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# AN ENVIRONMENT DECOMPOSITION-BASED APPROACH TO DESIGN CONCEPT GENERATION

Y Zeng and P Gu

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## 1. Introduction

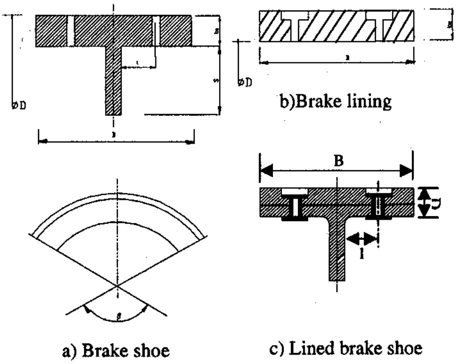
Conceptual design is one of the most critical design stages where some of the most important design decisions are made. Models and methods have been proposed to generate design concepts, based mostly on the systematic design approach. Conceptual design process is generally divided into the following steps: identify design specifications, establish function structures, search for solution principles for fulfiling the subfunctions, combine solution principles to fulfil the overall function, select suitable combinations to define design concepts, and evaluate concepts against technical and economic criteria[1]. Clearly, the definition of function and the establishment of function structure are fundamentaly important for the conceptual design process. However, one of the difficult aspects is that the generation of design concepts and the development of product descriptions are closely coupled. Establishing function structure is especially difficult for original design where no product structure exists. This makes conceptual design very challenging. Tomiyama and his co-workers [2] proposed to establish a function structure by capturing the design knowledge that transforms design requirements (in some cases, functions) into product descriptions or behaviors. However, definitions of product function and functional knowledge are subjective and domain-dependent if applying to a broader range of design problem solving. This paper proposes an environment decomposition based approach to the generation of design concepts from design specifications. This approach is based on a new definition of design requirements in the context of product environment, which is made possible through a function normalization process[3].

The following section provides a running example to illustrate the ideas presented in this paper. Section 3 decribes the design concept generation process based on environment decomposition. The concluding remarks are given in Section 4.

## 2. Running example

A rivet setting tool design is used as a running example to illustrate the ideas presented in this paper. This example was adopted from the book by Hubka et al[4]. Only the design concept generation process will be covered for the purpose of this paper.

The task is to design a tool for riveting brake linings onto brake shoes for internal drum brakes. Figure 1 gives the details and dimension of brake shoe, brake lining and rivets.




Data:
- Brake drum:
  inside diameter = 250~400mm
- Rivet to DIN standard 7338
  Shank diameter = 3~5mm
  Material: $C_u$
- Maximum shoe width
  $B_{max}$ = 100mm
- Maximum total thickness of parts:
  $D_{max}$ = 15mm
- minimum distance between rivet center line and rib
  $L_{1min}$ = 100mm
- Riveting stroke: ~3mm
- Riveting force: ~500N

Figure 1 Form of brake shoe and lining[4]

The following is a list of design specifications for this example:
1) Functional requirements: riveting of brake lining to brake shoe.
2) Physical requirements: the form and dimensions of the tool must be consistent with the form and dimensions of brake shoe and brake lining given in Figure 1.
3) Ergonomic requirements:
   - User: car mechanic
   - Hand force: ~200N
   - Foot force: ~400N
   - Working height: 0.5~1.0m
   - Safety: against accidents
4) Operational requirements
   - Service life: 5 years
   - Good transportability
   - Maintenance free
5) Appearance requirements : no special requirements
6) Manufacturing requirements: manufacturable in workshop of … Co. Ltd
7) Financial requirements: the maximum manufacturing costs ~ 190 Canadian Dollars.

Figure 2 shows two examples of the generated design concepts.

## 3. Environment decomposition based design concept generation

The objective of this paper is to establish a model of conceptual design process that starts from design specifications and ends with design concepts. Obviously, this process involves three elements: design specifications, product descriptions, and design knowledge. The details of product description modelling was discussed in other papers[5][6]. This section will include three subsections: design specifications, design knowledge, and the design process that transforms design specifications into design concepts using design knowledge.

