Estimating Effort and Time for Design Projects

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Abstract. In today's competitive environment, it is necessary to deliver products on time and within budget. The first step towards this achievement is to have estimation tools that are effective in producing realistic project estimates that become the basis of a project plan. Unfortunately, the capabilities of traditional estimation techniques are limited. This paper describes a number of models which constitute a complete quantitative, estimation methodology that can be used to provide initial estimates of project effort and duration as well as updates during project execution. The heart of the estimation technique is based on functional complexity Demonstrative examples are presented.

Key words: Design projects, Effort, Time, Estimation, Models.

1 Introduction

In many aspects, design projects are not very different from projects in any other discipline; they all require management skills, i.e., the ability to plan, organize, direct, coordinate, and control. However, design projects are characterized by a lack of easily measurable items that can provide data for the estimation of effort, duration, and feedback on performance. Schedule slippage and cost overrun are typical for most design projects. In published papers, the reported average schedule overrun ranges from 41% to 258%, and cost overrun ranges from 97% to 151% (Norris, 1971; Murmann, 1994). This problem persists in spite of the significant advances in design technology over the last two decades. In surveys investigating overrun, project planning has been identified as one of the major causes (Thamhain and Wilemon, 1986; Phan and Vogel, 1988). This is because the capabilities of traditional estimation techniques such as work breakdown structure, and network techniques (CPM, PERT), in producing realistic estimates for project effort and duration that become the basis of a project plan are limited (Murmann, 1994), especially for large projects (Leech, 1972; Putnam, 1978). The existence of such problems in the present era of shrinking product cycle times has made the need for sound estimation techniques more acute than ever before. The emphasis should be first directed to improve the accuracy of effort estimation. This is because reliable estimation of effort is a necessary prerequisite for developing reliable schedule and cost estimates (Adrangi and Harrison, 1987). Unfortunately, only a small amount of research has dealt with the issue of effort estimation models. Recently, Jacome and Lapinskii (1997) proposed a model which takes into account three major factors: size, complexity and productivity. The first factor captures the size (number of gates or transistors) of the design objects to be considered in the design task; the second factor accounts for the task's relative difficulty in a particular environment; and the third factor considers the rate (effort per gate or transistor) at which tasks progress. But, the model developed by Jacome and Lapinskii is applicable only for effort estimation for electronic design. The authors of this

paper have developed a parametric model that is applicable to a wide range of development environments (Bashir and Thomson, 1999a). Product functionality is used as a main predictor, in addition to severity of requirements. The accuracy of the model was tested using historical projects from two companies. Generally, the model performed well as indicated by a number of accuracy tests.

The rest of the paper is organized as follows. The parametric model described in detail in Bashir and Thomson (1999a) is briefly given in Section 2. Section 3 shows how the parametric model can be used to provide an estimate for project cost. In Section 4, the parametric model is used in conjunction with a resource allocation model, namely, Norden's model (Norden, 1970), to derive an estimate for project duration. Sections 5 and 6 show how to use the models to predict the expected changes in project duration and resource allocation due to changes in requirements while development is still in progress. The complete estimation methodology is summarized schematically in Figure 6.

2 A Parametric Effort Estimation Model

One approach to estimate design effort is to make it a function of one or more factors. These factors vary from one environment to another and can be identified among more than a hundred factors which influence the design process (Wallace and Hales, 1987). Nevertheless, after reviewing previously published research (Walston and Felix, 1977; Boehm, 1981; DeMarco, 1982; Wallace and Hales, 1987; Blessing, 1994; Bahill and Chapman, 1995) the following factors were identified as the major contributors to variations in productivity for design projects (Bashir and Thomson, 1999b):

- product complexity,
- technical difficulty: severity of requirements, use of new technology,
- experience, skill, and attitude of team members,
- team structure: team size, methods of communication,
- use of design assisted tools, and
- use of a formal process.

