

Functional Modeling in Conceptual Die Design

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Abstract—The use of function has been recognized as an important part of the design process over last two decades, especially at the conceptual design stage, due to its critical role in determining the final product's functionality. Although there are now some general methodologies dealing with functions or reasoning about functions, virtually no commercial CAD system can support conceptual design process due to their focus on geometrical modeling but not functional modeling. This paper presents a functional modeling approach to guide conceptual die design through functional reasoning steps including functional decomposition, functional supportive synthesis and function-structure mapping. The formed functional model provides a good basis to generate various die structures at the conceptual design stage, because function is a higher level of abstraction than structure, and helps to capture the designer's intent. The functional modeling process has been implemented in a computerized design environment to expedite the conceptual die design process.

Index Words—Conceptual design; Die structure design; Functional model; Functional modeling; Functional reasoning

1. INTRODUCTION

In engineering design, all products and artifacts have some intended reason behind their existence: the product or artifact functions [1]. In other words, engineering design process should be guided by functions. A crucial early stage in the design process is the conceptual design stage, during which an initial design solution to the design problem is devised to fulfill the required functions [2]. Functional design [3] has become a new perspective towards the research of conceptual design activity, and its objective is to provide computer tools to link design functions with the structural (physical) embodiments used to realize the functions. Generally designers agree that function is the most important concept in determining a product's basic characteristics, because products with problems in their main functions will never sell, no matter how sophisticated their details are.

In the present, the use of Computer-Aided-Design (CAD) systems has significantly improved designer's productivity and the quality of designs. However most of these CAD systems focus on the downstream design activity, i.e., detailed design, while have little impact at the conceptual design stage, in particular, to conceptual die design, due to two main issues: (a) they have concentrated on geometrical modeling, as opposed to providing support for functional modeling that is

needed at the conceptual design stage; and (b) they don't possess the ability to draw conclusions from incomplete and approximated information, in particular, functional information.

At the heart of the conceptual design stage lies the conceptual synthesis activity of feasible design solutions, i.e., how functional requirements of a design problem are transformed into feasible initial design solutions. Functional modeling approaches are promising for supporting such a synthesis activity by describing problems and solutions in terms of their functions, and allowing reasoning about them from functional hierarchy. We believe the explicit use of a functional model provides a good basis to generate various design solutions, because function is a higher level of abstraction than structure and enables design efforts to be more focused. The function search space will be smaller than the structure search space.

The study presented in this paper focuses on providing conceptual support for die structure design by using a functional modeling approach. The work was inspired by many research projects currently being pursued in the field of functional modeling. The developed conceptual die design system, though built upon ideas collected from the mentioned literature, differs from them in that it has developed a new functional modeling framework to represent design problems and solutions comprehensively through various functional reasoning steps including functional decomposition, functional supportive synthesis and function-structure mapping. In addition, the functional modeling approach has not been addressed in the literature of die design research.

2. RELATED WORK

In recent highly competitive industrial environment, metal stamping dies for producing sheet metal parts in mass production have been widely applied in various industries such as aerospace, electronics, machine tools, automobiles, refrigeration, etc., resulting in production automation at higher productivity, higher product quality and lower tooling cost. However, it has been well recognized that die design, even after many years of practice, still remains more of an art rather than a science. Historically, the work is mainly carried out manually, based on designers' trial-and-error experiences, skills and knowledge.

In order to speed up stamping die design, and reduce the experience and skill required, researches on the computer-aided die design have been widely reported since 1970s, providing productivity improvements, cost reductions and design automation. The first generation of CAD systems [e.g., 4, 5] for the design of stamping dies have been characterized by basic computer graphics facilities, standardization of die components, and standardization of design procedures, resulting in reduced design and drafting time. Since late 1980s, significant efforts have been made by worldwide researchers to integrate a wide variety of feature modeling, parametric modeling and knowledge-based approaches to develop intelligent die design systems [e.g., 6-10] aiming at detailed die design automation. However the previous work can only deal with geometric modeling and knowledge-based symbolic reasoning, but not handle more sophisticated functional modeling techniques (e.g., building the functional structure of a design object), which is the basis for supporting the conceptual design stage of die design process.

On the other hand, functional modeling has become a promising and leading technique to model a design and requirements from its functional aspects so as to allow reasoning about its function for general or some domain-specific engineering design researches.