## 3.1 Design specifications

An engineering system can be divided into two parts: product structure and its environment. For the example shown in Figure 2a), the product structure consists of all its components including spring, rack and pinion, stop, counter-weight, closure and perform heads. The environment could include natural environment such as gravity field, function environment such as the forces that the user may impose and the physical properties of brake lining and brake shoe, financial environment such as the price of each component, manufacturing environment such as available manufacturing tools, and so on. Theoretically speaking, everything else related to the product except the product itself can be seen as its environment. The interactions between the system structure and the environment are actions and responses. In the context of function environment for the running example, actions and responses can be force $\mathbf{F_h}$ from human hand, and the forces by closure and perform heads $\mathbf{F_r^u}$ and $\mathbf{F_r^d}$. They can be seen as the boundary between the structure and the environment. Another element of the boundary is the physical properties of the contacting enviornment components, which is directly connected to the product structure. For the same example, brake lining and brake shoe are part of environment components while the car mechanic is another. The car mechanic's hands can be seen as a contacting environment component. Graphically, an engineering system can be represented in Figure 3a).

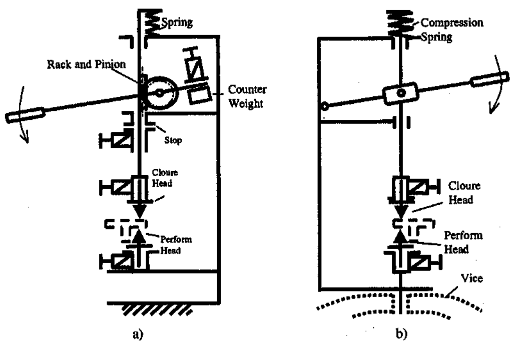



Figure 2 Example design concepts[4]

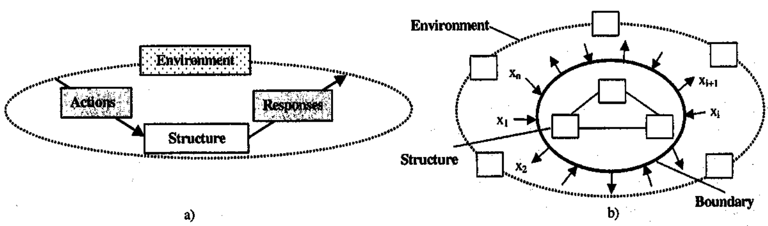



Figure 3 Engineering system

In engineering practice, only the boundary is important rather than the constituents of the enviornment. For instance, how the car mechanic looks is not the concern for this design problem, though it can be a part of environment. As a result, the environment can be represented by the boundary between product structure and product environment (It is shown in Figure 3b):

$$\mathbf{E} = \{\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, ..., \mathbf{x}_n\} \tag{1}$$

where **E** is environemnt and $\mathbf{x}_i$ can be either actions, responses, or product physical attributes.

It can be seen from Figure 3b) that only two possibilities exist to constrain an engineering system: the constraints on either product structure or product performances. Correspondingly, we have two types of design requirements: structural and performance, though there could be other design requirements in engineering applications, such as requirements for safety, for manufacturability and for serviceability. However, all these requirements can be modelled in these two forms through a normalization process[3]. Each design requirement can be mathematically represented as,

$$\mathbf{r}^d = \lambda(\mathbf{x}_i, [\mathbf{x}_i]) \tag{2}$$

where $[\mathbf{x}_i]$ is the constraint, quantitatively and/or qualitatively, on $\mathbf{x}_i$. $\lambda$ is a logical operator such as =, ≥, ≤, and so forth. Then, design requirements for a design problem can be writtean as

$$\mathbf{R}^d = \{\mathbf{r}^d : \mathbf{r}^d = \lambda(\mathbf{x}_i, [\mathbf{x}_i]), \mathbf{x}_i \in \mathbf{E}\} \tag{3}$$

where $\mathbf{R}^d$ is a set of design requirements.

