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THE DESIGN RESEARCH PYRAMID: A THREE LAYER FRAMEWORK

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ABSTRACT
To support knowledge-based design development, considerable research has been conducted from various perspectives at different levels. The research on knowledge-based design support systems, generic design artefact and design process modelling, and the inherent quality of design knowledge itself are some examples of these perspectives. The structure underneath the research is not a disparate one but ordered. This paper provides an overview of some ontologies of design knowledge and a layered research framework of knowledge-based engineering design support. Three layers of research are clarified in this pattern: knowledge ontology, design knowledge model, and application. Specifically, the paper highlights ontologies of design knowledge by giving a set of classifications of design knowledge from different points of view. Within the discussion of design knowledge content ontology, two topologies, i.e., ideology and evolutionary, are identified.

Keywords: Research framework, Knowledge-based design support systems, Design knowledge

1 INTRODUCTION

Designing is one of the most intelligent and complex human activities. The research in this area, engineering design research, is to explore, describe, arrange, rationalise, and utilise design knowledge [1]. 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) [2], generic design artefact or process modelling [3-7], and the inherent quality of design knowledge itself [8-10] represent some of the previous work which 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 which can be regarded as a foundation for KBDSSs research. This pattern is presented as design research pyramid in this paper, of which a three-layer research framework lays underneath the various research.

In this three-layer framework, design knowledge builds the ontology basis, providing support for 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. By presenting this research pyramid, this paper emphasises the knowledge ontologies in design, which provide an overview of different knowledge classifications. Specifically, the paper presents two topologies of design knowledge, i.e., ideology and evolutionary. They reveal the supportive and evolutionary relationships among design artefact, design process, design management, and design supplementary knowledge, which is a classification based on design knowledge content. The research not only provides support for knowledge-based design support system development, but also clarifies the framework of the research in this area.

To reveal this framework, the following sections cover the research conducted in each layer of the pyramid, as well as the research pattern underneath them. Section 2 presents the research in KBDSSs. Design knowledge modelling research is described in section 3. In section 4 the existing ontology of design knowledge is described. Finally, the research framework presented as the layered pyramid model is given in section 5.

2 KNOWLEDGE-BASED DESIGN SUPPORT SYSTEMS

To support design development, a number of KBDSSs have been developed, of which a knowledge base is associated with storing knowledge to support design development more efficiently and effectively through numerous applications. In this respect, C3 [11], DeNote [12], DRed [13], Function-based design synthesis approach [14], and PDCS [15], among others, are examples of KBDSSs.

There are two categories of design support system (DSS) that reflect two extremes of the philosophy concerning their role in design [16], i.e., automated design systems and design assistant systems. While the former considers a DSS to be a designers' substitute and could conduct designing independently once it is input design requirements, the later considers it to be a designers' subordinate, which means DSS could not completely substitute designers, but just support designers with its fast reliable computing and massive storage capacity.

A closer look at the aforementioned systems shows that they were developed to support one specific type of design or one, as opposed to all, of the design phases, thereby solving one type of design problem. For example, Function-based design synthesis approach and PDCS were specifically developed for conceptual design. As a result, different knowledge models are required for different types of systems and applications.

3 DESIGN KNOWLEDGE MODELLING

To support design from a knowledge level, a DSS is normally based on a valid knowledge model that provides an appropriate knowledge framework. Design knowledge is then structured in the defined framework. As mentioned earlier, most KBDSSs 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 process or artefact for various design situations to meet different purposes [4, 5, 17-19].

Generally, there are two main categories of design knowledge models: one is the design artefact and the other is the design process [5]. This division is based on the knowledge content classification that will be discussed in the next section, knowledge ontologies. Of these two categories, the former describes different aspects of the artefact throughout its lifecycle, such as functional, behavioural, structural models, or causal relationships among these aspects. For example, the FBS model [17] introduced function, behaviour, and structure as the basic types of artefact knowledge. Similarly, Deneux and Wang [19] proposed a knowledge model in which concepts and relations were represented as nodes and edges in a knowledge network.