One of the most well-known functional modeling frameworks is that of Pahl & Beitz [2], i.e., *systematic approach*, which is based on the concept of flow (and sometimes effort) [11]. They model the overall function and decompose it into sub-functions operating on the flows of energy, material, and signals. Based on Pahl & Beitz's work, many other researchers [12-15, etc.] have made significant contributions to functional modeling frameworks in the general engineering design domain as well. For example, Multilevel Flow Modeling (MFM) [12] models a technical system by expressing it in terms of its goals and in terms of flow functions (source, sink, storage, transport, barrier and balance) that describe the mass, energy and information flows in the system. Functions are linked to goals by two types of *means-ends* relations: *achieve* and *condition*. Instances of flow functions are connected together to build flow structures. Umeda et al. [13] proposed a Function-Behavior-State (FBS) modeler that reasons about function by means of two approaches: causal decomposition and task decomposition. Szykman et al. [14] proposed a standardized set of functions and flows as part of a computable data structure to represent product function and its link to product structure. An analysis-based functional design environment has been proposed by Deng et al. [15] to support the early stage of mechanical product design. In this system, the functional modeling process begins with an initial functional decomposition and ends in a mapping from the fundamental mechanical function to physical structure. The resulting functional model establishes the functional and structural relationships of a product to satisfy the product's specifications and verifies the realization of the functions.

Mukherjee & Liu [16] presented a sketching abstraction scheme for conceptual design of stamping metal parts, using the function-form relations in a design. The functionally critical part of the geometry is represented using a set of functional features, while the rest of the geometry is abstracted as a set of linkages. Part functionality is correlated with the sketching abstraction using data structures called function-form matrices. Although the work was pioneering and promising in the application domain of sheet metal manufacturing, its usefulness is limited in providing conceptual design support for stamping metal part but not die structure.

In the past few years, functional modeling approach has also proven to be suitable for tooling design such as injection mould design [17, 18], though the application is still in its infancy stage. However, no literature exists so far applying functional modeling technique in die structure design. Hence in this paper we hope to utilize the advantages of functional modeling approach to provide conceptual support for die structure design, with which, various functional reasoning techniques should be integrated to develop a comprehensive functional structure of die design object.

3. A COMPREHENSIVE FUNCTIONAL MODELING FRAMEWORK

3.1. Functional relationships

In functional modeling, various functional relationships between functions and structures should be elaborated in order to develop a comprehensive functional model. Three critical types of relations, i.e., *decomposed into*, *realized by*, and *supported by* relations are defined in this paper.

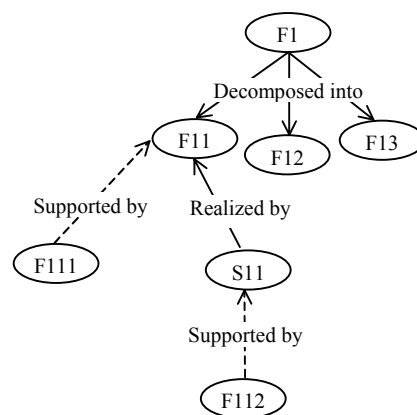


Figure 1. Functional relationships between functions and structures.

Decomposed into relation: This relation indicates a function is decomposed into simple sub-functions. Referring to figure 1, a main function *F1: Perform the stamping operation* is decomposed into simple sub-functions *F11: Form the stamping part*, *F12: Strip the stamping part*, and *F13: Eject the stamping part*.

Realized by relation: This relation indicates a function is realized by a physical structure through a mapping between them. Referring to figure 1, the function $F11$: *Form the stamping part* is realized by a physical structure $S11$: *Punches*.

Supported by relation: This relation depicts the dependency of one function (or structure) on other functions that provide supporting roles. In other words, if needed supportive functions are not provided, their supported function (or structure) may not be fully actualized. Referring to figure 1, the function $F11$: *Form the stamping part* that directly influences the immediate achievement of the purpose is supported by a supportive function $F111$: *Support the stamping part* that is not responsible for the immediate achievement of the purpose but affects soundness of achievement of the purpose. In other words, the function $F11$ may only be fully actualized due to the presence of the supportive function $F111$. Similarly, the structure $S11$: *Punches* may only be fully actualized due to the presence of another supportive function $F112$: *Guide the punches*. Incorporation of supportive function was borrowed from Multilevel Flow Modeling (MFM) based reasoning approach [19] from different views of modeling space, though in a more generic, lower level functional context, facilitates generation of a comprehensive functional model.

3.2. A functional modeling framework with various functional reasoning paths

Figure 2 shows the features of the proposed functional modeling framework that consists of two layers, namely function layer and structure layer. The function layer defines some functions necessary to compose other functions, or support other functions (or structures). The structure layer describes the underlying physical embodiments of the functions.