The design process is to evolve the set of design specifications and product descriptions until all design requirements are satisfied[7][8]. In the evolution process, the earlier environment and product description can be seen as the constraints and requirements on the later design. As a result, the design requirements in Equations (2) and (3) can be represented as a set of environment elements. $\mathbf{x}_i$ and $[\mathbf{x}_i]$ are just the elements of product environment in different satges of a design process.

For design specifications of the running example, the product-environment system should be firstly formulated as shown in

Figure 4. The environment can be written as:

$$\mathbf{E} = \{\mathbf{F}_f \cup \mathbf{F}_h, \mathbf{F}_r^u, \mathbf{F}_r^d, \mathbf{W}_b, \mathbf{G}_b, \mathbf{h}_w, \mathbf{x}_{mf}, \mathbf{x}_f, \mathbf{x}_s, \mathbf{x}_t, \mathbf{x}_{mt}\} \tag{4}$$

The symbols are self explanatory in the figure except that $\mathbf{G}_b$ is the geometric model of the brake lining and brake shoe. All design specifications can be represented in the following tables.

Table 1 Performance requirements

| Type | Input | Output |
|---|---|---|
| Functional | $\mathbf{F}_h$ or $\mathbf{F}_f, \mathbf{F}_h \le 200\mathrm{N}, \mathbf{F}_f \le 400\mathrm{N}$ | $\mathbf{F}_r^u, \mathbf{F}_r^d, [\mathbf{F}_{rmin}] \le \mathbf{F}_r^u, \mathbf{F}_r^d \le [\mathbf{F}_{rmax}]$ |
| Financial | Market information | $x_f$, $x_f \le$CAN$190.0 |
| Manufacturing | Manufacturing factors | Difference between design and product |

Table 2 Structural requirements

| Type | Environment | Product Descriptions |
|---|---|---|
| Physical | Geometric model of brake lining and brake shoe | Forms and dimensions of closure and perform heads |
| Ergonomic | Comfortable working height | $h_w$ |

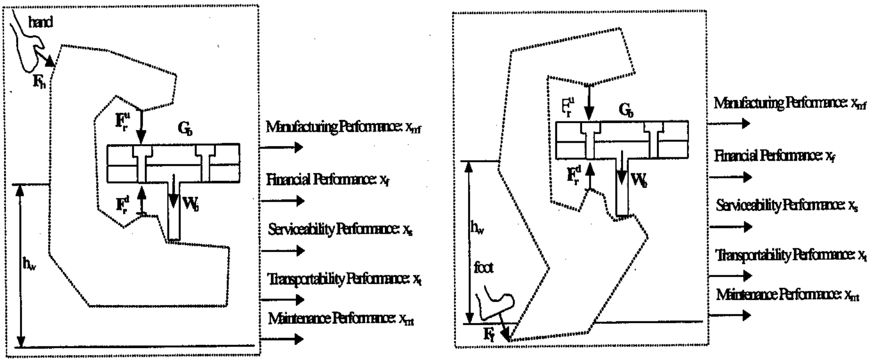



Figure 4 Initial environment for riveting tool design problem

## 3.2 Design knowledge

The basic design knowledge about a product is the knowledge about its causality. It adresses the causal relations between actions and responses with reference to the product. This can be simply represented as in Figure 5a) with a symbolic representation in Figure 5b).

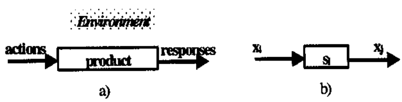



Figure 5 Basic form of product knowledge

The objective of most scientific explorations is to find the law governing the causal relation between actions and responses. Some of the laws are deterministic, such as Newton's law, the others are nondeterministic, such as chaotic dynamics. Figure 6 is an example regarding the relations of two forces, which can be used for the running example given before.

