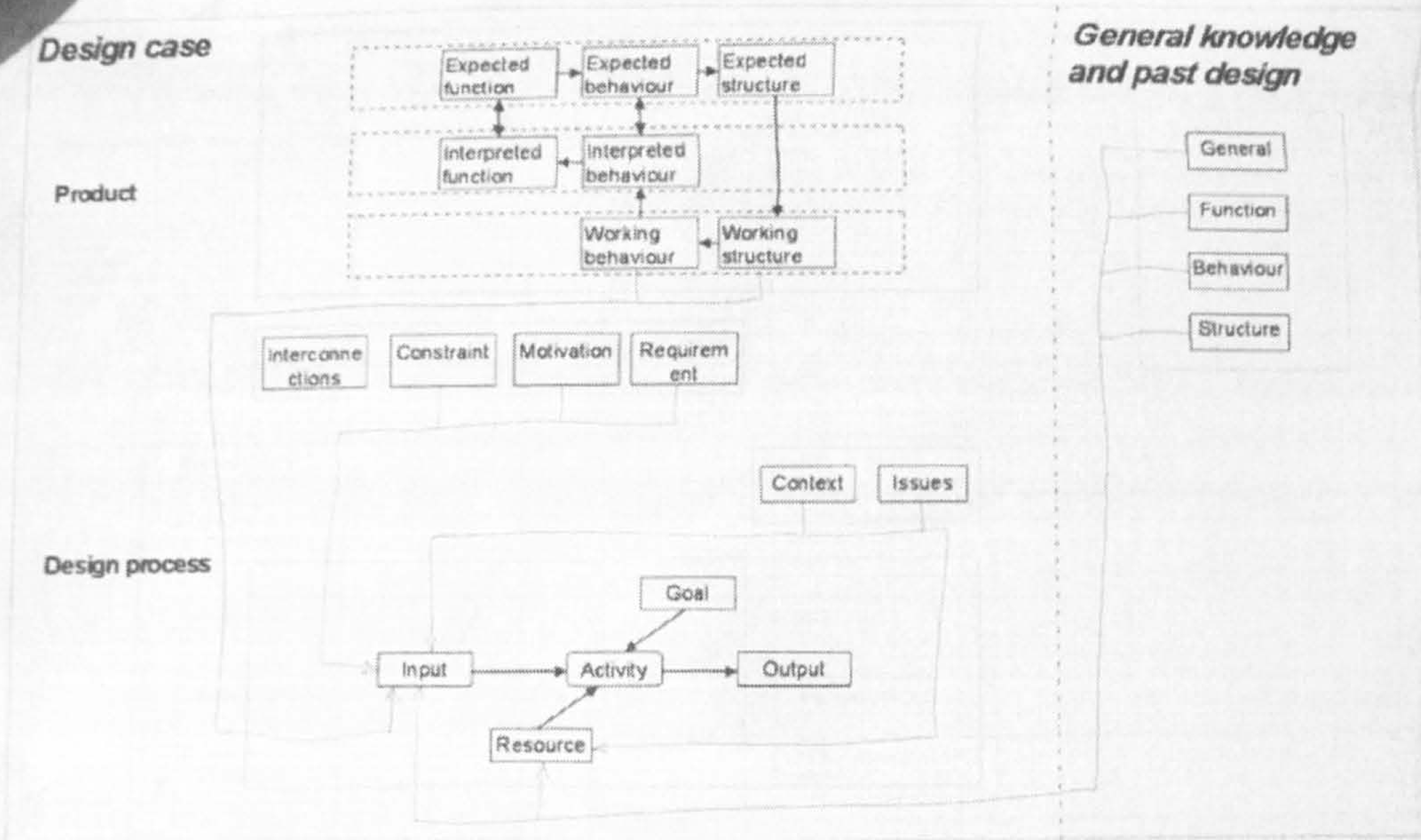
Part I Design knowledge elements exploration

Category		Design knowledge elements	Frequency: Never	Frequency: Occasionally	Frequency: Often	Frequency: Very often	Trend pattern (Choose A-L from Appendix, if no pattern match, please draw here): A-L	Trend pattern: Draw	Example - "Pen design"	My design project (Note down some examples for your mapping convenience) CUP Project duration: 2 hour(s) / day(s) / month(s) / year(s)
General knowledge and past design		General knowledge (General)				✓	H		Types of pen: Ballpoint, Fountain, Gel, Marker…	
		Function (F)				✓	A		Writing, marking, …	
		Behaviour (B)				✓	A		Ink (liquid) flow of a fountain pen	
		Structure (S)			✓		C		Clip, Cap, Nib, Body of a fountain pen	
Design case: Product		Need/Motivation (M)		✓			C		"Slipping", "Difficult to hold"	
		Requirement (Rq)				✓	A		"Easy to hold"	
	Expected/Intended/Planned /Required (E)	Function (Fe)				✓	A		"Easy to be held"	
		Behaviour (Be)				✓	A		"There should be friction between pen and finger"	
		Structure (Se)			✓		C		"Rubber grip"	
	Actual/Working (W)	Structure (Sw)		✓			F		"3D computer model" "Prototype"	
		Behaviour (Bw)		✓			F		"Friction between rubber and finger" "Stretch and elastic"	
	Interpreted (I)	Behaviour (Bi)			✓		E		"The selected material provide the friction" "Attach to the pen body"	
		Function (Fi)			✓		E		"Non-slip, easy hold"	
		F-B-S mapping, inter-connections (Cn)				✓	A		Non-slip — (Rubber) material — (Rib) texture	
		Constraint (Ctr)				✓	A		"The diameter of the rubber grip is bigger than the pen body"	
Design case: Design process		Activity (A)				✓	F		"Choose material" "Evaluate the pen"	
		Goal (G)				✓	E		"To find a material" "To formulate the function"	
		Input (In)				✓	A		"Material solution"	
		Output (Out)				✓	A		"Rubber grip"	
		Resource (Rs)				✓	A		"Designer", "CAD tools", "Computer" "Available materials"	
		Context (C)			✓		F		"The material solution that has been decided"	
		Issues (I)				✓	F		"Find the proper material"	

Please indicate any other elements, which were not listed here but can be recognised in your work (You can write at the back of this page)