Inclusion one or more of the above factors in a model depends on the characteristics of the historical projects in the data set. The form of the model has to be guessed. Unfortunately, there is no specific approach that helps to define the form that best fits historical data; however, the authors have proposed the following form (Bashir and Thomson, 1999a),

$$\hat{E} = a \, PC^b \, SR^c \tag{1}$$

where

$$\begin{aligned}
\hat{E} &= \textit{design effort} \\
PC &= \textit{product complexity} \\
SR &= \textit{severity of requirements} \\
a, b, c &= \textit{constants.}
\end{aligned}$$

Product complexity is estimated by the following metric (Bashir and Thomson 1999c),

$$PC = \sum_{j=1}^{l} F_j j \tag{2}$$

where

$$F_j = \textit{number of functions at level j}$$

$$l \ = number\ of\ levels$$

The formula for product complexity (equation (2)) is not derived. It was created when considering how to estimate product complexity. From previous work (Bashir and Thomson, 1999a,b,c), it is clear that number of functions does not work well as an estimate of complexity. The authors have tried many possible formulations using the form of a functional tree from functional analysis. The formula given in equation (2) worked well in tests of individuals doing design work as well as large design projects in companies. Intuitively, the more functions in a design, the more complex is the design; the deeper a given function is in a functional tree, the more complex, the design; thus, the formula weights more heavily functions deeper in a functional tree.

Severity of requirements is rated on a scale of 1 to 3, where
1: design requirements are not too difficult to meet,
2: design requirements are difficult to meet, and
3: design requirements are extremely difficult to meet.
In the cases where the severity of requirements factor does not vary substantially between projects, then, equation (1) reduces to equation (3).

$$\hat{E} \ = a\ PC^b \tag{3}$$

The constants in equations (1) and (3) vary from one development environment to another and can be determined by regression analysis applied to historical data. For example, in Bashir and Thomson (1999a), the following parametric models were derived for the specific development environments of two companies.

$$\hat{E} \ = 70.6\ PC^{1.15}\ SR^{.87} \tag{4}$$
$$\hat{E} \ = 24.3\ PC^{1.39} \tag{5}$$

Figures 1 and 2 are the plots of the estimated product complexity using equation (2) against actual design effort for sets of projects carried out by companies 1 and 2, respectively.
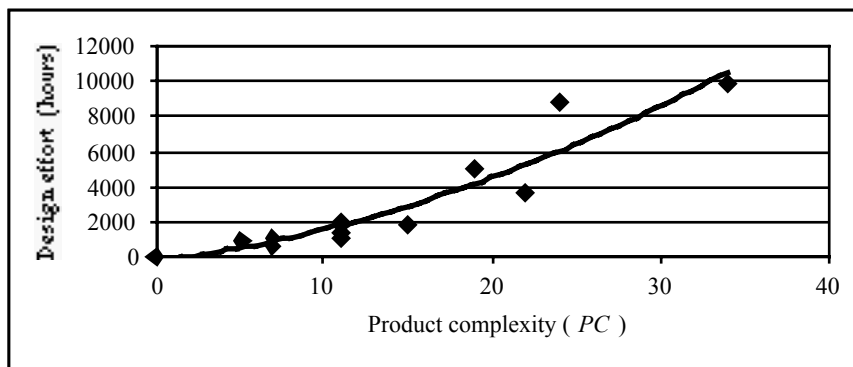

Figure 1. Product complexity versus design effort for a set of projects (company 1)

3 Project Cost Estimation

An important aspect of any project is to estimate how much it will cost. Multiplication of estimated design effort, $\hat{E}$, using the parametric model times the average cost per man-hour, AC, gives an estimate for total manpower cost, TC. Since labor costs make up the majority of the cost for most development environments, TC provides a good estimate of project cost.

$$TC = \hat{E}\,AC \tag{6}$$

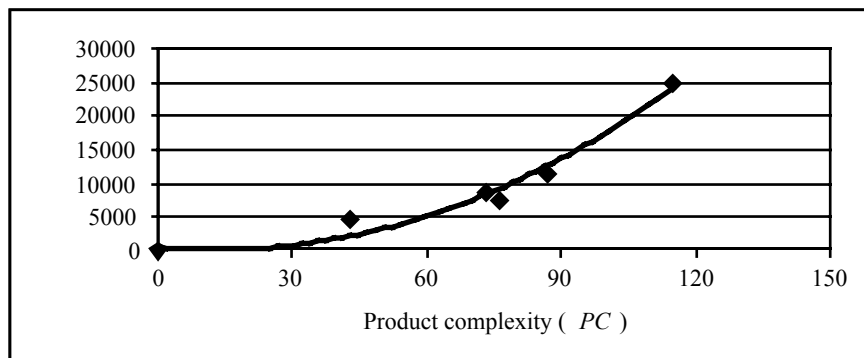Equation (6) can be more complicated if the different cost structures for managers, designers, etc., are used.