The latter category represents knowledge models of the design process which includes descriptive, prescriptive, and/or computational [20]. Descriptive models can be further divided into protocol studies, which consider how designers design and perform in the design process, and cognitive models, which address the description, simulation or emulation of the mental processes used by a designer during the process of creating a design [20]. Typical work following this category can be found in Darlington et al. [21], Maher and Tang [22], and Reymen et al. [23]. Prescriptive models show how the design process should be organised and executed. They integrate many different aspects involved in the design process so that the whole design process becomes logical and comprehensible [24]. They also offer systematic procedures of the design process that make it more transparent and effective [20]. Examples in this category can be found in Hubka [25], Pahl and Beitz [24], Reymen et al. [23], and Ullman [26]. The last category, computational models express methods, which are formalisations 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, Gero [27], Braha and Reich [4], Smithers [28], and Tomiyama [29], 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 which are combinations of them. For example, the Common Product Data Model (CPDM), developed by Cambridge University's Engineering Design Centre [30], supports both artefact and process description. At the same time, Gorti et al. [31] put forward the SHARED object model, which could model design knowledge including both artefact and process. Moreover, Brazier et al. [32] developed a generic task model of design in which they combined artefact and design process knowledge by relating static aspects (design artefact) and dynamic aspects (design process) to subtasks of this model.

4 KNOWLEDGE ONTOLOGIES

To construct design knowledge models, design knowledge can be described or explained in terms of ontologies, which reveals the nature and structure of design knowledge by defining different types of design knowledge, their relationships and basic operations to knowledge chunks [8, 10, 33]. This section explores the complexity and heterogeneity of knowledge evolved in design by presenting a description of design knowledge ontologies – which are depictions of different design knowledge classifications from different points of view. The following eight classifications are examples of the types of design knowledge:

1. Tacit and explicit knowledge [34];
2. Documented and unwritten knowledge [35];
3. Formal and informal knowledge [36];
4. Textual and graphical [37];
5. Declarative and procedural knowledge [38];
6. Descriptive and prescriptive knowledge [3, 9];
7. Current working and domain knowledge [12]; and
8. Design artefact, design process, management, and supplementary knowledge [5, 35].

With regard to different researchers' views of the above 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. This section attempts to give an account of some of the most commonly used classifications in engineering design while attempting to accommodate such differences. Of these classifications, the first seven could be applied to general knowledge but not limited to engineering design per se. The last, however, is dedicated to knowledge classification in the engineering design domain.

4.1 Knowledge accessibility – tacit and explicit knowledge

According to whether knowledge could be articulated in a direct way, or it is accessible, design knowledge can be categorised into tacit and explicit [8, 34]. Implicit [39] and codified [9] are other terms that are used for tacit and explicit knowledge respectively, although differences do exist between tacit and implicit.

According to Nonaka and Takeuchi [34], tacit knowledge is subjective and experience based knowledge that can not be articulated in words, sentences, numbers or formulas. Similarly, Sim and Duffy [8] pointed out that tacit knowledge is personal and context-specific. Therefore it is hard to formalise and communicate with [34]. Due to the difficulty of expression, it is relatively not easy to access tacit knowledge. An example of tacit knowledge is design experience. With this experience, expert designers know why they make a decision in one specific situation; however, it is difficult for them to express the rationale in a way that makes others readily access it. Explicit knowledge, on the other hand, refers to knowledge that is comparatively objective, rational and is transmittable in formal, systematic expression [8, 34]. Compared to tacit knowledge, generally, it is therefore easier to access. Examples of explicit knowledge are knowledge captured in diagrams, tables, and documents.

4.2 Knowledge availability – documented and unwritten knowledge

The second classification is based on knowledge availability, which categorises knowledge in terms of documented and unwritten knowledge [35]. The former is the knowledge that has been recorded in detail by writing, filming or recording 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, the latter refers to the knowledge that has not been documented. It may be either knowledge undiscovered or that has been discovered, however, still maintained in a human being's mind. In addition, unwritten knowledge could contain tacit as well as explicit knowledge.

4.3 Knowledge style – formal and informal knowledge

According to whether knowledge has an ordered, organised method or style, it can be categorised into either formal or informal knowledge. Overall, formal knowledge is either knowledge that has been expressed in a systematic way or an ordered, organised style. For Conklin [36], formal knowledge is the knowledge that could be found in books, manuals, and documents, and can be easily shared. Rules and strategies are examples of formal knowledge. In contrast to formal knowledge, informal knowledge 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 creating formal knowledge [36]. For example, needs, desires, and ideas are those that can be used to create formal descriptions of artefact functional knowledge.