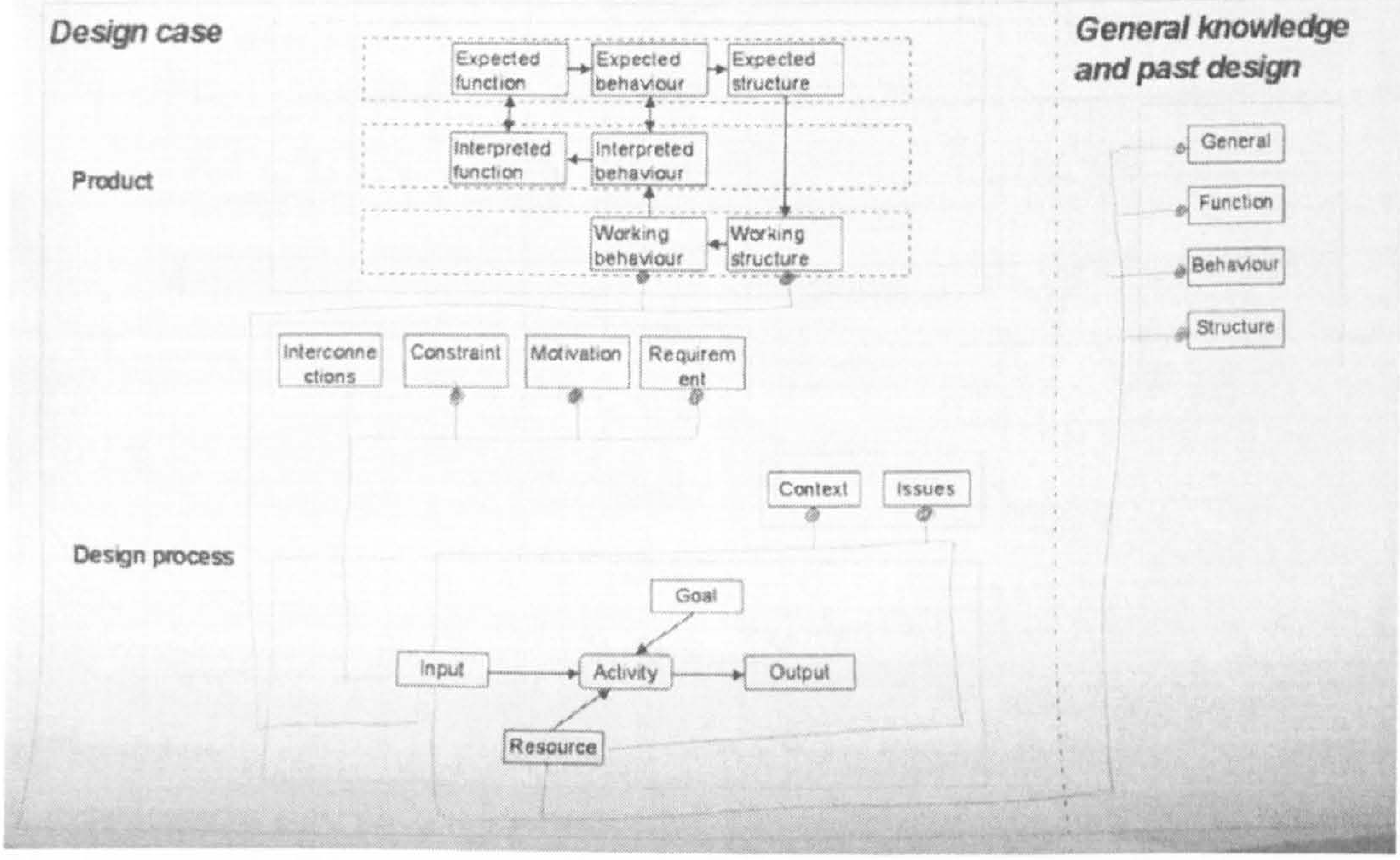
In the Figure 1, please indicate where does the "Cause-effect link of creation" exist among these elements (A → B indicates A causes the creation of B).

Figure 1 Creation links



In the Figure 2, please indicate where does the "Containment link" exist among these elements (A → B indicates A contains B).

Figure 2 Containment links



Designer 4, SFS

Part I Design knowledge elements exploration

Name: Ref 4

Category		Design knowledge elements	Frequency: Never	Frequency: Occasionally	Frequency: Often	Frequency: Very often	Trend pattern (Choose A-L from Appendix, if no pattern match, please draw here): A-L	Trend pattern: Draw	Example - "Pen design"	My design project (Note down some examples for your mapping convenience) Project duration [illegible] hour(s) / day(s) / month(s) / year(s)
General knowledge and past design		General knowledge (General)				✓	H		Types of pen: Ballpoint, Fountain, Gel, Marker	
		Function (F)			✓		H		Writing, marking	
		Behaviour (B)		✓			H		Ink (liquid) flow of a fountain pen	
		Structure (S)				✓	E		Clip, Cap, Nib, Body of a fountain pen	
Design case: Product		Need/Motivation (M)				✓	A		"Slipping", "Difficult to hold"	
		Requirement (Rq)				✓	A		"Easy to hold"	[illegible]
	Expected/Intended/planned Required (E)	Function (Fe)				✓	B		"Easy to be held"	
		Behaviour (Be)			✓		E		"There should be friction between pen and finger"	
		Structure (Se)				✓	A		"Rubber grip"	
	Actual/Working (W)	Structure (Sw)				✓	A		"3D computer model" "Prototype"	
		Behaviour (Bw)			✓		B		"Friction between rubber and finger" "Stretch and elastic"	
	Interpreted (I)	Behaviour (Bi)				✓	E		"The selected material provide the friction" "Attach to the pen body"	
		Function (Fi)				✓	B		"Non-slip, easy hold"	
		F-B-S mapping, Inter-connections (Cn)				✓	F		Non-slip → (Rubber) material → (Rib) texture	
		Constraint (Ctr)				✓	A		"The diameter of the rubber grip is bigger than the pen body"	[illegible]
Design case: Design process		Activity (A)			✓		H		"Choose material" "Evaluate the pen"	
		Goal (G)				✓	B		"To find a material" "To formulate the function"	
		Input (In)			✓		L		"Material solution"	
		Output (Out)			✓		F		"Rubber grip"	
		Resource (Rs)				✓	F		"Designer" "CAD tools", "Computer" "Available materials"	[illegible]
		Context (C)				✓	A		"The material solution that has been decided"	
		Issues (I)				✓	A		"Find the proper material"	[illegible]

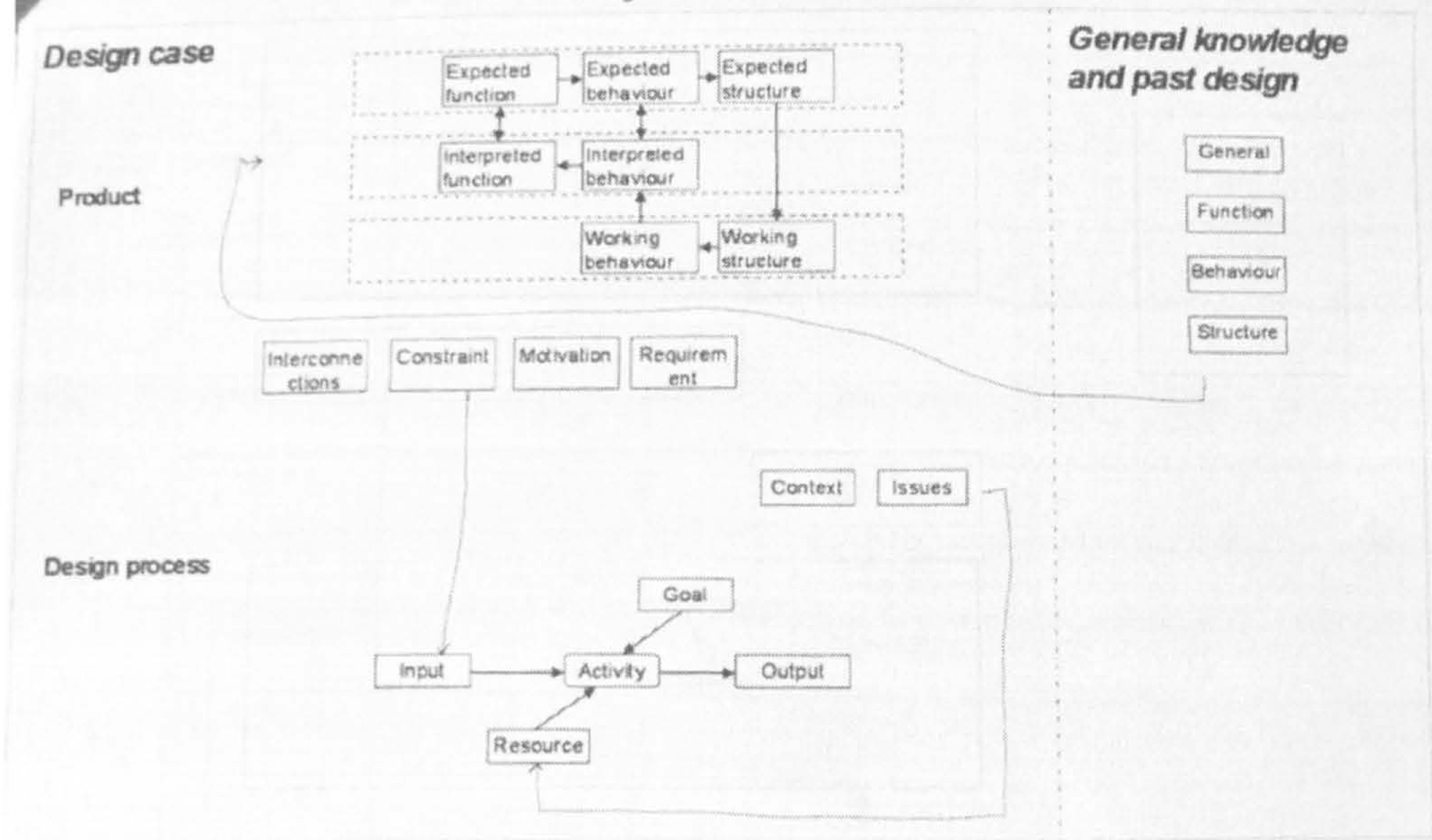
Please indicate any other elements, which were not listed here but can be recognised in your work!
(You can write at the back of this page)

Part II Link product with design process

Please indicate in the following two figures of the two types of links among these elements.

