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A TRIANGULATION APPROACH FOR DESIGN RESEARCH

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ABSTRACT
Triangulation has been adopted in social science in the study of the same phenomenon through applying and combining several data sources, research methods, investigators, and theoretical schemes. From a post-positivism view point, this paper presents a triangulation approach in design research from two perspectives, data sources and research methods. Data triangulation was achieved through collecting data from multiple sources including company design documents, student design projects, and company design projects. Different research methods, e.g. interview, content analysis, protocol analysis, and questionnaire, were used to conduct data collection and analysis into a particular aspect of design, the nature of coupling design artefact and process knowledge. The paper presents the methods used and concludes that triangulation can provide an effective means for design research.

Keywords: Design research, research methodology, triangulation, research philosophy, post-positivism

1 INTRODUCTION
Since its recognition in the 1950s [1], post-positivism has provided an alternative to the traditional positivism approach for conducting disciplined inquiry. Positivism is a philosophy that regards objective reality as existing while being independent of human being's thought and behaviour [2]. People who hold this philosophy, i.e., positivists, believe that science should study only those aspects of the world which we can be positive (certain) about. However, 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" [3]. In contrast, post-positivist researchers believe that reality is closely related to the mind of a human being [3]. As one of the most common forms of post-positivism, critical realism holds this understanding of reality: *There is a "real world" independent of the human mind, which is driven by natural causes and can be studied by science* [4]. *However, people have different perspectives towards such a "real" or physical world. Hence, there could be various constructions of reality depending on its different contexts.* From a post-positivism view, all observations are therefore fallible and have error, and all theories are revisable. Human beings are unable to know the true reality with certainty. Despite their tendency to objectivity, post-positivists believe that knowledge and facts are subjective [2]. Believed to being able to better represent the world where human beings exist, post-positivism has been used pervasively by researchers in human centred research, such as social science [2, 5]. Because of the characteristics of post-positivism, i.e., all observations are fallible and knowledge of facts is subjective, attention has been given to the use of triangulation to strengthen the validity and reliability of research.
In navigation, surveying, and military strategy, triangulation refers to measurement by using triangles. It is defined in the book of Plane and geodetic surveying as:

> *Triangulation is the method of location of a point from two others of known distance apart, given the angles of the triangle formed by the three points [6, p 145].*

Hence if the absolute positions of two reference points are known, that of the third point can also be determined, given relative angles [6]. Triangulation has been adopted in social research as a research framework for over five decades [7]. Despite being endowed with different metaphors [8], it has been mostly interpreted as the study of the same phenomenon through applying and combining different data and methods [9]. Though bearing some debate [8], it has proven of value in research where different methods might reveal different aspects of the same empirical event [10].

Much of the nature of design research is similar to cognitive psychology or sociology due to involvement of people, society and organisations [11]. Accordingly, there has been a growing appreciation that designing is a social process. For example, Bender et al. [12], Cross and Cross [13], and Horvath [14], amongst others, have identified that the research methods used in social sciences should also be taken into account in design research. Due to the often social nature of design research, to take account of the human elements and their behaviour in design, a post-positivism triangulation approach was adopted for a research project (reported in this paper) to model the nature of evolutionary artefact and design process knowledge coupling. This paper presents the approach and shows how a methodology in social science could be applied in design research.

Denzin [9, p301] proposed that research could be triangulated in terms of data, investigator, theory, and methodological. *Data triangulation* refers to the need to retrieve data from a number of different sources with similar foci for the purpose of validation. *Investigator triangulation* involves the use of a number of investigators to observe the same problem, thus attempting to ensure objectivity and avoid bias. Moreover, *theory triangulation* is the use of multiple perspectives to interpret a single set of data, or provide alternative explanations for the same phenomenon. Finally, *methodological triangulation* is the use of multiple methods, which can be either "within-method" or "between-method". The former involves the same method being used on different occasions, and the latter uses different methods with the same object of study. Within the study reported in this paper, data and between-method triangulation was adopted. Specifically, 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.

The choice of data sources and methods depends on many factors, in particular, the nature of the research being undertaken. In the interest of the research undertaken, the nature of the coupling, the following issues were considered for building the research methodology in order to develop a coupling model:

1. What has been done by former researchers on this research topic?
2. Does industry have any problems related with this topic?
3. What kind of data is required to explore the coupling?
4. How to develop the model so that it is based on both theoretical analysis and empirical study?
5. How to develop the model so that it is a good reflection on the nature of the coupling?
6. 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 data sources and research methods. To illustrate the use of the methodology adopted in the research, the following two sections address the above questions by describing how the triangulation was conducted in terms of data sources and research methods. Section 4 discusses the application of the approach and section 5 gives a concluding remark to the paper.