4.4 Knowledge representation – textual and graphical knowledge

Design knowledge is complex also in that it can be represented in various ways, such as video, audio, text, symbol, graphic, and table. In general, texts and graphics are considered as the main representation formats of design knowledge [37]. 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.

4.5 Knowledge cognition – declarative and procedural knowledge

From cognitive psychologists' view, design knowledge can be considered to contain declarative and/or procedural knowledge [21, 38, 40]. The former is the knowledge about "know what", which contains description of objects, events or methods, and how they are related to each other. On the other hand, the latter is knowledge of "know how" that encodes how to perform certain tasks so as to achieve a particular result. Therefore, this type of knowledge is normally stored in terms of procedures.

In engineering design, an artefact might be represented by both declarative and procedural knowledge. However, a chunk of knowledge could be viewed as declarative or procedural knowledge in different contexts. As researchers in the AI laboratory of University of Michigan [41] proposed, whether knowledge is viewed as declarative or procedural, is based on how people read from it. As a result, the distinction between them is somewhat subjective in that the judgement depends on human being's expectation. For example, the colour of pedestrian barriers is declarative knowledge of its properties. However, it can also be viewed as procedural if it is used to combine with its function – that is to draw attention of pedestrians.

4.6 Knowledge function – descriptive and prescriptive knowledge

In a review of design models, Love [42] and Finger and Dixon [20], among others, delineated two types of design model: descriptive and prescriptive. In a similar vein, others (e.g. [3, 9, 43]) talked about the function of design knowledge, which can also be characterised by descriptive and prescriptive design knowledge. The former describes what constitutes the design artefact and what typically occurs during a design process. For example, description of an artefact's components can be regarded as artefact's descriptive knowledge. However, the latter specifies how something should be or should be done [9]. In the design world, prescriptive knowledge prescribes how the artefact should look, behave and/or how design should be undertaken. For example, a designer may prescribe the function that roadside furniture should be easily visible by people with visual impairments. Therefore, prescriptive knowledge could guide designers' decision making to proceed with the design.

4.7 Knowledge source – current working and domain knowledge

During designing, 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) [12]. This classification is consistent with Aken's "Specific design knowledge" and "General design knowledge" [9, p.387]. According to Zhang [12], CWK refers to the knowledge of the design on which the designer is currently working, and DK is the knowledge of past designs in a domain. As she pointed out, DK can consist of generalised knowledge that is applicable to different design cases (i.e. general knowledge), and the knowledge of specific past designs (i.e. past cases) [44]. Design rules (including design operations and their conditions) are examples of general knowledge [11]. In particular, when creating new designs designers rely on experiences from past design. This experiential knowledge also belongs to general knowledge.

4.8 Knowledge content – design artefact, process, management, and supplementary knowledge

To some researchers, one frequently used classification of design knowledge is associated with its content. In this respect, a number of researchers (e.g. [5, 31, 45, 46]) generally recognise that design knowledge is composed of knowledge about the design artefact and design process.

Design artefact knowledge is the knowledge that concerns the nature of the artefact, for example, how the design is constructed, how the design works and what the design is used for [12]. Bunge [47] regards artefact knowledge as "substantive knowledge", which includes *function*, *behaviour,* and *structure* of the design artefact [17, 31, 48-50]. In addition to these three complementary elements, design artefact knowledge also contains *constraints* of these three elements [12, 31] and any associated *causal relationships* among them [7, 50].

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. **Design process knowledge,** as Aken [9] has argued, is the realisation knowledge of an artefact. For Yoshioka [45], design process knowledge is operational knowledge that manipulates design artefact knowledge. In a similar vein, Bunge [47] uses "operative knowledge" to describe it. Regarding its elements, design process knowledge includes *design context*, *design goal*, *design activity*, *design rationale,* and *design decision*. Moreover, task, though not considered as a basic design process knowledge element in this paper, is an indispensable concept in a design process. Task is considered as an undertaking specified a priori and could reflect the desired output required to meet the goal [51].

