PREDICTING EFFORT AND DURATION FOR PRODUCT DESIGN FROM A FUNCTIONAL PERSPECTIVE

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Abstract It is difficult to deliver products on time and within budget, and with ever increasing product complexity, the design of a product suffers greater risk of undermined estimation for project completion. Bashir and Thomson (1999a) introduced a method based on functional decomposition (FAST diagram) and a product complexity metric to estimate project effort. The present paper introduces a new complexity metric from the perspective of knowledge. A product is considered to be the result of integrating knowledge-intensive functions; so, the metric measures the complexity of individual functions as well as integration tasks. The application of the new method is illustrated with an example of a hydroelectric generator.

Keywords product design, complexity, metric, knowledge, effort estimation

Introduction

Product design has been acknowledged as a dynamic process of knowledge creation, transfer and exploitation (Štorga and Andreasen, 2004; Madhavan and Grover, 1998; Davis et al., 2005). The process has the characteristics of multiplicity, interaction and uncertainty, where multiple, knowledge-intensive functions are developed and integrated into a whole product, and during the process, designers coordinate activities to reduce uncertainty by acquiring more product knowledge and by resolving interface issues. As companies respond to competition by improving product functions, introducing new technology and accelerating innovation, they are generally faced with continuously increasing complexity characterized by intense knowledge requirements. Budget overruns, schedule slippage, and flawed quality have been observed as complexity rises (Braun and Lindemann, 2008). Inaccurate estimation of design effort has been identified as one of the major causes (Lederer and Prasad, 1995; Bashir and Thomson, 1999a). Measurement is the key to controlling the design process, as it is difficult to manage what cannot be measured (DeMarco, 1986).

Although complexity has been interpreted from various points of view, many complexity metrics revolve around the quantification of three characteristics: multiplicity (size, number), interaction (coupling, dependency) and uncertainty. Indicators of multiplicity include: the number of physical components (Caprace and Rigo, 2012), and the number of functions and technologies (Griffin, 1993). The measurement of interaction often involves the representation of system organization such as a product structure from the physical viewpoint (Rodriguez-Toro et al., 2002), the network of components (Sosa et al., 2005; Tamaskar et al., 2011), the network of development processes (Singh et al., 2012), functional decomposition (Bashir and Thomson, 1999a; Ameri et al., 2008), and Design Structure Matrices (Pimmler and Eppinger, 1994; Lindemann et al., 2008).

Bashir and Thomson (1999ab) introduced a method to estimate project effort based on functional decomposition and a product complexity metric to estimate project effort. They determined that functions, and their interaction had the greatest effect on product complexity. The Bashir-Thomson method uses functional decomposition (FAST diagram) to estimate complexity. To estimate the effort required to design a product, a relationship between product complexity and the amount of effort needed from historical projects is determined. With this relationship, the effort to design a new product can be determined using its measure of complexity. Figure 4 shows such a relationship.

In recent years, product design has been recognized as a knowledge intensive process (Nissen and Levitt, 2002; Štorga and Andreasen, 2004; Madhavan and Grover, 1998; Davis et al., 2005; McGrath and Argote, 2008). The multi-disciplinary nature of product design was found to be a key factor driving complexity (Barclay and Dann, 2000; Tomiyama et al., 2007), which indicated the important contribution of designers' knowledge to complexity (Boisot, 2011). Knowledge is the link among product, process and organization, as knowledge is embedded into product functions, which requires designers with corresponding knowledge to realize them.

Bashir-Thomson Complexity Metric

The advantage of functional decomposition is that functionality is independent of the embodiment of a product, i.e., the shape, materials, and organization of functions, as well as the methodology to design a product (Otto and Wood, 2001). So, a FAST diagram can be used to represent the essence of a product before the embodiment of a design concept is achieved. An example of the Bashir-Thomson method is shown through decomposing the functions of a kettle.