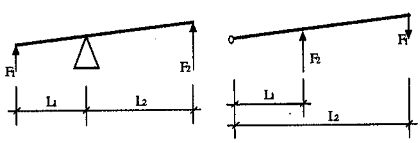


Figure 6 Example product knowledge

In this example, $L_1$ and $L_2$ are physical properties of structure while $F_1$ and $F_2$ are action and response, respectively. The knowledge can be written as

$$\forall \mathbf{lever}, F_2 = \frac{L_2}{L_1} F_1 \wedge F_1 \rightarrow F_2 \tag{5}$$

This relation from actions to responses is called product performance.

$$\forall S \; \exists P \subseteq A \times R \tag{6}$$

where **P** is a set of product performances, **A** is a set of actions, and **R** is a set of responses. In the above example, the performance can be named after 'transmit'. **A** and **R** are $F_1$ and $F_2$, respectively. Mathemmatically, it is described as

$$\forall \mathbf{lever}\ \exists \mathbf{transmit} \subseteq \mathbf{F_1} \times \mathbf{F_2} \tag{7}$$

However, the name of the above relation is artificial and subjective. The word 'transit' can be replaced by 'change', 'increase to', and many others. As will be seen in the following discussion, only actions and responses as well as structure will be involved in solving design problems. This is different from function based approaches. The following is the only form of knowledge used in the design process model presented in this paper,

$$\forall \mathbf{s_i}\ \exists \mathbf{x_i} \exists \mathbf{x_j} \exists \mathbf{k_i^m}, \mathbf{k_i^m} : \mathbf{x_i} \rightarrow \mathbf{x_j} \tag{8}$$

## 3.3 Environment decomposition based design concept generation

Zeng and Gu[7][8] formulated a design process model, mainly based on a dynamic model of product descriptions. There were several points that are not quite operational. In this section, a modified design process model is proposed based on the definition of design specifications and design knowledge described above. Figure 7 is the scheme of this model.

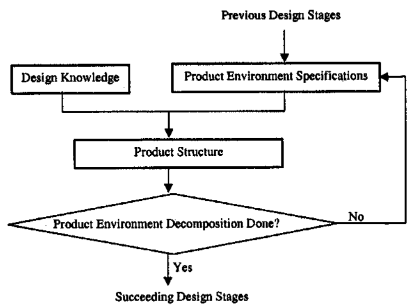



Figure 7 Environment decomposition based conceptual design process

This design process model can be described as follow:

1) Extract one environment element from the environment set;
2) If there is a piece of design knowledge mapping the extracted environment element to another action or response, then product structure s attached to this knowledge will be a component of design concepts. The extracted environment element is replaced by that mapped environment element;
3) Add component s to existing product structure **S**;
4) Detect the performance conflicts between the newly generated product component and existing product structure;
5) Form a new environment set;
6) If further environment decomposition cannot be done, then proceed to succeeding design stages, or else go to step 1.

Mathematically, the process can be formulated as

**Design($R^d$,S)**

{

repeat

{

$\exists \mathbf{x}_k \in \mathbf{E}$ ; //decomposition of product environment

$\mathbf{if}\ \exists \mathbf{s}_l\, \exists \mathbf{k}_l^m : \mathbf{x}_k \rightarrow \mathbf{x}_n$
//application of design knowledge
$\mathbf{if}\ \exists \mathbf{s}_l\, \exists \mathbf{k}_l^m : \mathbf{x}_n \rightarrow \mathbf{x}_k$

$\mathbf{S} = \xi(\mathbf{s}_l, \mathbf{S})$ ; //combination of component into partial product

$\mathbf{E}' = (\mathbf{E}/\{\mathbf{x}_k\}) \bigcup \{\mathbf{x}_n\}$ ; //updating of product environment