In addition to artefact and design process knowledge, another type of design knowledge is **design management knowledge** [9, 52], which concerns the characteristics and properties of a design process and is used to reason and manage the design process. For example, the "Design Activity Management Model" presented by O'Donnell [52, p.52], in which the knowledge is concerned with the decision which directs the design activities, i.e. manage design activities, belongs to this scope. Moreover, strategic knowledge [53] and knowledge from project management and organisational design are examples of this type of knowledge.

Furthermore, besides artefact, design process, and design management knowledge, other types of knowledge that are applied during designing are classified as **design supplementary knowledge** in this paper. It could be from either a technical or social domain. For example, it can involve the environment, organisational culture, designer's preferences and organisation strategies. In addition, computer tools knowledge, design for X knowledge and team collaboration knowledge are other examples of this type of knowledge.

From the above, two topology relationships of design knowledge can be derived: **teleology topology** and **evolution topology**. Figure 1 shows the teleology topology, in which "supportive relationships" among these four types of knowledge are represented as uni-directional solid arrows. Dashed arrows in the model stand for "representation relationships" between these object entities in the material and ideology world. 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. Since artefact, design process, and design management knowledge are representations of these object entities in an ideology world, they possess the same

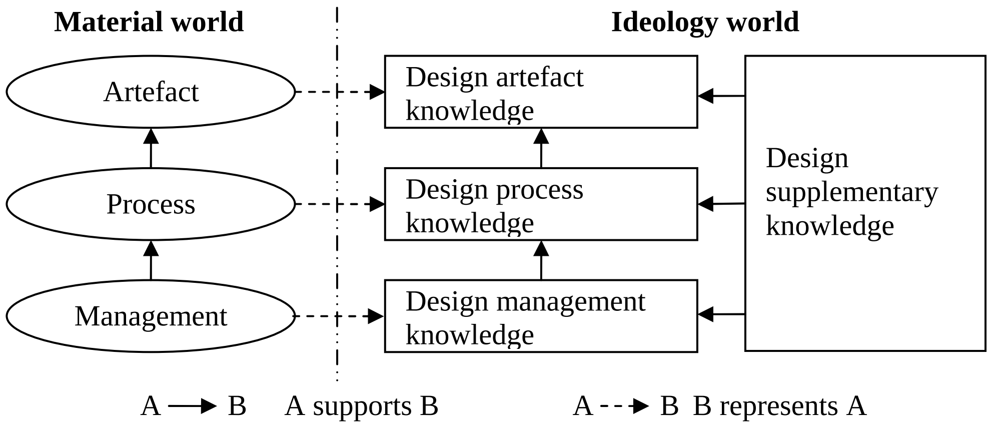

Figure 1. Teleology topology model of design knowledge

supportive relationships. That is to say, design management knowledge supports the development of design process knowledge, which provides supports 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.

Design knowledge evolves throughout designing [12, 22] and the four types of design knowledge evolve each other from the outset. Accordingly "knowledge evolutionary relationships" exist among them. These relationships are depicted in Figure 2. As Figure 2 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 teleology topology model, these evolutionary relationships are bi-directional. That is to say, for example, it is not only design process knowledge which evolves design artefact knowledge, the latter affects the former at the same time.

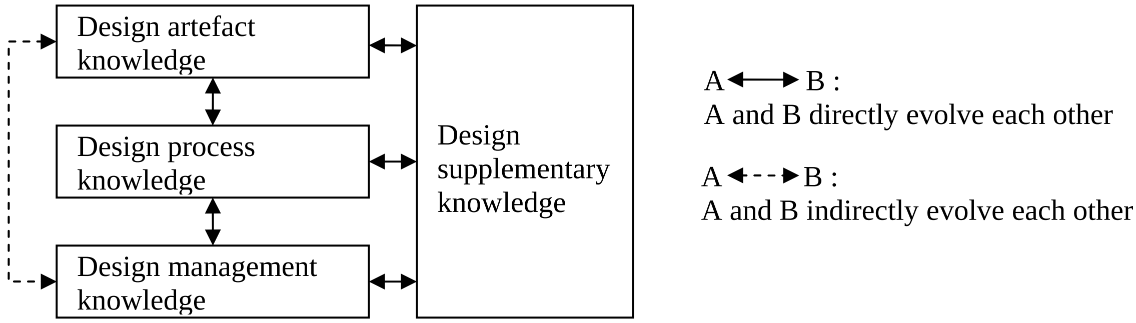

Figure 2. Knowledge evolutionary topology model of design knowledge

For clarity, Table 1 summarises the design knowledge classifications discussed in section 4. It should be noted that, a chunk of knowledge could belong to different knowledge ontologies at the same time. For example, it could be descriptive, declarative, and design artefact function knowledge. Thus, different knowledge ontologies can intersect.