Product complexity is defined as

$$\mathrm{PC} = \sum_{\mathrm{j}=1}^{\mathrm{l}} \mathrm{F_j j} \tag{1}$$

where Fj is the number of functions at level j. Using this metric, the complexity of the kettle, shown in Figure 1, is calculated as PC=4×4+7×3+4×2+1×1=46. Tise metric has been successfully applied in many companies (Bashir and Thomson, 1999a, 2004; Thomson, 2001) and is now used in textbooks.

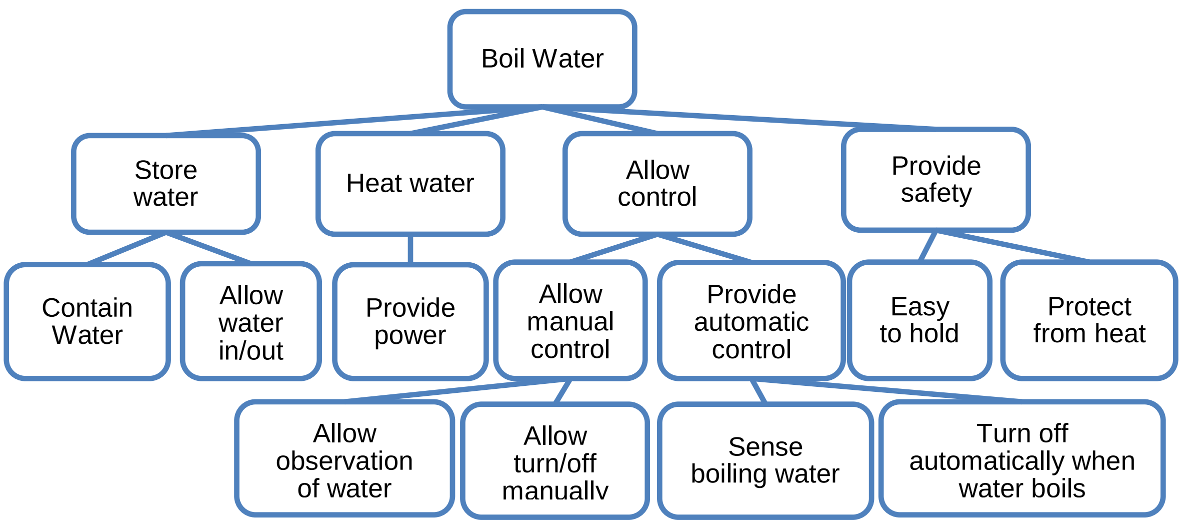

Figure 1 FAST diagram of a kettle

Bashir-Zhang-Thomson (BZT) Metric

The Bashir-Zhang-Thomson (BZT) approach to measuring complexity from the knowledge perspective is summarized in Figure 2. The essence of product development is the application of knowledge by designers to realize desired product functions. Since knowledge is embedded in product functions, a FAST diagram is used to include the mapping of knowledge to product functions. A scale is used to evaluate the required knowledge in designing a product function. Based on the required knowledge, the complexity metric measures the complexity of individual functions as well as the complexity of integrating functions. Each step of the approach is explained in the following sub-sections.

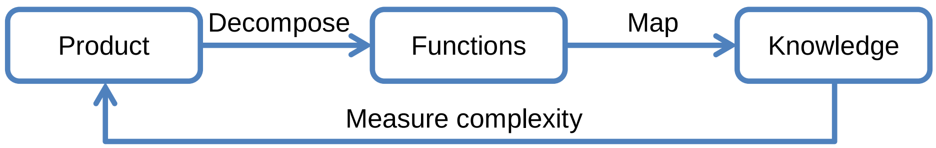

Figure 2 The relationship of product, functions and knowledge in the complexity metric