In this functional modeling framework, if a desired function (or physical structure) may only be actualized when other functions are present, the latter should first be synthesized as supportive functions to generate a more complete functional design. On the other hand, a desired function is not decomposed into sub-functions, unless a matching physical structure can not be found to realize the desired function. The proposed approach can prevent the domain problem being decomposed “too fine”, causing combinatorial explosion.

Generally, a desired function (overall functional requirement, sub-function or supportive function) or a physical structure can be accomplished in the following generalized functional reasoning path types:

- Functional reasoning path type I: a desired function is realized by a physical structure through function-structure mapping.
- Functional reasoning path type II: a desired function is supported by supportive functions through functional supportive synthesis, which are then realized by physical structures.

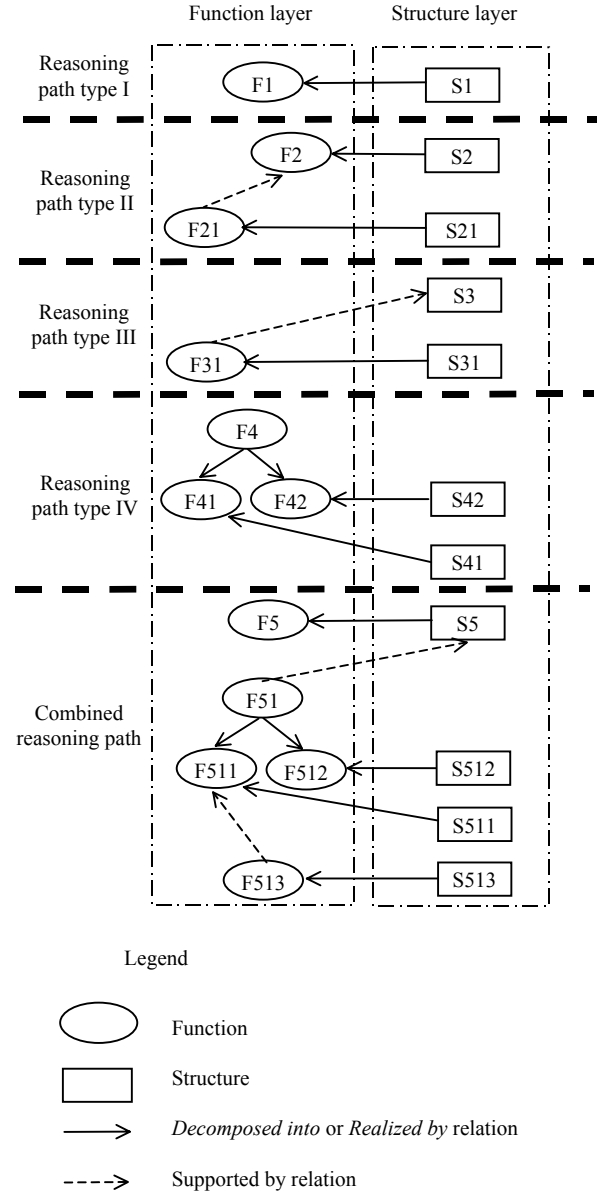


Figure 2. The features of the proposed functional modeling framework.

- Functional reasoning path type III: a physical structure is supported by supportive functions through functional supportive synthesis, which are then realized by other physical structures.
- Functional reasoning path type IV: a desired function is broken down into simple sub-functions through functional decomposition, which are then realized by physical structures.

For example, in the functional reasoning path type I, a desired function $F1$ in the function layer is realized by a physical structure $S1$ in the structure layer through function-structure mapping process. However, if a desired function (or physical structure) may only be actualized due to the presence of some other functions, the latter should first be synthesized

as supportive functions to generate a more complete functional design through functional supportive synthesis process. For example, in functional reasoning path type II, a desired function $F2$ may only be fully actualized due to the presence of a supportive function $F21$. Both functions $F2$ and $F21$ are then realized by physical structures $S2$ and $S21$ respectively. In functional reasoning path type III, a physical structure $S3$ may only be fully actualized due to the presence of a supportive function $F31$ that is then realized by the other physical structure $S31$. If a desired function is too complex and cannot be realized by any available structure directly, it will be broken down into simple sub-functions for further function-structure mapping. For example, in functional reasoning path type IV, a desired function $F4$ is first decomposed into sub-functions $F41$ and $F42$, followed by a further function-structure mapping process.

In order to establish a comprehensive functional model of a design system, usually various functional reasoning path types in the functional modeling framework should be used together to solve a complex functional design problem. For example, in a combined functional reasoning path, a desired function $F5$ is first realized by a physical structure $S5$, which may only be fully actualized due to the presence of a supportive function $F51$. $F51$ is broken down into simple sub-functions $F511$ and $F512$, followed by a further function-structure mapping and functional supportive synthesis process. As a result, a supportive function $F513$ is synthesized to provide support for sub-function $F511$, and is then realized by a physical structure $S513$. Sub-functions $F511$ and $F512$ are respectively realized by physical structures $S511$ and $S512$.