Figure 2. Product complexity versus design effort for a set of projects (company 2)

4 Project Duration Estimation

Once an estimate of project effort is made, the next important question is, how long will the project take? For this purpose, Norden's model can be used. Norden (1970) noted that there are regular patterns of manpower usage during a development project independent of the type of work done, that is related to the way people solve problems. On the basis of his analysis, Norden succeeded in creating a useful model (equation (7)) that describes the utilization of manpower during each of the design phases: planning, design, model, and release. Depending on the amount of overlap between the phases, the entire project cycle may be represented or at least approximated by the model. Norden's model is as follows.

$$y' = 2\hat{E}\alpha\,t e^{-\alpha t^2} \tag{7}$$

where

y' = *manpower utilized in each time period (t)*
$\hat{E}$ = *total design effort*
α =*shape parameter (governing the peak manpower to time relationship)*

The shape parameter, α, depends upon the point in time at which y' reaches its maximum. From equation (7), it is simple to derive the following relationship,

$$\alpha = 0.5 / t_o^2 \tag{8}$$

where t_o is the time at which peak effort occurs.

The main application of Norden's model is to estimate the required design effort at any point of time. In addition, it can be used to estimate project duration. However, to do so, the required total design effort, $\hat{E}$, and the shape parameter, α, need to be estimated. The total design effort can be estimated by using the parametric model described by equation (1) or equation (3). The shape parameter can be estimated subjectively by estimating the peak effort

or the time to reach it. It is worth mentioning that to minimize the use of pure subjectivity, Putnam (1978) found an interesting empirical relationship between $\hat{E}$, t_o, and the difficulty of a software project. Such a relationship needs to be developed for design projects, in general; however, this needs a large number of historical projects to be analyzed. Alternatively, the average ratio of total design effort to time-to-peak, r, for a number of previously completed projects may be used. Then, the shape parameter is computed as follows.

$$\alpha = 0.5/(\hat{E}/r)^2 \tag{9}$$

Since the curve obtained by Norden's model tails out to infinity, a method is needed to estimate a project's end point. The average ratio of effort spent during the last month to the total effort, x, for a number of previously completed projects is used to derive a model for estimating project duration, t_d, as follows.
Integrating equation (7) yields

$$y = \hat{E}(1 - e^{-\alpha t^2}) \tag{10}$$

where y represents cumulative manpower up to t.
Thus, cumulative manpower up to $t_d - 1$ is given by

$$\hat{E}(1 - x) = \hat{E}(1 - e^{-\alpha(t_d - 1)^2}) \tag{11}$$

Rearranging equation (11) gives

$$t_d = (-\ln x/\alpha)^{0.5} + 1 \tag{12}$$

where t_d represents project duration.

From equations (9) and (12)

$$t_d = (-2\ln x(\hat{E}/r)^2)^{0.5} + 1 \tag{13}$$

From equations (1), (3), and (13) the following two equations are obtained

$$t_d = (-2\ln x(aPC^b SR^c/r)^2)^{0.5} + 1 \tag{14}$$
$$t_d = (-2\ln x(aPC^b/r)^2)^{0.5} + 1 \tag{15}$$