Mapping Functions to the Knowledge Space

There are usually three main groups of knowledge associated with products: design knowledge, manufacturing knowledge, and domain-specific knowledge. The set of knowledge used in design projects is classified where the levels of knowledge required for designing a function are defined with a scale. A numerical value is used for each level where the lower limit is 1 and the upper limit is *r,* whose value is determined by the user. When developing a knowledge scale, the following attributes are suggested for each knowledge item:

a. Serial number: for the convenience of reference
b. Name: knowledge items which should be as independent as possible. ‘Geometry’ and ‘Weight’ are good examples, whereas ‘Geometry’ and ‘Shape’ are not.
c. Scale: To avoid favoritism towards any knowledge item, all knowledge items should have the same scale range [1, r] ($r \in \mathbb{N}^+$), where users can determine the value of r. If we take r as 5, the simplest weighting is 1 (No) – 5 (Yes). Levels can be added if needed, for example, 1 (None) – 3 (Simple) – 5 (Difficult).

An example of different knowledge scales is shown in Table 1.

Table 1 Examples of knowledge scales

Knowledge Group	#	Knowledge Item	Scale
Design Knowledge	1	Geometry	1 (None), 2 (Simple), 4 (Medium), 5 (Difficult)
	2	Weight	1 (No), 5 (Yes)
Manufacturing Knowledge	3	Material	1 (No), 5 (Yes)
	4	Methods	1 (None), 3 (Simple), 5 (Difficult)
	5	Process	1 (No), 5 (Yes)
Domain-specific Knowledge	6	Stress Analysis	1 (No), 5 (Yes)
	7	Kinetics	1 (No), 5 (Yes)

Since knowledge items are independent, *K* knowledge items can form a *K*-dimensional space. For a function F_i in the function tree, its involved knowledge can be represented as a vector in the knowledge space: $\vec{F_i} = (k_{1i}, k_{2i}, \dots, k_{ni}, \dots, k_{Ni})$ where k_{ni} is the value of knowledge item *n* for the function F_i. For instance, the knowledge vector for a function in knowledge space from Table 1 is $\vec{F} = (2,1,5,3,5,1,1)$.

Measuring Product Complexity

Complexity of individual functions

It is assumed that functions requiring more knowledge are more complex to design; so, the complexity of an individual function F_i is measured as the root mean square of the elements in its knowledge vector as shown in the following formula.

$$\mathrm{W}_i = \sqrt{\frac{1}{N} \cdot ({k_{1i}}^2 + {k_{2i}}^2 + \dots + {k_{ni}}^2 + \dots + {k_{Ni}}^2)} \tag{2}$$

Integration complexity

Functions often have constraints, such as geometric alignment, signal transformation, etc. Combining the sub-functions into a larger system also contributes to product complexity, which we name integration complexity. Two main factors, knowledge difference between functions and the number of interfaces, are considered to contribute to integration complexity.

When two functions involve the same set of knowledge, they have the same vector in knowledge space. When there is no common knowledge, the two functions are orthogonal to each other. Therefore, we use the intersection angel θ of two knowledge vectors as an indicator of their difference regarding knowledge content. The difference increases with larger θ; so, $\sin\theta_{i,j}$ reflects the difference $D_{i,j}$ between functions F_i and F_j. To keep $D_{i,j}$ consistent with function complexity W_j in terms of the order of magnitude, we use the following metric to measure the knowledge difference between functions F_i and F_j:

$$\mathrm{D}_{i,j} = r^{\sin\theta_{i,j}} = r^{\sqrt{1-\frac{\vec{F_i}\cdot\vec{F_j}}{\|\vec{F_i}\|\cdot\|\vec{F_j}\|}}} \tag{3}$$

where r is the upper limit of scale range of knowledge items.

In general, the more interfaces between two functions, the more complex it is to integrate them. Thus, $N_{i,j}$, the number of interfaces between functions i and j, is an indicator of integration complexity. Common interfaces include spatial alignment, energy exchange, information transformation and material exchange (Pimmler and Eppinger, 1994). The number of interfaces of interdependent functions can be identified and documented through a Design Structure Matrix (DSM) of functions.