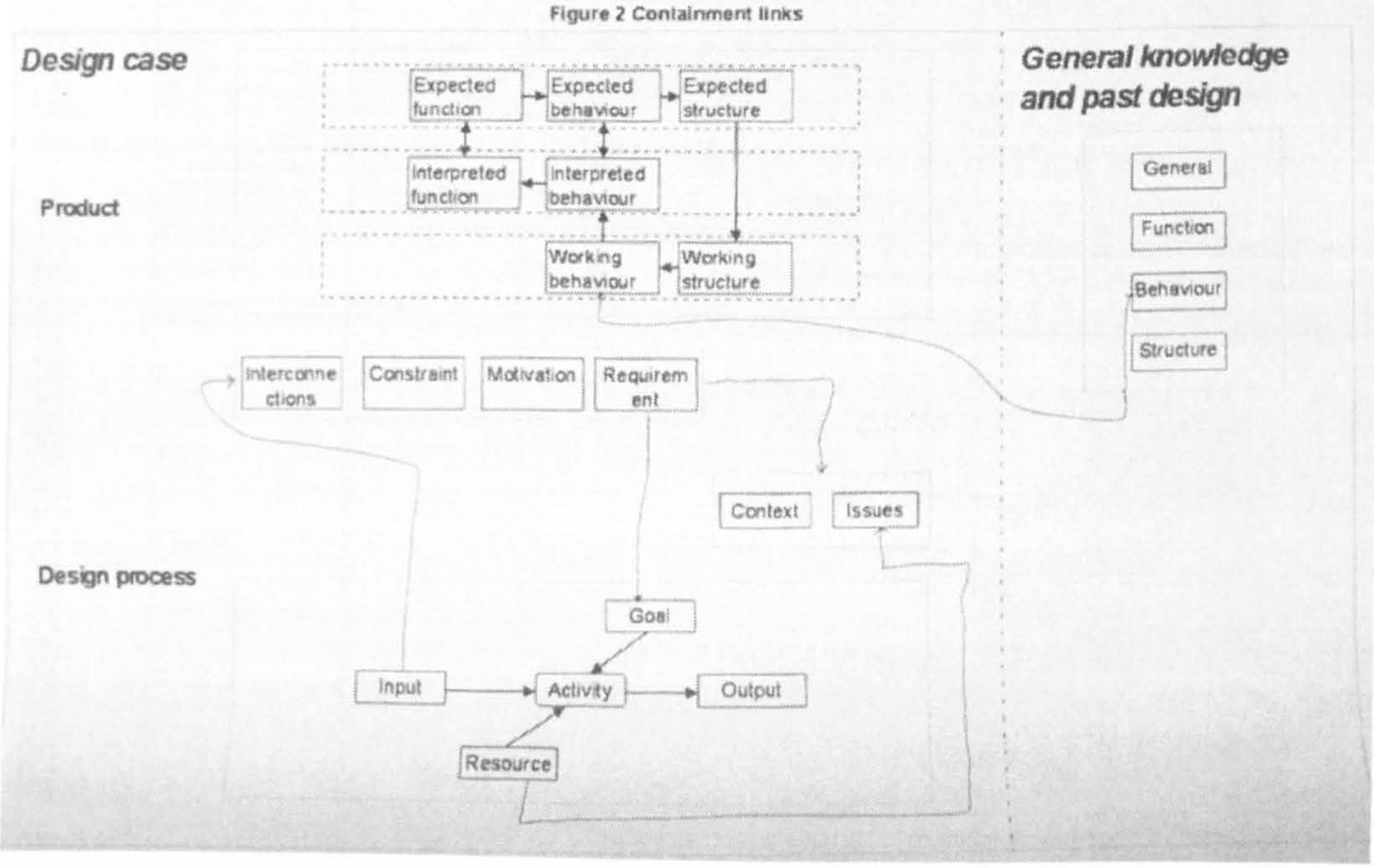
In the Figure 1, please indicate where does the "Cause-effect link of creation" exist among these elements ([A]→[B] indicates A causes the creation of B).

Figure 1 Creation links



In the Figure 2, please indicate where does the "Containment link" exist among these elements ([A]→[B] indicates A contains B).

Figure 2 Containment links



Designer 5, SFS

10 YEARS

Part I Design knowledge elements exploration

Name: Ref 5

Category	Design knowledge elements	Frequency: Never	Frequency: Occasionally	Frequency: Often	Frequency: Very often	Trend pattern (Choose A-L from Appendix, if no pattern match, please draw here): A-L	Trend pattern: Draw	Example - "Pen design"	My design project (Note down some examples for your mapping convenience) C.U.F. Project duration: 2½ hours(s)/day(s)/month(s)/year(s)
General knowledge and past design	General knowledge (General)				✓	H		Types of pen: Ballpoint, Fountain, Gel, Marker	Much reference to previous projects to draw info from ~~pre~~ lessons learnt & product successes & failures.
	Function (F)		✓			I		Writing, marking	Only some reference as new product may only share some functions with previous
	Behaviour (B)		✓			D		Ink (liquid) flow of a fountain pen	
	Structure (S)			✓		K		Clip, Cap, Nib, Body of a fountain pen	
Design case – Product	Need/Motivation (M)				✓	A		"Slipping", "Difficult to hold"	Very often as necessary to meet customers needs yet not overdesign
	Requirement (Rq)				✓	A		"Easy to hold"	
	Expected/Intended/Planned (Required) (E): Function (Fe)			✓		B		"Easy to be held"	
	Expected/Intended/Planned (Required) (E): Behaviour (Be)			✓		B		"There should be friction between pen and finger"	
	Expected/Intended/Planned (Required) (E): Structure (Se)			✓		C		"Rubber grip"	
	Actual/Working (W): Structure (Sw)			✓		E		"3D computer model" "Prototype"	
	Actual/Working (W): Behaviour (Bw)				✓	F		"Friction between rubber and finger" "Stretch and elastic"	
	Interpreted (I): Behaviour (Bi)				✓	K		"The selected material provide the friction" "Attach to the pen body"	
	Interpreted (I): Function (Fi)				✓	L		"Non-slip, easy hold"	
	F-B-S mapping, inter-connections (Ch)				✓	F		Non-slip — (Rubber) material — (Rib) texture	
	Constraint (Ctr)			✓		C		"The diameter of the rubber grip is bigger than the pen body"	
Design case – Design process	Activity (A)			✓				"Choose material" "Evaluate the pen"	level of activity increases as deadline date approach the process.
	Goal (G)			✓		L		"To find a material" "To formulate the function"	
	Input (In)		✓			I		"Material solution"	
	Output (Out)			✓		F		"Rubber grip"	
	Resource (Rs)				✓	D		"Designer", "CAD tools", "Computer" "Available materials"	More & varied resources required when the project moves out of the concept design phase
	Context (C)		✓			L		"The material solution that has been decided"	Mostly taken account of in the early stages & likely to need revisited towards stage 2.
	Issues (I)			✓		F		"Find the proper material"	Problems more prevalent in later stages following modelling, testing etc.