Example 1
Substituting for different values of PC in equation (5) and for the resultants, $\hat{E}$, $x = 0.04$, and $r = 1728$ in equation (13), a useful chart is obtained as shown in Figure 3. The graph gives the relationship between product complexity (horizontal axis), effort in man-months (left-hand axis), and duration in months (right-hand axis). A man-month consists of 152 hours. The chart can be used to obtain quick estimates for project effort and duration at different levels of product complexity. For example, a project will require 18 man-months of effort and will need 5 months to be completed if its corresponding product complexity is 30.
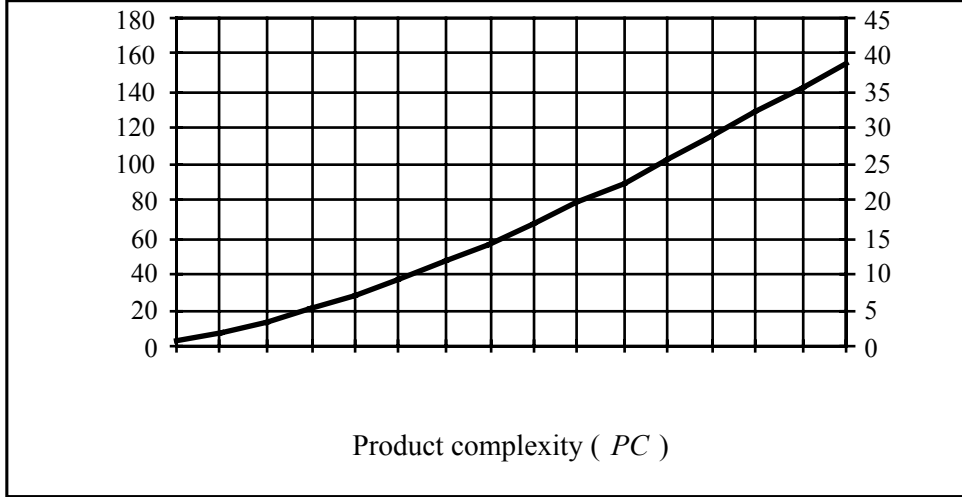
Figure 3. The relationship among product complexity, design effort, and duration for
the product development environment of company 2

5 Change in Design Requirements

Design requirements are demands and wishes that clarify the design task in the space of needs (Pahl and Beitz, 1984). These requirements are usually set at the beginning of the project. However, while development is in progress, many changes can arise. These changes can lead to a change in product complexity, severity of requirements, or any other parameter, and thus, a change in the estimate of project effort and duration.

For a change in design requirements which leads to an increase in product complexity, a relationship between initial product complexity, PC_i, new product complexity, PC_n, and a new estimate for project duration, t_{dn}, can be approximated. A new estimate for project effort, $\hat{E}_n$, is given by

$$\hat{E}_n = aPC_n^b - (aPC_i^b(1 - e^{-0.5t^2/(aPC_i^b/r)^2}) - aPC_n^b(1 - e^{-0.5t^2/(aPC_n^b/r)^2})) + R \qquad (16)$$

where R represents time to be spent on rework.

Equation (16) can be rewritten as

$$\hat{E}_n = 2aPC_n^b - aPC_n^b e^{-0.5t^2/(aPC_n^b/r)^2} - aPC_i^b + aPC_i^b e^{-0.5t^2/(aPC_i^b/r)^2} + R \qquad (17)$$

Substituting for $\hat{E}_n$ in equation (13) gives

$$t_{dn} = (-2\ln x((2aPC_n^b - aPC_n^b e^{-0.5t^2/(aPC_n^b/r)^2}$$
$$- aPC_i^b + aPC_i^b e^{-0.5t^2/(aPC_i^b/r)^2} + R)/r)^2)^{0.5} + 1 \qquad (18)$$

Example 2
Substituting for a = 24.33, b = 1.39, r = 1728, and x = 0.04, and PC_i = 90 in equation (15), gives an initial project duration estimate, t_d, of 20 months. If after 3 months (t = 3), some changes in design requirements have led to a new estimate for product complexity, (PC_n, =

120), and no rework is required ($R = 0$), then, substituting for a, b, PC_i, PC_n, r, t, and x in equation (18) gives a new estimate for project duration, t_{dn}, of 28 months. Thus, the expected time slippage is about 8 months.