As discussed above, knowledge difference ($D_{i,j}$) and number of interfaces ($N_{i,j}$) contribute to integration complexity. Thus, the following metric is used to determine the complexity $I_{i,j}$ of integrating functions F_i and F_j.

$$I_{ij} = D_{i,j} \cdot N_{i,j} \tag{4}$$

Total complexity

After decomposing a product using a FAST diagram, the functional complexity for each function is determined along with the integration complexities for each pair of interacting functions. Then, the total product complexity C is:

$$\mathrm{C} = \sum_{i,j} I_{i,j} + \sum_{i} W_i \cdot L_i \tag{5}$$

where $I_{i,j}$ is the integration complexity between functions i and j, W_i is the complexity of function *i*, and L_i is the level of function i in the function tree.

Application

The FAST diagram of a hydroelectric generator from GE Hydro is shown in Figure 3. The product is decomposed into five major functions – control environment, provide housing, provide monitoring, provide safety and control power. These functions are further decomposed into sub-functions, which gives 57 functions in total.

The knowledge involved in the design was obtained by consulting the personnel who worked on projects. Ten types of knowledge were identified, including HVAC (heating, ventilating and air conditioning), air circulation, water circulation, heat transfer, electric-heat generation, control, mechanical engineering, sensor technology, physics and electrical engineering. Three levels were assigned to the knowledge items: minimum (numerical value = 1), general (numerical value = 2) and intense (numerical value = 3). The knowledge requirement for each function was known. For example, the environment control system required knowledge related to heat transfer; additionally, in order to provide housing knowledge, mechanical, control and heat transfer knowledge were required.

Using the knowledge required by each function, we were able to calculate the functional complexity for each function. For example, the function “remove heat”, a sub-function of “environment control”, required general knowledge of six knowledge items including HVAC, air circulation, water circulation, heat transfer, electric-heat generation, and control as well as minimal knowledge of the other four types of knowledge. Thus, functional complexity was calculated as

$$Complexity_{remove\ heat} = \sqrt{\frac{2^2+2^2+2^2+2^2+2^2+2^2+1^2+1^2+1^2+1^2}{10}} \approx 1.7$$

Integration complexity was also calculated. For example, it was known that the function “cool air” and the function “circulate air” were to be integrated. “Cool air” required general knowledge of electric-heat generation, control, mechanical engineering and sensor technology as well as minimum knowledge of the other types of knowledge. “Circulate air” required general knowledge of heat transfer, control, mechanical engineering and sensor technology as well as minimum knowledge of the other types of knowledge. The upper limit of the knowledge scale was 3, i.e. r=3. Thus, using formula (2), the knowledge difference was calculated as

$$D_{cool,circulate} = r^{\sin\theta_{cool,circulate}} = 3^{\sqrt{1-\frac{(1,1,1,1,2,2,2,2,1,1)\cdot(1,1,1,2,1,2,2,2,1,1)}{\|(1,1,1,1,2,2,2,2,1,1)\|\cdot\|(1,1,1,2,1,2,2,2,1,1)\|}}} \approx 1.3$$

There was one interface between the two functions; so, the integration complexity was $I_{cool,circulate} = 1 \times 1.3 = 1.3$. The total complexity calculated using formula (4) was 469.5.