Table 1. Classifications of engineering design knowledge

Classification criteria	**Knowledge types**	**Examples**
Accessibility	Tacit knowledge	Design experience
	Explicit knowledge	Physical laws
Availability	Documented knowledge	Company procedures
	Unwritten knowledge	Designer's intuition of a design
Style	Formal knowledge	Company procedures
	Informal knowledge	Sketches
Representation	Textual knowledge	Paragraphs describing design specification
	Graphical knowledge	3D drawing of a design
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
Source	Current working knowledge	Functions of the current working design
	Domain knowledge	Functions of a past design case

Content	Design artefact knowledge	Functions, behaviours, structures, relationships, constraints
	Design process knowledge	Design goals, activities, contexts, rationales, decisions
	Design management knowledge	Process planning knowledge
	Design supplementary knowledge	Enterprise cultures, national policy strategies

5 LAYERED DESIGN DEVELOPMENT SUPPORT PATTERN – A PYRAMID FRAMEWORK

The above sections show various researches conducted to support knowledge-based design. However, the research is not a disparate one. Based on the above discussions, research in this area can be structured as a layered pyramid (Figure 3). In this pyramid, research on the ontologies of design knowledge builds the base layer. As Chandrasekaran pointed out, ontologies are situated in the heart of any knowledge representation system [33]. Therefore, ontology research provides support for the development of design knowledge models. Research in this layer could, for example, be defining different categories of knowledge and revealing the relationships among them.

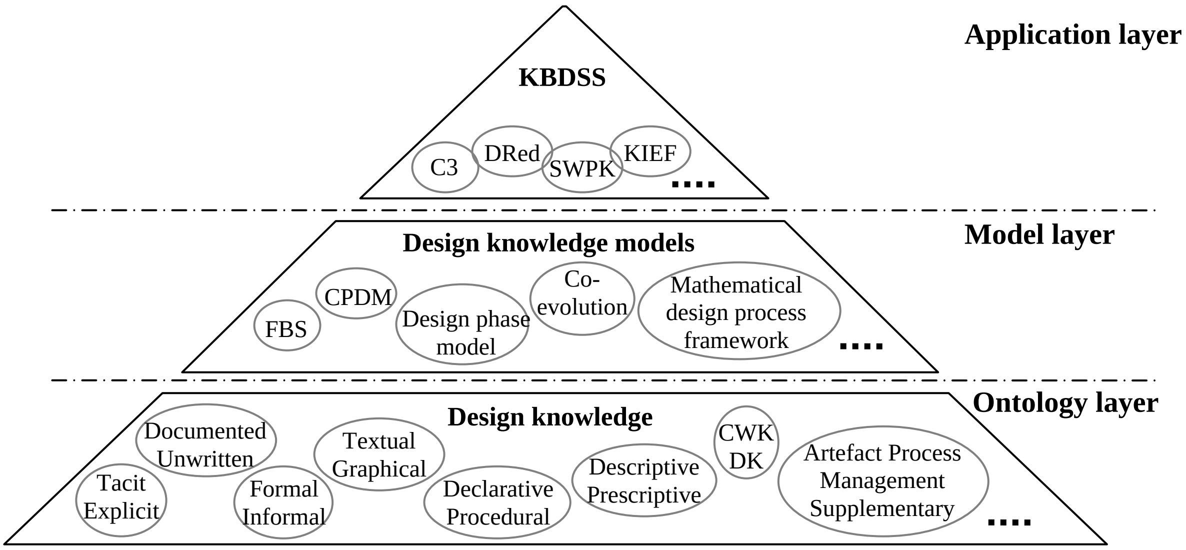

Figure 3. Design research pyramid in knowledge-based supporting

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). Therefore, design knowledge models, located in the middle of the pyramid, play the role of connecting the basic research on design knowledge with that on design support applications.