2 DATA TRIANGULATION

Research based on only one single source of data has lower reliability. Errors might occur in the process of data production and processing. Different types of data are inclined to have different types of errors [15]. However, if the same result is obtained from different sources of data, people are likely to have more confidence in the result. To minimise errors, data triangulation retrieves data from a number of different sources with similar foci for the purpose of validation. Three main sources of data were used in the coupling research to determine and model its nature, in addition to three data sources used to define the research problem.

To find out what has been done by former researchers on the research topic, literature from previous research was used for an initial understanding of the coupling of design knowledge.

In order to identify whether industry has any problems regarding the research problem, questionnaire results from a workshop in June 2004 in Company A [1] that was intended to identify the opportunities, drivers, and problems of Product Lifecycle Management (PLM) were analysed. In addition, viewpoints and opinions were collected from designers during a follow-up extended visit , which identified further issues encountered by the company relating to the coupling of artefact and design process knowledge.

[1] Identification withheld to maintain confidentiality.

To explore the coupling, for the purpose of collecting related data from different sources for validation, it was decided to collect data from company documents, student design projects, and company designers/projects. To this end, design related documents were collected, protocols from a supervised student design project were transcribed, and questionnaires were answered by eight designers regarding their participation in design projects.

Design is an 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 design data from Company A and design projects from educational (student) projects were studied. This, in turn, resulted in an evolved model that can benefit from both theory and empirical input. The company information was based on a number of design related documents collected from Company A, when one of the authors participated in the development of a Product Lifecycle Management (PLM) project within the company, from July 2004 to April 2005, and was actively engaged to support, analyse, and develop their strategic PLM system. 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 was collected from different environments, which covered different categories of design, such as by individual (student projects) and group (company projects), in academia (student projects) and industry (company projects), as well as by both experienced designers (company projects) and novices (student projects).

To evaluate the research, following the development of the coupling model, it was, in turn, evaluated against eight designers' views collected through two workshops conducted in Company A and BAE Systems Surface Fleet Solutions Limited (SFS), based on design projects they had participated in.

In short, 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 the three main data sources are summarised in Table 1.

Table 1: Main data sources of the research

	Company A design documents	Undergraduate students design projects	SFS design projects
Commercial	Yes	No	Yes
Group work	Yes	No	Yes
Design scale	Large	Small	Large
Distributed	Yes	No	Yes
Formal	Yes	No	Yes
Designers	N/A	Novice	Experienced
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

This section briefly lists the data triangulation used in the research. How they were analysed is presented in more detail in the following section along with a description of the research methods adopted.

3 BETWEEN-METHOD TRIANGULATION

From a post-positivism viewpoint, all research methods are biased and different methods reveal different aspects of the same reality [9]. Hence the result obtained from different research methods can increase its reliability. Between-method triangulation is to use different methods in studying the same phenomenon. Four different methods were adopted in the design research towards the coupling of the artefact and design process knowledge: literature review, interview, content analysis, and protocol analysis. The former two were used to identify the research problem and the latter two were adopted to analyse and solve the research problem. These methods are described in the following sub-sections.

3.1 Literature review

In order to obtain an initial understanding of the domain of design knowledge, literature was reviewed in the domain of engineering design knowledge. In terms of knowledge elements involved in the coupling, the review resulted in the identification of seven fundamental and four contextual artefact, and five fundamental and two contextual design process knowledge elements [16]. In terms of coupling, the research gap was then identified through analysing state of the art research related to the relationships among the artefact and design process knowledge elements. The review mainly focused on three main research categories, which included research on the relationship between: 1) artefact and artefact, 2) process and process, and 3) artefact and design process. The research focus was derived based on the review, i.e. to explore the nature of the coupling of evolutionary artefact and design process knowledge.

3.2 Interview

During the visit to Company A three designers were interviewed in order to identify whether industry had encountered any problems related to the coupling. Through the interview, problems concerning the integration of the artefact and design process were raised. The main problems were caused by the lack of change propagation, as considerable changes were made to the artefact as well as its related design process throughout designing that weren't appropriately managed. Problems arising during the interview 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 revealed insufficient knowledge of the relationships between the artefact and the design process in industry. Consequently, 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 the nature of their coupling needs to be understood.