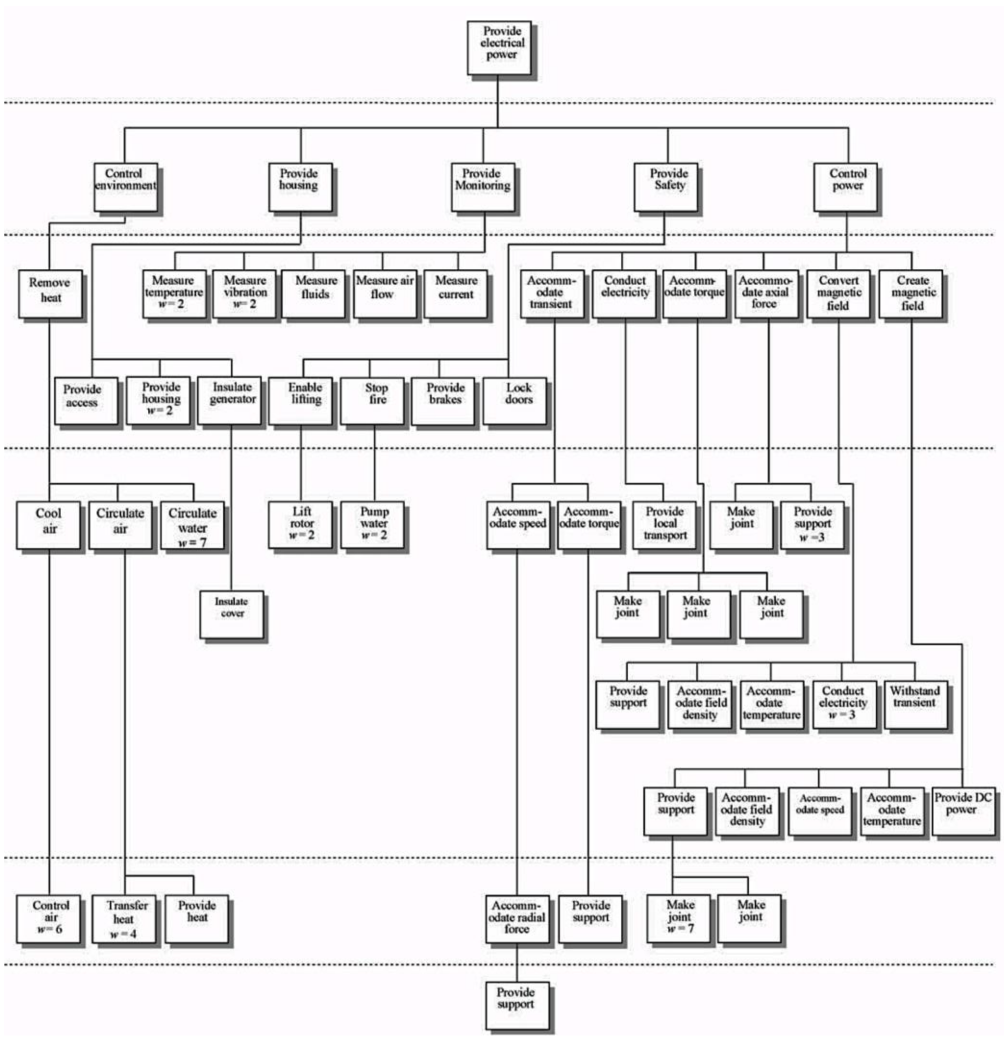

Figure 3 The FAST diagram of a hydroelectric generator (Bashir and Thomson, 2004)

Complexity is the main effort driver in product design. The relationship between complexity and the effort consumed in product design for a hydroelectric generator was analyzed and is shown in Figure 4. For the product with a complexity of 469.5, the total effort can be read from Figure 4 as 14,270 hours. For a new product, the total complexity, C, is calculated, and then, the required effort is obtained from the graph.