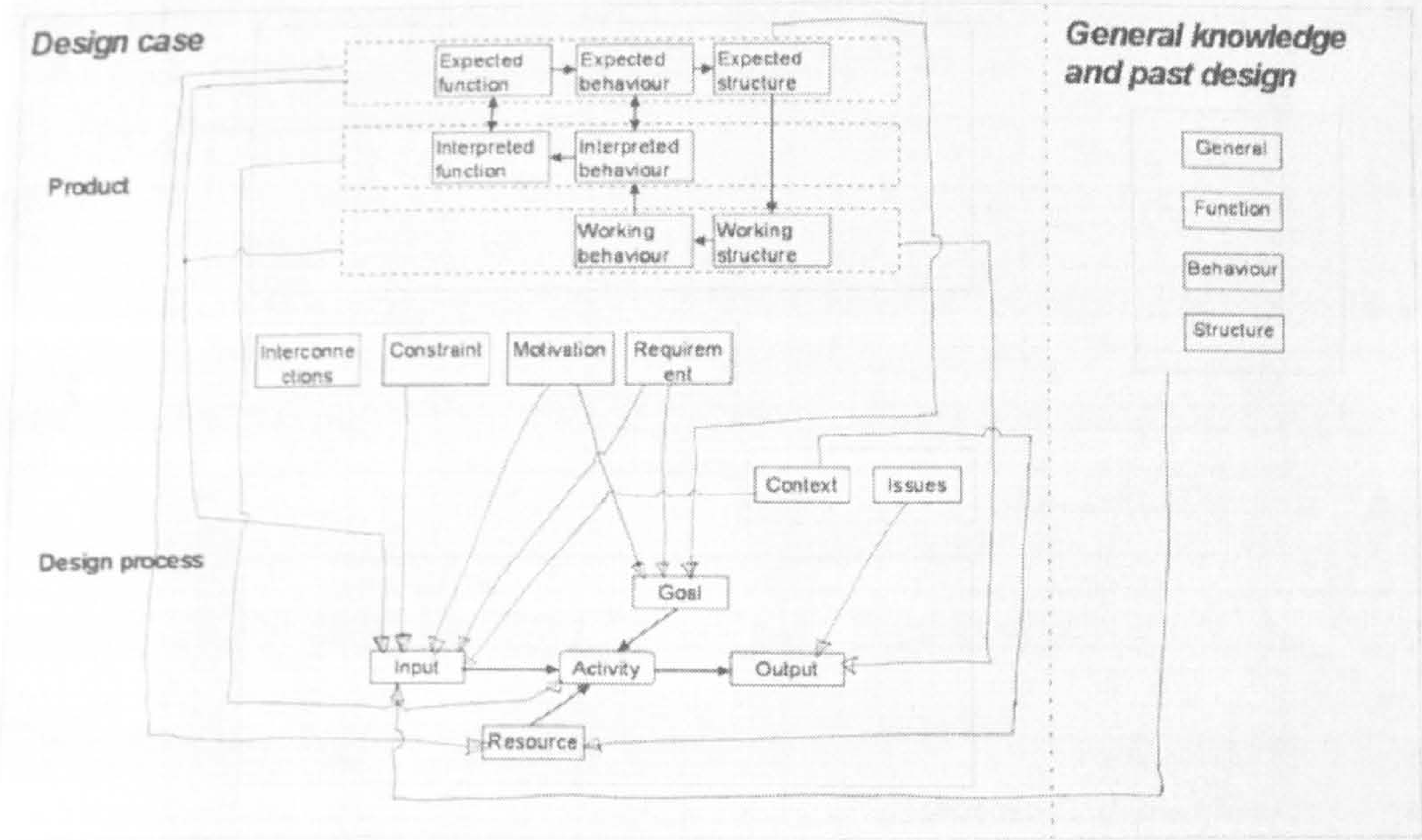
Please indicate any other elements, which were not listed here but can be recognised in your work (You can write at the back of this page)

Part II Link product with design process

Please indicate in the following two figures of the two types of links among these elements.

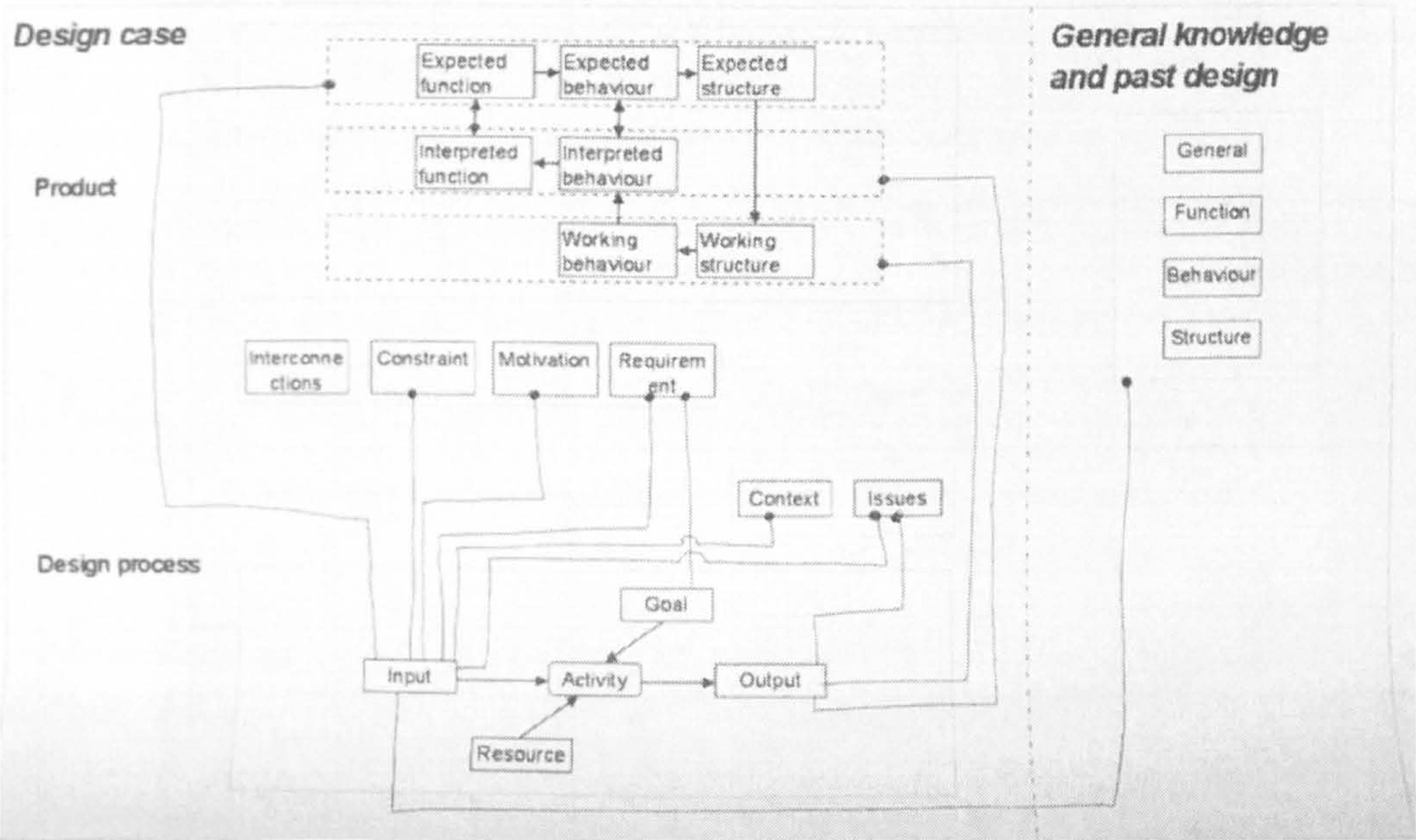
In the Figure 1, please indicate where does the "Cause-effect link of creation" exist among these elements (A → B indicates A causes the creation of B).