3.3 Content analysis[2]

Content analysis is a method for analysing the content of communications, such as books, paintings, and documents, in their context [17], through which the characteristics of messages are identified objectively and systematically [18]. 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.
- The documents could include either information that describe the entire artefact, or those that describe specific components of the artefact.

The eight analysed documents were numbered 1 to 8 sequentially as listed in Table 2. Among them, the first three documents are in the context of product lifecycle management. Document 4 describes artefact knowledge through 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 to study the coupling [16]. Table 2 lists the eight documents giving a reference number, document title, pages, created date, focus, and covered design phases.

[2] The coding (including the knowledge elements and coupling links) presented in this paper are only intended to show readers how the content and protocol analysis were conducted in the research.

Table 2: 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

In order to obtain an initial insight to 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:
Current Working Knowledge (WK) or Domain Knowledge (DK) elements, identified through the literature review, were used as the basis for analysis, which included: Expected behaviour (B_e), Instantiated behaviour (B_{ts}), 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 [16]. Although these terms were not explicitly used in the documents, specific key words in the documents were analysed that reflected these elements. The key words were then extracted from each document.

Step 2:
After the knowledge elements were identified, 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 or utilises the other [16]. These links were found, through this initial analysis, to be the basic types of links that constitute the coupling of the artefact and design process. Within each document, these two types of links were identified between a number of artefact and design process knowledge elements. A full description of the identified links from all the eight documents can be found in [16].
As the result of the content analysis, 6 creation and 15 employment links were identified between the artefact and design process knowledge, which composed the initial coupling model [16].

3.4 Protocol analysis

One frequently used method to understand complex cognitive processes is to explore the subjects' internal states by verbal methods [19], which is termed 'protocol analysis' [20]. 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 [21], such as design activity [22], design artefact function evolution [23], design decisions [24], and learning in design [25, 26].
Protocols of seven undergraduate student design projects were recorded in the Department of Design, Manufacture and Engineering Management (DMEM), University of Strathclyde, from September 2005 to May 2006. The supervision meetings of the projects were recorded between the students and their supervisor until the students finished building the prototypes of their designs. Of the seven recorded projects, one was studied in detail 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" [27]. The project was the redesign of pedestrian barriers, in which a modular barrier system for ease of replacement was designed for different society environments. A concept of a "Locktab mechanism" 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" was filed for a British patent POST INSTALLATION (application filing number: 0613906.7).

To explore the coupling of the artefact and design process over task clarification (7th Oct - 4th Nov 2005), conceptual (18th Nov - 2nd Dec 2005), and embodiment design (10th - 24th Mar 2006), 12 sessions that covered the three phases of the project were analysed. The division of the three design phases was based on the authors' interpretation of the transcription, and was confirmed by the student designer. Following transcription of the audio recordings to raw protocols, Gero's protocol analysis approach [21] was adopted for segmentation, coding, analysis, and interpretation of the data. Each of these stages is briefly explained as follows.

Segmentation

To facilitate the analysis process, protocols can be segmented differently depending on the purpose of the analysis. For example, Gero and McNeill [21] used change of designer's intention to segment the protocols in their investigation of how designers design. The purpose of the research was to explore the coupling between artefact and design process knowledge. As such, it was intended to segment the protocols through focussing 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 the design process. It was therefore decided that the protocols were segmented semantically according to discussion topics. That is, a 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 the time-based analysis presented in [16] shows, segmenting protocols semantically by discussion topics did not affect the analysis result,.

Coding scheme

Protocol data can provide a deep insight into designing from various viewpoints depending on the focus of the research. For researchers, however, it is the knowledge structure of the protocol that is of most import, rather than the protocol and the transcripts themselves. 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 was necessary. Based on the literature review, content analysis, 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, seven types of current working knowledge of design artefact, four types of contextual current working artefact knowledge, five types of current working knowledge of design process, and two types of current working design process contextual knowledge were considered to be the main elements that are involved in the coupling. The 22 elements and their associated codes are listed in Table 3.