$\mathbf{X}_l = \mathbf{K}_l(\mathbf{s}_l)$;
// properties of component and partial product
$\mathbf{X}_p = \mathbf{K}_p(\mathbf{S})$;

$\mathbf{E}'' = \mathbf{X}_l \updownarrow \mathbf{X}_p$ ; //conflicts between partial and component

$\mathbf{E} = \mathbf{E}' \cup \mathbf{E}''$ ; //updating of product environment

until no more environment decomposition can be done

}

This process can be described in Figure 8:

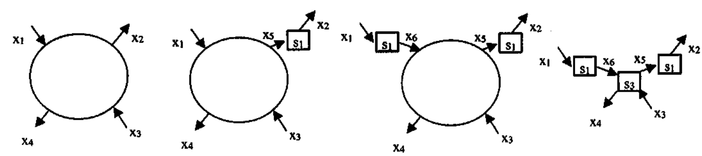



Figure 8 Graphic explanation of environment decomposition based conceptual design process

Figure 9 gives two intermideate steps of generating a design concept of riveting tool. In each step, there could be many alternatives. However, to save space, we only list one alternative.

For Figure 9a) the updated environment and product descriptions are:

$$\mathbf{E} = \{\mathbf{F}_h, \mathbf{F}^u, \mathbf{F}^d, \mathbf{W}_b, \mathbf{G}_h, \mathbf{x}_{mf}, \mathbf{x}_f, \mathbf{x}_s, \mathbf{x}_t, \mathbf{x}_{mt}\} \quad (9)$$
$$\mathbf{S} = \{\mathbf{h}_w, \mathbf{G}_h\}$$

For Figure 9b) the updated environment and product descriptions are:

$$\mathbf{E} = \{\mathbf{F}_l, \mathbf{F}^u, \mathbf{F}^d, \mathbf{W}_b, \mathbf{G}_h, \mathbf{G}_l, \mathbf{x}_{mf}, \mathbf{x}_f, \mathbf{x}_s, \mathbf{x}_t, \mathbf{x}_{mt}\} \quad (10)$$
$$\mathbf{S} = \{\mathbf{h}_w, \mathbf{G}_h, \mathbf{G}_l\}$$

It should be noted that only forces contributing to the function of components are given in Figure 9.

## 4. Concluding Remarks

This paper proposed a design process model based on the environment decomposition. It deals with problem decomposition in a way different from widely used function/task decomposition. A predefined function structure is not necessary for this model. Performance knowledge is the only knowledge needed for this process. The development of this model comes from defining the environment as the boundary between product and environment. A computer aided conceptual design software is under development based on this model.

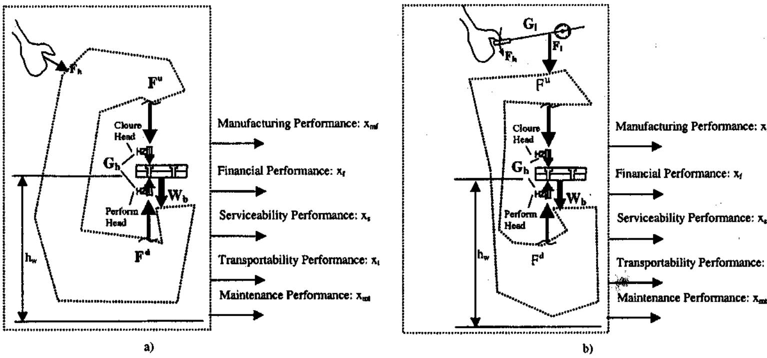



Figure 9 Two intermediate environment for the running example

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Yong Zeng and PeihuaGu
Department of Mechanical and Manufacturing Engineering
The University of Calgary, Calgary, Alberta, Canada T2N 1N4
Fax:+1-403-282-8406, E-Mail: (yzeng, gu)@enme.ucalgary.ca