Figure 1 Creation links

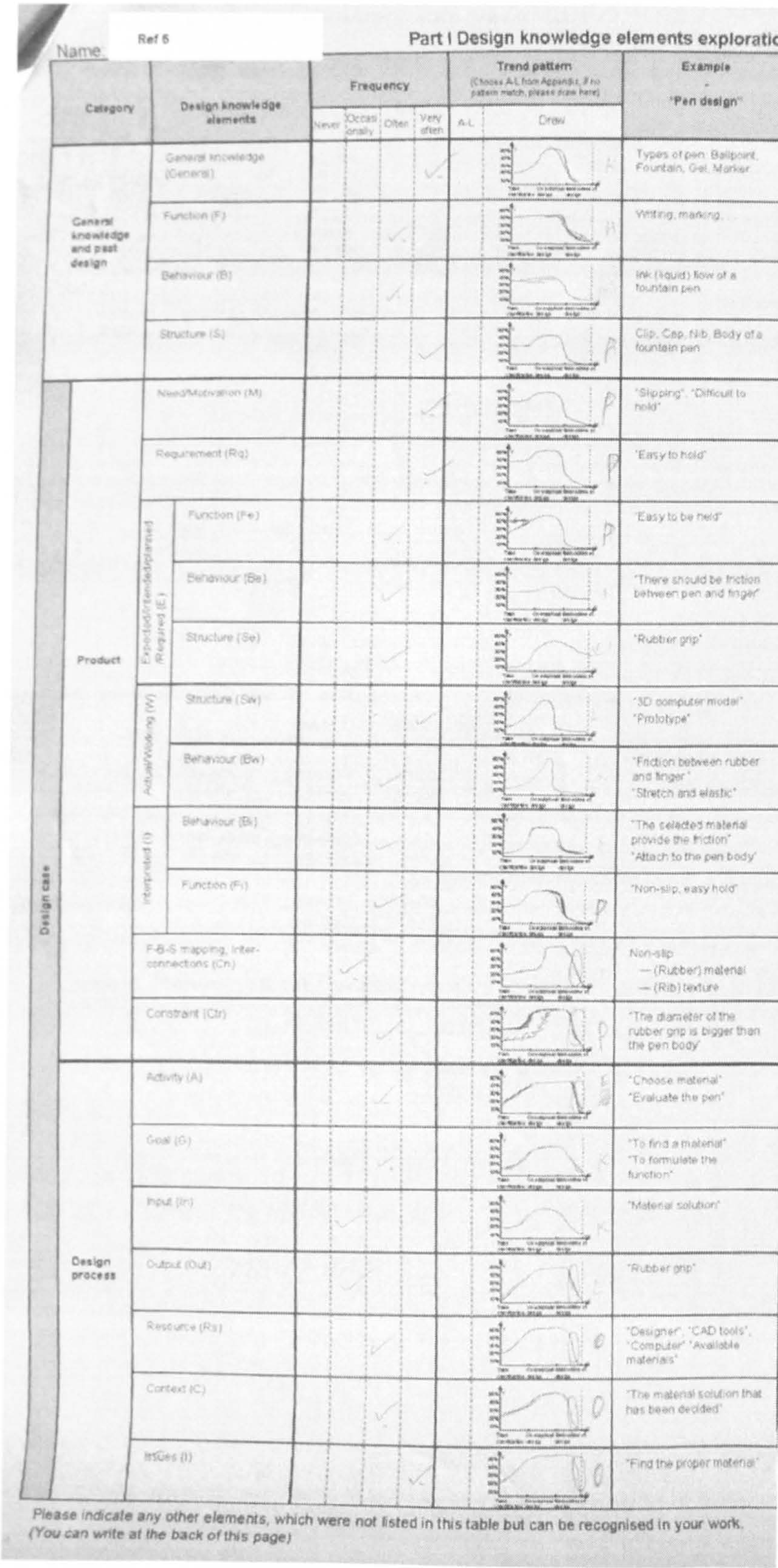


In the Figure 2, please indicate where does the "Containment link" exist among these elements (A ◆ B indicates A contains B).

Figure 2 Containment links



Designer 6, Company A



Name: Ref 6

Part I Design knowledge elements exploration

Category		Design knowledge elements	Frequency: Never	Frequency: Occasionally	Frequency: Often	Frequency: Very often	Trend pattern (Choose A-L from Appendix; if no pattern match, please draw here): A-L	Trend pattern: Draw	Example - "Pen design"
General knowledge and past design		General knowledge (General)				✓		K	Types of pen: Ballpoint, Fountain, Gel, Marker
		Function (F)			✓			H	Writing, marking.
		Behaviour (B)			✓				Ink (liquid) flow of a fountain pen
		Structure (S)				✓		P	Clip, Cap, Nib, Body of a fountain pen
Design case	Product	Need/Motivation (M)				✓		P	"Slipping", "Difficult to hold"
		Requirement (Rq)				✓		P	"Easy to hold"
	Expected/Intended/planned/Required (E)	Function (Fe)			✓			P	"Easy to be held"
		Behaviour (Be)			✓				"There should be friction between pen and finger"
		Structure (Se)			✓				"Rubber grip"
	Actual/Working (W)	Structure (Sw)				✓			"3D computer model" "Prototype"
		Behaviour (Bw)			✓				"Friction between rubber and finger" "Stretch and elastic"
	Interpreted (I)	Behaviour (Bi)			✓				"The selected material provide the friction" "Attach to the pen body"
		Function (Fi)			✓			P	"Non-slip, easy hold"
		F-B-S mapping, inter-connections (Cn)		✓					Non-slip — (Rubber) material — (Rib) texture
		Constraint (Ctr)			✓			P	"The diameter of the rubber grip is bigger than the pen body"
	Design process	Activity (A)			✓			E	"Choose material" "Evaluate the pen"
		Goal (G)			✓			K	"To find a material" "To formulate the function"
		Input (In)		✓				K	"Material solution"
		Output (Out)		✓					"Rubber grip"
		Resource (Rs)			✓			O	"Designer", "CAD tools", "Computer" "Available materials"
		Context (C)			✓			O	"The material solution that has been decided"
		Issues (I)				✓		O	"Find the proper material"

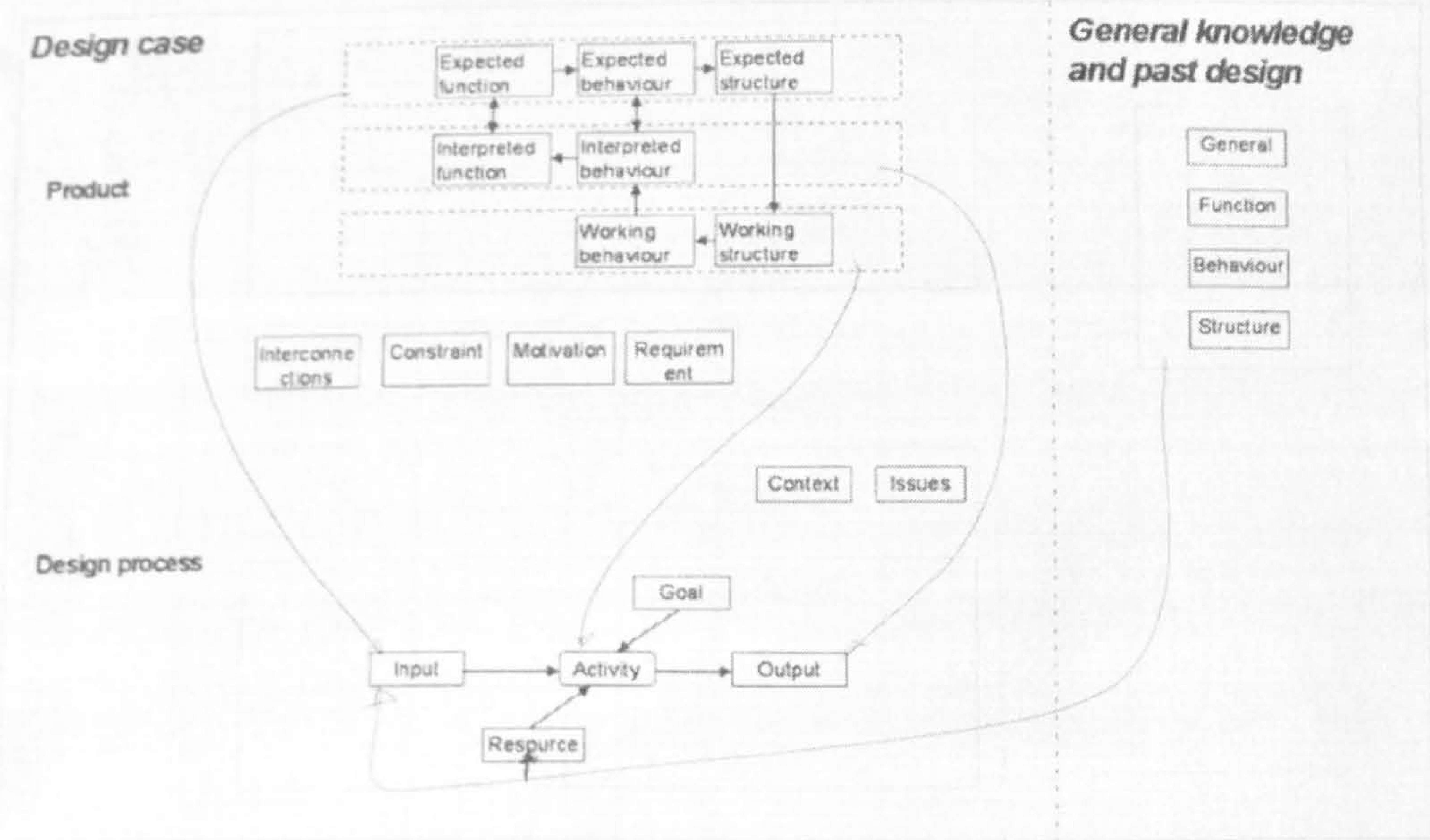
Please indicate any other elements, which were not listed in this table but can be recognised in your work. (You can write at the back of this page)