Table 3: 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 (B_{it})
	$DK_{A\text{-}Fit}$	Interpreted artefact function (F_{it})
	$DK_{A\text{-}Sis}$	Instantiated artefact structure (S_{is})
Fundamental Current Working Artefact Knowledge ($WK_{A/F}$)	$WK_{A\text{-}Be}$	Expected artefact behaviour (B_e)
	$WK_{A\text{-}Bis}$	Instantiated artefact behaviour (B_{is})
	$WK_{A\text{-}Bit}$	Interpreted artefact behaviour (B_{it})
	$WK_{A\text{-}Fe}$	Expected artefact function (F_e)
	$WK_{A\text{-}Fit}$	Interpreted artefact function (F_{it})
	$WK_{A\text{-}Se}$	Expected artefact structure (S_e)

	$WK_{A\text{-}Sis}$	Instantiated artefact structure (S_{is})
Contextual Current Working Artefact Knowledge ($WK_{A/C}$)	$WK_{A\text{-}CR}$	Causal relationship (CR)
	$WK_{A\text{-}Ct}$	Artefact constraint (Ct)
	$WK_{A\text{-}M}$	Design motivation (M)
	$WK_{A\text{-}Rq}$	Artefact requirement (Rq)
Fundamental Current Working Design Process Knowledge ($WK_{P/F}$)	$WK_{P\text{-}A}$	Design activity (A)
	$WK_{P\text{-}G}$	Design goal (G)
	$WK_{P\text{-}In}$	Activity input (In)
	$WK_{P\text{-}Out}$	Activity output (Out)
	$WK_{P\text{-}R}$	Design resource (R)
Contextual Current Working Design Process Knowledge ($WK_{P/C}$)	$WK_{P\text{-}C}$	Design context (C)
	$WK_{P\text{-}I}$	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* and *link of employment* have already been identified 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 4 gives further explanations and representations of the five types of links used in the protocol analysis. Though the *link of employment* identified through content analysis was not used in the protocol analysis, it was found that it has close affinity with these four basic types of links, and employment links can be deduced from these four types.

Table 4: The coding scheme of five types of links

Link type	Representation	Explanation
Cause-effect link of creation	A ⟶ B	Element A causes creation or occurrence of element B.
Link of employment	A - - - -● B	Element A employs 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 knowledge elements involved in the coupling. Meanwhile, the four types of links between these elements were identified and encoded. The full version of encoded knowledge elements and their associated links can be found in a report [28].

Analysis and interpretation

The analyses were conducted in Microsoft Excel 2003. The occurrences of the four types of links over the 12 sessions were analysed in order to reveal the coupling model. 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 considered as *links of employment*. Moreover, some of employment links could also be deduced from some 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 link. As a result of the protocol analysis, 18 creation and 15 employment links were identified.

Combining with the creation (CL-C) and employment links of the coupling (EL-C) identified from the content analysis, the evolved coupling model was then derived, which is composed of 19 creation (CL) and 17 employment links of the coupling (EL) [16].

3.5 Workshop and questionnaire

In order to evaluate the research, a questionnaire was used by engineering designers. The questionnaire is composed of two parts: ‘Design knowledge elements exploration’ and ‘Link product with design process’. In the first part, designers were asked to select the knowledge elements’ occurrence frequency during design development from "Never", "Occasionally", "Often", and "Very often". In addition, they were also asked to choose or draw occurrence pattern of each elements over task clarification, conceptual, and embodiment design phases. In the second part, designers were then asked to draw all the possible creation and employment links between knowledge elements.

Two workshops were organised on the 4th and 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 participating. Table 5 summarises the profile of the eight designers who participated in the workshops. 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. Moreover, the designers' experiences ranged from 0.5 year to 35 years.

Table 5: 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
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

Due to several inconsistencies within the results given by designer 8 and their relative inexperience, to minimise the impact of such inconsistency on the validity of the evaluation, the questionnaires answered by designers 1 to 7 were used as the basis and main source of the evaluation.

Through the evaluation, it was found that the designers had a diversity of views among themselves of not only the occurrence trend of knowledge elements, but also the coupling links of the artefact and design process. Moreover, their views also show differences between the results obtained from the analysis. Specifically, the seven designers have at least four different views of each element's occurrence trend. Of the 22 elements, 2 were viewed with the same occurrence trend as that obtained from the protocol analysis, while 7 were viewed with similar, and 13 were viewed with different trends. The evaluation resulted in 48 creation and 42 employment links, of which 9 creation and 12 employment links were identified from the analysis. The difference between the results obtained from analysis and evaluation could be explained in terms of the limited duration of the evaluation workshops, the difference between student and commercial design projects as well as individual and collaborative design projects. The designers' diversity of views might be caused by a number of factors, such as the designers' different design experiences, different product focus, different projects used for the evaluation, as well as their different understanding of the knowledge elements and links.