In such a comprehensive functional modeling framework, it is also noted that the modeling strategy is two-way and flexible. For example, a function in the function layer can be realized by a structure in the structure layer; on the other hand, a structure in the structure layer may be fully actualized due to the presence of a supportive function in the function layer, a transformation from the structure layer to the function layer. Due to its comprehensiveness and flexibility, the proposed functional modeling framework will be used in this paper to guide conceptual die design through various functional reasoning steps including functional decomposition, functional supportive synthesis and function-structure mapping.

4. FUNCTIONAL MODELING IN CONCEPTUAL DIE DESIGN

We consider that conceptual design is to construct a consistent and feasible functional model of a design by detailing and embodying the functional specifications on the functional modeling framework. Using a general stamping die as an illustrative example, the design specification from the functional viewpoint is an overall functional requirement, i.e.,

Perform the stamping operation. The logical steps of the conceptual die design process in a computerized design environment proceed as follows:

(1) For a desired function (or physical structure), the starting point is to consider whether it may only be actualized due to the presence of some other functions through functional supportive synthesis. If it is applicable, the latter should first be synthesized as supportive functions to generate a more complete functional design, and this point will not be repeated in the following discussion when it is not applicable. Referring to figure 3 (The legend in figure 2 is still applied here), for the overall functional requirement $F1$, three supportive functions $F11$, $F12$ and $F13$ are synthesized to fully actualize $F1$ in the function layer.

Where,

- $F1$: Perform the stamping operation;
- $F11$: Guide the stock;
- $F12$: Locate the stock;
- $F13$: Guide the stamping motion.

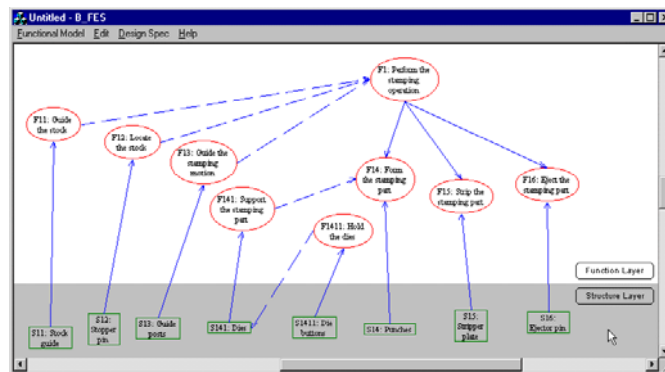


Figure 3. Computerized functional modeling process in conceptual die design.

(2) After incorporation of its supportive functions, the desired function $F1$ is checked whether it can be realized by a physical structure through function-structure mapping. Because $F1$ is too complicated to be realized by any available structure directly, it is decomposed into three simple sub-functions $F14$, $F15$ and $F16$ for further function-structure mapping.

Where,

- $F14$: Form the stamping part;
- $F15$: Strip the stamping part;
- $F16$: Eject the stamping part.

(3) Then, for a new desired function $F14$, a supportive function $F141$ is synthesized to fully actualize $F14$. It is also found that physical structures $S14$ and $S141$ can realize $F14$ and $F141$ respectively. To fully actualize $S141$, a supportive function $F1411$ is further synthesized, which is then realized by a physical structure $S1411$.