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 in this paper. For example, a design process model in the middle layer could be a domain-independent model such as [23], or an engineering design process model such as [24]. However, a KBDSS in the top layer normally is dedicated to one specific design problem, design phase or artefact, such as design synthesis problem, conceptual design or aircraft design.

A typical illustration of this pyramid could be found in Zhang's thesis [12] (see Figure 4), in which DeNote 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.

KBDSS:	DeNote System
Design knowledge models:	Multi-Viewpoint Evolutionary Current Working Knowledge Model Multi-Viewpoint Evolutionary Domain Knowledge Model
Design knowledge:	*Current working knowledge* Function, working principle, solution, part, required behaviour, actual behaviour, desired mode of action, actual mode of action, construction, relation, constraint. *Domain knowledge* General function, working principle, solution, part, relation, constrain.

Figure 4. An example of the research pyramid [12]

Presenting a formalism order in engineering design research, Horvath [54] presented a comprehensive framework of design research, which organised research to category, domain and trajectory. In addition, Duffy and O'Donnell [55] presented a research framework (see Figure 5) for conducting design research, which showed a holistic view of conducting research, as well as the evolution of the framework through the research's affecting reality.
To some extent, this research pyramid is similar to Duffy and O'Donnell's research framework in that both contain three aspects of design research, i.e., knowledge (phenomena [55]), model, and system (computer model [55]). However, compared with their work, the three layered framework, presented in this paper, 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.

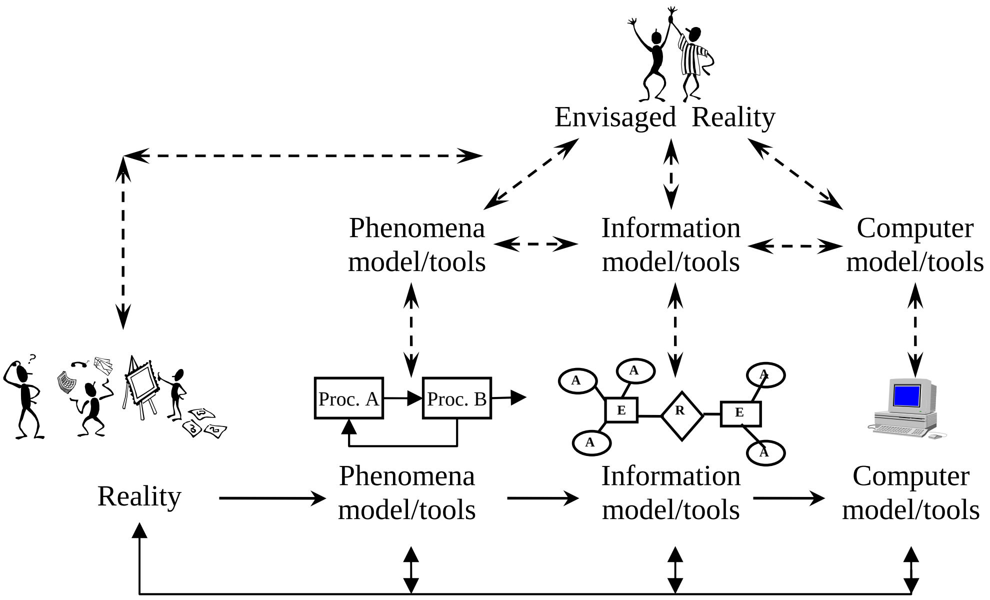

Figure 5. Research Framework [55]

6 SUMMARY

This paper presents a research framework, a pattern for the research conducted in knowledge-based design support based on discussion on KBDSS, design knowledge modelling, and design knowledge ontology. Specifically, it highlights the knowledge ontologies within engineering design domain and presented teleology and evolutionary topology that reveal two types of relationships among artefact, design process, design management, and design supplementary knowledge. Moreover, comparing with similar work, the research framework, represented with a layered knowledge pyramid, focuses on knowledge-based design support, and reveals the domain zooming-in characteristics of the research. By presenting such a research framework, this paper not only provides support for knowledge-based design support system development, but also can assist novice researchers in positioning their research by clarifying such a framework.

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