4 DISCUSSION

Error! Reference source not found. summarises the two aspects of triangulation adopted, and Figure 2 shows how the research methods contributed to the research in the nature of the coupling.

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)

Between-method triangulation
- Literature review
- Interview (Company A)
- Content analysis (Company A)
- Protocol analysis (University of Strathclyde)
- Workshop and questionnaire (Company A and SFS)

Figure 1: Triangulation research of artefact and design process coupling

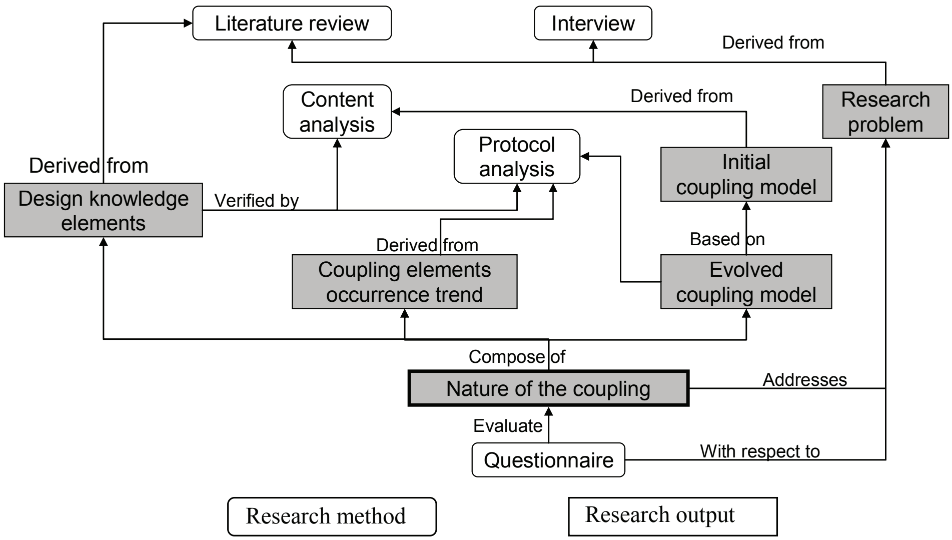

Figure 2: Research structure of artefact and design process coupling

The triangulation approach has been adopted throughout the research of "The nature of evolutionary artefact and design process knowledge coupling", which helped the authors deliver a comparatively representative and reflective coupling model by using multiple data sources and research methods.

The data triangulation ensures that not only company practise but also empirical design data were used in analysing the research problem. The between-method triangulation ensures that the coupling not only applies to the scenario of individual design by a 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 content and protocol analysis.

Though triangulation provided the aforementioned strengths, it was limited by the time permitted for conducting the research. For example, only protocol of one project was transcribed and analysed among the seven recorded design projects. In addition, the length of the research also constrained the research from analysing protocols of an industrial design case, which can last several or tens of years. Moreover, *investigator triangulation* was not adopted due to the nature of the research. However, it is hypothesised that such adoption could have contributed to the completeness and conformation of the research.

Overall, the triangulation approach showed advantages in the research, as it provided the authors with multiple perspectives of the phenomenon under consideration and minimised potential errors from using a single data source or research method. The work illustrates that the approach has potential in providing more objective and comprehensive research results and could be more widely used in the area of design research.

5 CONCLUSION

From a post-positivism view point, this paper presented a triangulation approach in design research towards the nature of evolutionary artefact and design process knowledge coupling. Two aspects of triangulation were adopted in the research, i.e, data sources and research methods. Research data was collected from multiple sources, which included company design documents, student design projects, and company design projects. Different research methods, e.g. interview, content analysis, protocol analysis, and questionnaire, were adopted to carry out data collection and analysis, to investigate the nature of the coupling. The literature review and interview helped the authors identify the research problem. Content analysis and protocol analysis resulted in 22 coupling design knowledge elements, their occurrence trend during task clarification, conceptual and embodiment design, and an evolved coupling model. The coupling was then evaluated through a questionnaire answered by eight practising designers during two workshops.

The approach helped the authors deliver a comparatively representative and reflective coupling model by using multiple data sources and research methods. The data triangulation ensures that not only company practise but also empirical design data were used in analysing the research problem. The between-method triangulation ensures that the coupling not only applies to the scenario of individual design by a novice designer, but also collaborative design by experienced designers.

The work conducted has shown that the triangulation approach has significant potential to provide design researchers with more objective and comprehensive research results and could be more widely applied within the field.

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