Part II Link product with design process

Please indicate in the following two figures of the two types of links among these elements.

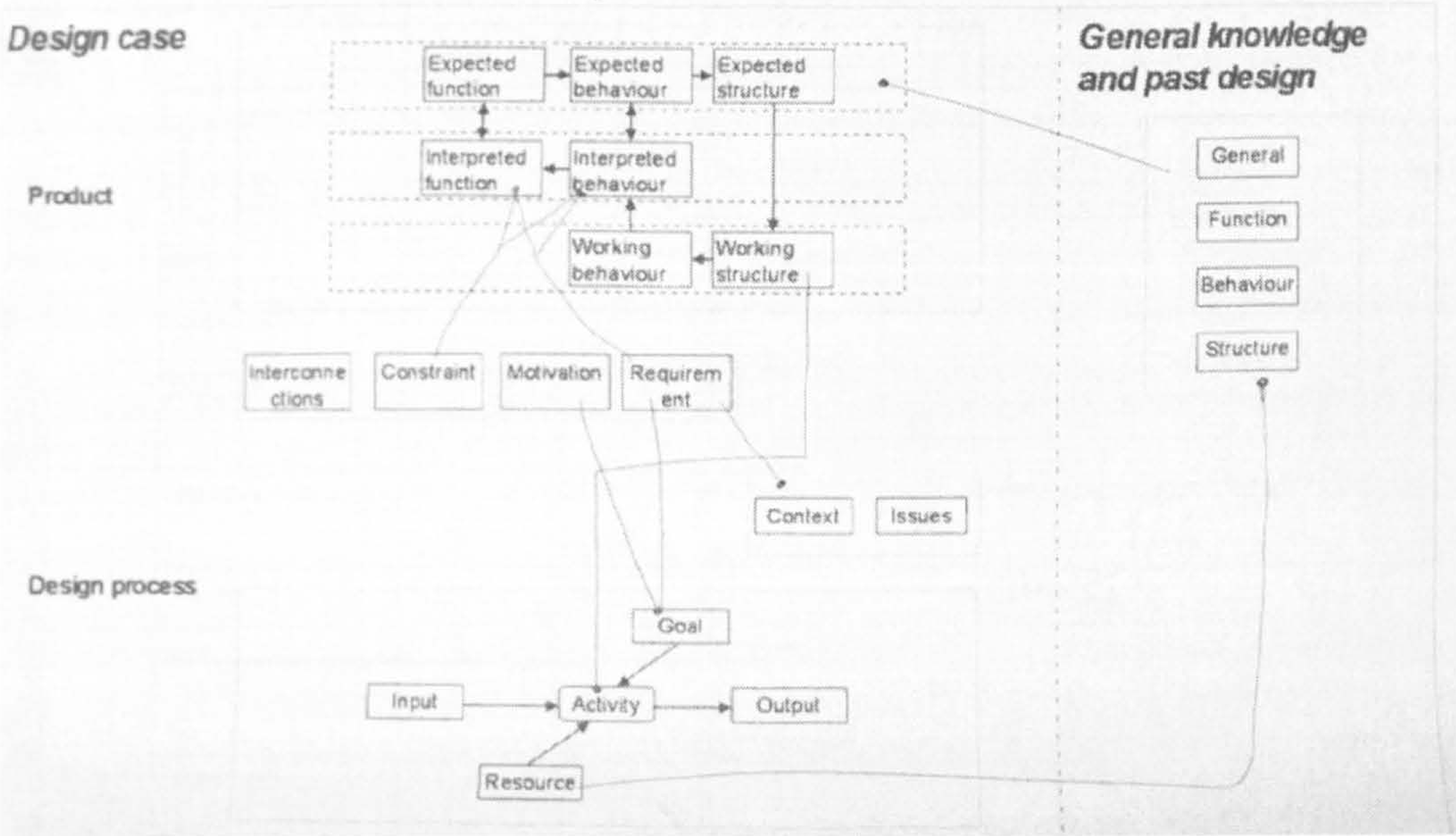
In the Figure 1, please indicate where does the "Cause-effect link of creation" exist among these elements
(A → B indicates A causes the creation of B)

Figure 1 Creation links



In the Figure 2, please indicate where does the "Containment link" exist among these elements (A ◆ B indicates A contains B).

Figure 2 Containment links



Designer 7, Company A

Name: Ref 7

Part I Design knowledge elements exploration

Category	Design knowledge elements	Frequency: Never	Frequency: Occasionally	Frequency: Often	Frequency: Very often	Trend pattern (Choose A-L from Appendix, if no pattern match, please draw here): A-L	Trend pattern: Draw	Example - "Pen design"
General knowledge and past design	General knowledge (General)			✓		H		Types of pen: Ballpoint, Fountain, Gel, Marker
	Function (F)				✓			Writing, marking
	Behaviour (B)			✓				Ink (liquid) flow of a fountain pen
	Structure (S)			✓		B		Clip, Cap, Nib, Body of a fountain pen
Design case – Product	Need/Motivation (M)				✓	A		"Slipping", "Difficult to hold"
	Requirement (Rq)			✓		G		"Easy to hold"
	Expected/Intended/planned/Required (E): Function (Fe)			✓		H		"Easy to be held"
	Expected/Intended/planned/Required (E): Behaviour (Be)		✓			G		"There should be friction between pen and finger"
	Expected/Intended/planned/Required (E): Structure (Se)				✓	A		"Rubber grip"
	Actual/Working (W): Structure (Sw)			✓		E		"3D computer model" "Prototype"
	Actual/Working (W): Behaviour (Bw)		✓					"Friction between rubber and finger" "Stretch and elastic"
	Interpreted (I): Behaviour (Bi)			✓		G		"The selected material provide the friction" "Attach to the pen body"
	Interpreted (I): Function (Fi)			V		H		"Non-slip, easy hold"
	F-B-S mapping, inter-connections (Ch)				✓			Non-slip — (Rubber) material — (Rib) texture
	Constraint (Ctr)		✓					"The diameter of the rubber grip is bigger than the pen body"
Design case – Design process	Activity (A)			✓		H		"Choose material" "Evaluate the pen"
	Goal (G)			✓		H		"To find a material" "To formulate the function"
	Input (In)				✓			"Material solution"
	Output (Out)			✓		K		"Rubber grip"
	Resource (Rs)				✓			"Designer", "CAD tools", "Computer" "Available materials"
	Context (C)			✓				"The material solution that has been decided"
	Issues (I)			✓				"Find the proper material"