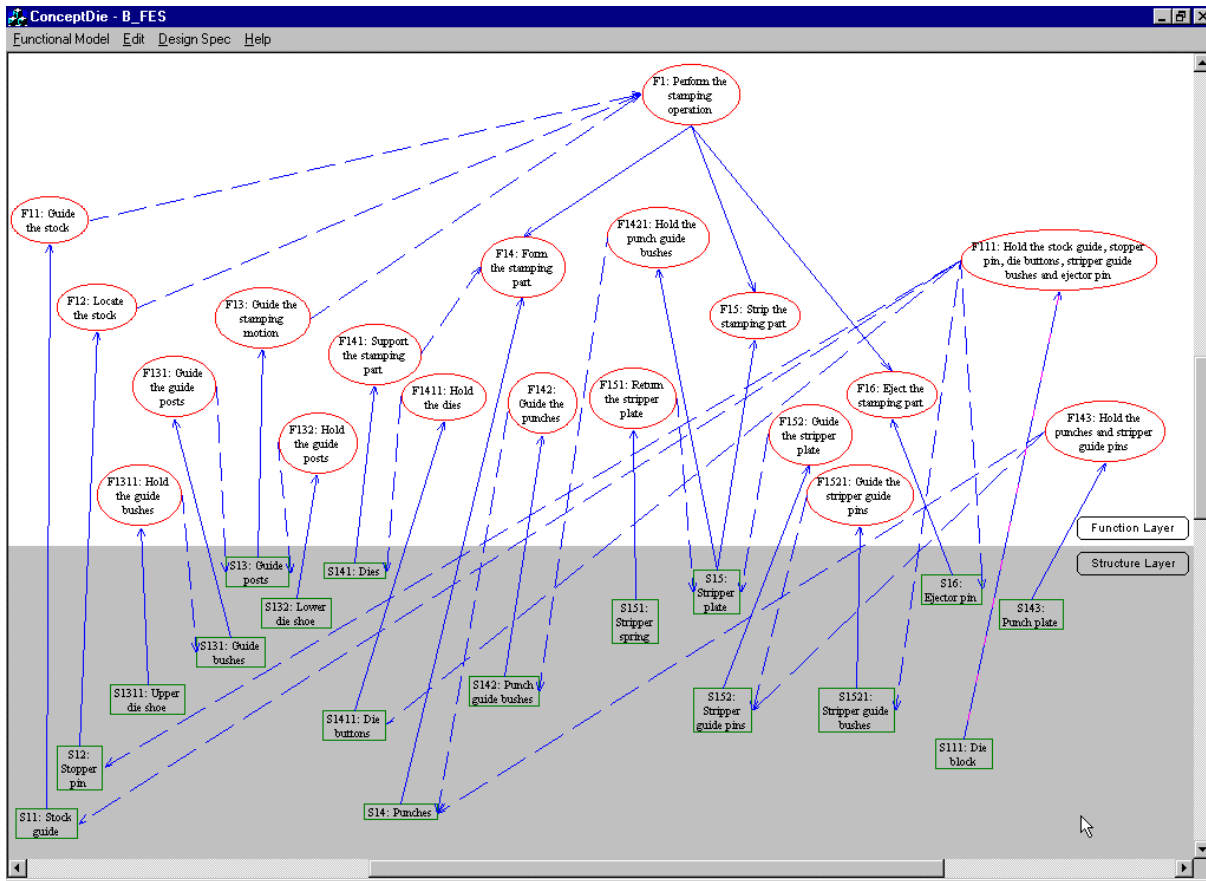


Figure 4. Constructed functional model of die structure in the computerized design environment.

Where,

F141: Support the stamping part;

F1411: Hold the dies;

S14: Punches;

S141: Dies;

S1411: Die buttons;

(4) Similarly, physical structures *S11, S12, S13, S15, S16* are developed, which realize the desired functions *F11, F12, F13, F15, F16* respectively.

Where,

S11: Stock guide;

S12: Stopper pin;

S13: Guide posts;

S15: Stripper plate;

S16: Ejector pin.

(5) After further functional supportive synthesis and function-structure mapping, other remained physical structures are developed, including *Guide bushes, Upper die shoe, Lower die shoe, Punch guide bushes, Stripper springs, Stripper guide pins, Stripper guide bushes, Die block, and Punch plate*. Figure 4 shows the constructed functional model of the die structure.

During above functional modeling process, the functional structure of die design object is developed, which provides a good basis to generate various physical die structures at the conceptual design stage, because function is a higher level of

abstraction than structure, and helps to capture the designer's intent. The functional modeling approach is advantageous to the conventional geometrical modeling approach in providing the conceptual support for die structure design, because the latter can not deal with function and does not possess the ability to draw conclusions from functional relationships that exist in the early design stage.

5. CONCLUSIONS

This paper presents the methodology development in die structure design using functional modeling approach, which is more natural than the traditional CAD systems to simulate the thought of die designers at the conceptual die design stage. Conceptual design is regarded as a constructing process of a consistent and feasible functional model of a design by detailing and embodying the functional specifications on the functional modeling framework.

In functional modeling, die design problems and solutions are represented comprehensively through various functional reasoning steps including functional decomposition, functional supportive synthesis and function-structure mapping. If a desired function (or physical structure) may only be fully actualized due to the presence of some other functions, the latter should first be synthesized as supportive functions to generate a more complete functional design. On

the other hand, a desired function is not decomposed into sub-functions, unless a matching physical structure can not be found to realize the desired function. The proposed approach can reduce the possibility of combinatorial explosion that may occur during functional decomposition.

The functional modeling process has been implemented in a computerized design environment to expedite the conceptual die design process, and provide a good basis in bridging the gap between conceptual die design and traditional computer-aided detailed die design.

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