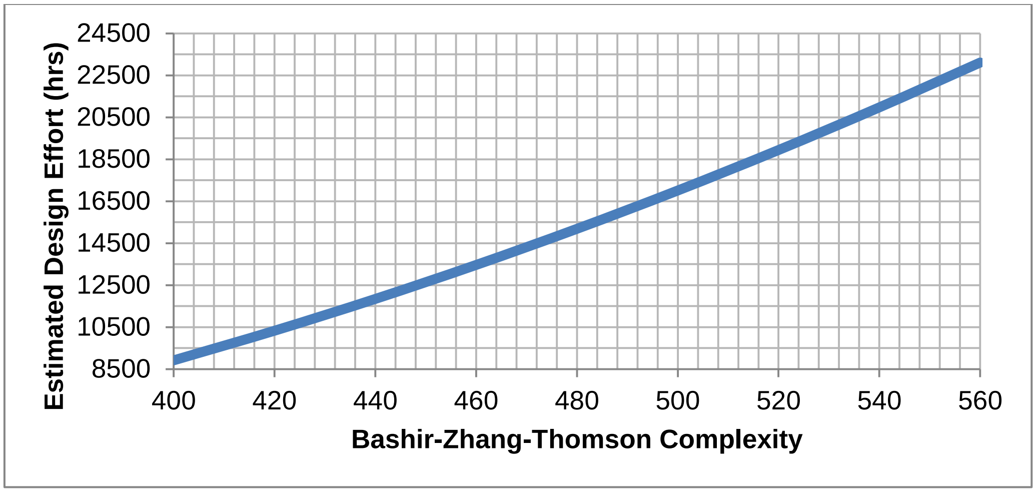

Figure 4 Complexity versus effort for the design of a hydro electric generator

Adopting the method described in (Bashir and Thomson 1999b), we can estimate project duration using Norden's model (Norden, 1964) shown in the following formula.

$$y' = 2\hat{E}\alpha t e^{-\alpha t^2} \quad (6)$$

where y' is the effort utilized at time t, $\hat{E}$ is the total effort, and α is a shape parameter.

The shape of Norden's model is a skewed normal distribution. It shows how manpower changes with time during a project. When the manpower becomes very low at the right end, the project can be viewed as completed, and the corresponding time on the horizontal axis indicates the project duration. The area under this curve is the total effort for a project. Since the value of total effort can be obtained from Figure 4 and the function for the shape of the curve is given by Norden's model, we can derive the project duration with these values as inputs.

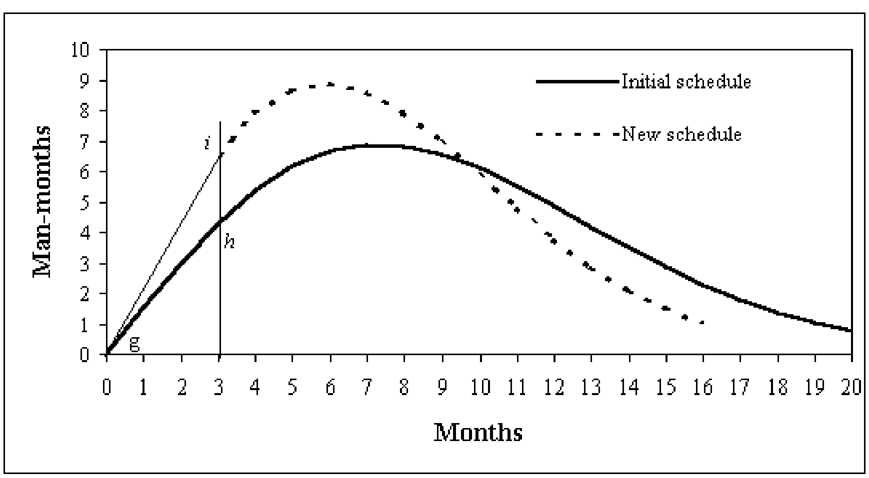

Figure 5 Norden's Model (Bashir and Thomson 1999b)

Conclusions and Future Work

This paper has introduced the Bashir-Zhang-Thomson method for estimating project effort and duration. It used the example of the design of a GE Hydro hydroelectric generator. The BZT method adds the knowledge requirements for each function and the complexity of designing interfaces between functions to the original Bashir-Thomson method. The BZT method highlighted the use of a FAST diagram as an analytical tool to represent design intent without embodiment information, which allowed the estimation of product complexity using required knowledge. Although the demonstration of the BZT method in this paper was for product design, the BZT method can be used for any type of project where project content can be represented by a FAST diagram and the required knowledge is known.

Additional projects of applying the BZT method to estimate project effort and duration are underway with some aerospace companies. Future work will focus on perfecting the method and on relating required project knowledge to the knowledge of the project team in order to help manage the assignment of personnel to projects.

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