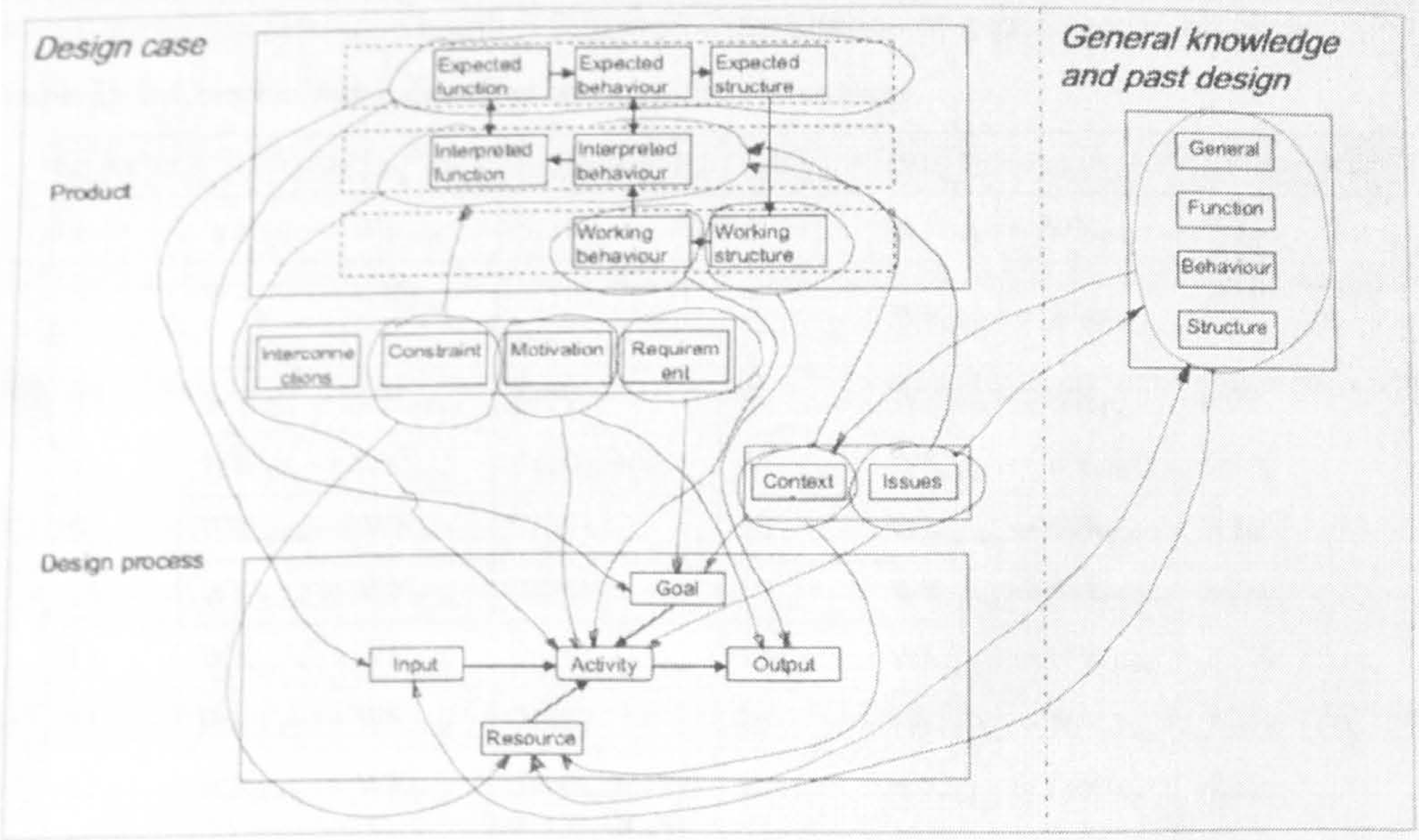
Please indicate any other elements, which were not listed in this table but can be recognised in your work. (You can write at the back of this page)

Part II Link product with design process

Please indicate in the following two figures of the two types of links among these elements.

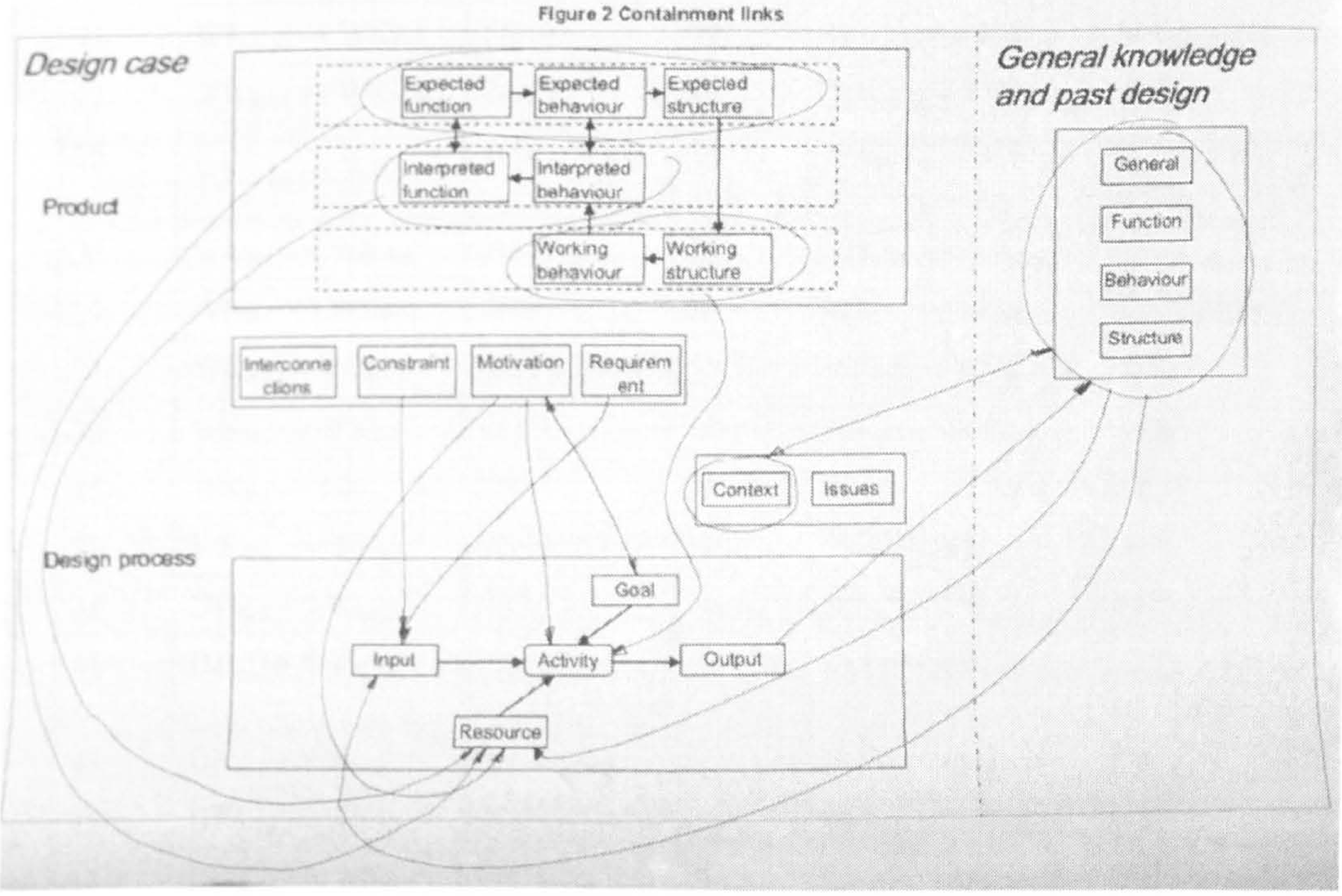
In the Figure 1, please indicate where does the "Cause-effect link of creation" exist among these elements (A → B indicates A causes the creation of B).

Figure 1 Creation links



In the Figure 2, please indicate where does the 'Containment link' exist among these elements (A ◆ B indicates A contains B).

Figure 2 Containment links



Creation links identified through the evaluation

48 creation links listed in Table H-1 were considered by designers during the evaluation as coupling links. Among them, eight were already identified through the protocol analysis and 40 were not. The 'Designers' columns show the designers identified the link, who are identified by the reference number followed with duration of experience in brackets.

Table H-1: Creation links identified through the evaluation

No.	Links	Designers	No.	Links	Designers
1	$WK_{A/E} \rightarrow WK_{P-R}$	5(10)	2	$WK_{A/E} \rightarrow WK_{P-G}$	7(35)
3	$WK_{A/E} \rightarrow WK_{P-In}$	5(10), 7(35), 6(7)	4	$WK_{A/It} \rightarrow WK_{P-A}$	5(10), 7(35)
5	$WK_{A/It} \rightarrow WK_{P-Out}$	6(7)	6	$WK_{A/Is} \rightarrow WK_{P-A}$	6(7)
7	$WK_{A/Is} \rightarrow WK_{P-In}$	5(10), 3(12)	8	$WK_{A/Is} \rightarrow WK_{P-Out}$	5(10)
9	$WK_{A-Bit} \rightarrow WK_{P-A}$	7(35)	10	$WK_{A-Se} \rightarrow WK_{P-G}$	5(10)
11	$WK_{A-Se} \rightarrow WK_{P-In}$	2(25)	12	$WK_{A-Sis} \rightarrow WK_{P-Out}$	7(35)
13	$WK_{A-CR} \rightarrow WK_{P-In}$	2(25)	14	$WK_{A-Ct} \rightarrow WK_{A-Fit}$	1(25)
15	$WK_{A-Ct} \rightarrow WK_{A/It}$	7(35)	16	$WK_{A-Ct} \rightarrow WK_{A-Rq}$	2(25)
17	$WK_{A-Ct} \rightarrow WK_{P-In}$	5(10), 4(12), 3(12), 2(25)	18	$WK_{A-Ct} \rightarrow WK_{P-R}$	7(35)
19	$WK_{A-M} \rightarrow WK_{A-Rq}$	2(25)	20	$WK_{A-M} \rightarrow WK_{P-A}$	7(35)
21	$WK_{A-M} \rightarrow WK_{P-G}$	5(10)	22	$WK_{A-M} \rightarrow WK_{P-In}$	5(10), 3(12)
23	$WK_{A-M} \rightarrow WK_{P-Out}$	7(35)	24	$WK_{A-Rq} \rightarrow WK_{A-Fe}$	2(25)
25	$WK_{A-Rq} \rightarrow WK_{P-G}$	5(10), 7(35)	26	$WK_{A-Rq} \rightarrow WK_{P-In}$	5(10), 3(12), 1(25)
27	$WK_{P-C} \rightarrow WK_{A/It}$	7(35)	28	$WK_{P-C} \rightarrow WK_{P-G}$	7(35)
29	$WK_{P-C} \rightarrow WK_{P-In}$	5(10)	30	$WK_{P-C} \rightarrow WK_{P-R}$	5(10), 7(35)
31	$WK_{P-I} \rightarrow WK_{P-A}$	2(25), 7(35)	32	$WK_{P-I} \rightarrow WK_{P-G}$	2(25)
33	$WK_{P-I} \rightarrow WK_{P-In}$	7(35)	34	$WK_{P-I} \rightarrow WK_{P-Out}$	5(10)
35	$WK_{P-I} \rightarrow DK_{A}$	7(35)	36	$WK_{P/C} \rightarrow WK_{P-In}$	3(12)
37	$WK_{P/C} \rightarrow WK_{P-R}$	4(12), 3(12)	38	$DK_{A} \rightarrow WK_{A}$	4(12)
39	$DK_{A} \rightarrow WK_{A-CR}$	2(25)	40	$DK_{A} \rightarrow WK_{A-M}$	2(25)
41	$DK_{A} \rightarrow WK_{A-Bit}$	1(25)	42	$DK_{A} \rightarrow WK_{P-In}$	5(10), 3(12), 7(35), 6(7)
43	$DK_{A} \rightarrow WK_{P-R}$	3(12), 6(7)	44	$DK_{A} \rightarrow WK_{P-C}$	7(35)
45	$DK_{A-G} \rightarrow WK_{P-I}$	2(25)	46	$DK_{A-Fit} \rightarrow WK_{P-C}$	2(25)
47	$DK_{A-Bit} \rightarrow WK_{P-C}$	2(25)	48	$DK_{A-Sis} \rightarrow WK_{P-C}$	2(25)

Employment links identified through the evaluation

42 employment links were considered by designers during the evaluation as coupling links that are shown in Table H-2. Among them, eight were already identified through the protocol

analysis. The 'Designers' columns show the designers identified the link, who are identified by the reference number followed with duration of experience in brackets.

Table H-2: Employment links identified through the evaluation

No.	Links	Designers	No.	Links	Designers
1	WK_{A-Brt} —● DK_{A}	1(25)	2	WK_{A-Fit} —● WK_{A-Ct}	1(25)
3	WK_{A-CR} —● DK_{A}	2(25)	4	WK_{A-Ct} —● DK_{A}	2(25)
5	WK_{A-Ct} —● $WK_{A/It}$	6(7)	6	WK_{A-M} —● DK_{A}	2(25)
7	WK_{A-M} —● WK_{P-G}	6(7)	8	WK_{A-Rq} —● WK_{A-Fe}	1(25)
9	WK_{A-Rq} —● $WK_{A/It}$	6(7)	10	WK_{A-Rq} —● WK_{A-Ct}	2(25)
11	WK_{A-Rq} —● WK_{A-M}	2(25)	12	WK_{A-Rq} —● WK_{P-G}	6(7)
13	WK_{A-Rq} —● $WK_{P/C}$	6(7)	14	WK_{A-Rq} —● WK_{P-C}	4(12)
15	WK_{A-Sis} —● WK_{P-A}	6(7)	16	WK_{P-A} —● $WK_{A/Is}$	7(35)
17	WK_{P-A} —● WK_{A-M}	7(35)	18	WK_{P-A} —● WK_{P-I}	2(25)
19	WK_{P-G} —● WK_{A-Brt}	2(25)	20	WK_{P-G} —● WK_{A-M}	7(35)
21	WK_{P-G} —● WK_{A-Rq}	4(12)	22	WK_{P-In} —● DK_{A}	5(10), 3(12), 7(35)
23	WK_{P-In} —● $WK_{A/E}$	5(10)	24	WK_{P-In} —● $WK_{A/Is}$	3(12)
25	WK_{P-In} —● WK_{A-M}	5(10), 3(12)	26	WK_{P-In} —● WK_{A-Rq}	5(10), 3(12), 7(35)
27	WK_{P-In} —● WK_{A-CR}	4(12)	28	WK_{P-In} —● WK_{A-Ct}	5(10), 3(12), 2(25), 7(35)
29	WK_{P-In} —● $WK_{P/C}$	5(10), 3(12)	30	WK_{P-Out} —● DK_{A}	7(35)
31	WK_{P-Out} —● $WK_{A/It}$	5(10), 2(25)	32	WK_{P-Out} —● $WK_{A/Is}$	5(10)
33	WK_{P-Out} —● WK_{P-I}	5(10), 1(25)	34	WK_{P-R} —● DK_{A}	3(12), 2(25), 1(25), 7(35), 6(7)
35	WK_{P-R} —● $WK_{A/E}$	7(35)	36	WK_{P-R} —● $WK_{A/It}$	7(35)
37	WK_{P-R} —● WK_{A-M}	7(35)	38	WK_{P-R} —● $WK_{P/C}$	3(12)
39	WK_{P-R} —● WK_{P-I}	4(12)	40	WK_{P-C} —● DK_{A}	2(25), 7(35)
41	DK_{A-Brt} —● WK_{A-Brt}	4(12)	42	DK_{A} —● $WK_{A/E}$	6(7)