Both schedules are shown graphically in Figure 4 where the solid curve represents the initial schedule, and the dashed curve represents the new schedule. One interesting fact supported by Figure 4 is that projects that have many changes in requirements at different points of time have noisy manpower utilization data.
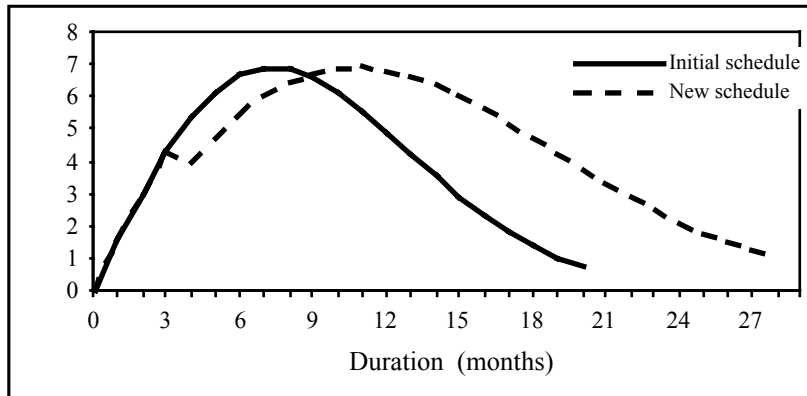

Figure 4. Impact on project duration for a change in product complexity from 90 to 120 after 3 months of project activity

6 Change in Resource Allocation

A possible quantitative way to estimate the required manpower at any point of time is to use Norden's model. If at a certain point of time, while development is in progress, it is decided to shorten project duration by allocating more resources, either by extending working hours or adding more people, decision-makers need to determine how many resources must be added in order to reduce project duration. This can be determined by substituting in equation (7), a new estimate for the shape parameter, α_n, that gives the desired new project duration.

α_n is simply obtained by rearranging equation (12),

$$\alpha_n = -\ln x / (t_d - 1)^2 \tag{19}$$

where t_d is the desired project duration.

Example 3
Consider the initial schedule of the project in example 2. If after 3 months ($t = 3$), it is decided to shorten the project duration by 4 months, then, substituting for $x = 0.04$ and $t_d = 16$ in equation (19) gives a new estimate for shape parameter, α_n, of 0.0143. The use of Norden's model (equation (7)) gives the required monthly design effort needed for the project as shown in Figure 5. Note that area *ghi* has been added to the initial project effort estimate. This is an artifact of the estimation technique since this time has actually passed. The increase in effort represented by the area *ghi* will have to be compensated for later in the project, or if small, could be neglected.

Obviously, as more resources are added, project duration decreases. However, this does not imply that more resources can be added indefinitely. In fact, adding more resources to a project is not always useful. As one can seen in Figure 5, if resources are added at the beginning of the project (months 3-8), there is a likelihood that duration can be decreased. However, if resources are added at the end of the project (months 10 forward), the project duration will probably not be shortened at all. Also reducing project duration depends on the availability of activities that can be tackled by the added resources. Thus, using equation (19) improperly can give false results. In fact, adding personnel above a certain level can cause project duration to increase.
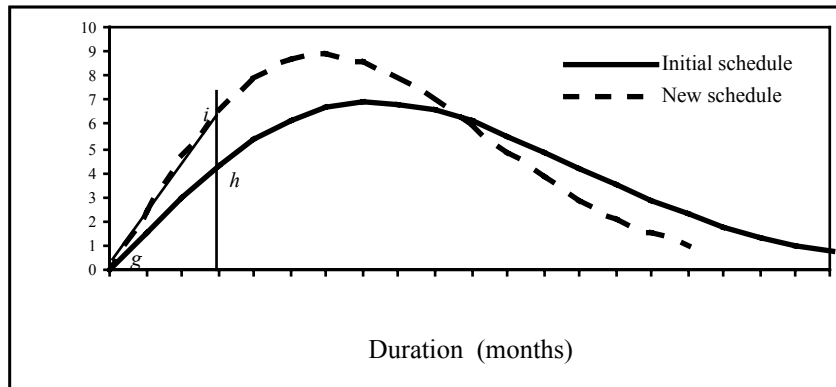

Figure 5. Impact of changes in resource allocation for a change in project duration from 20 to 16 months

7 Summary

The capabilities of traditional estimation methods for estimating project effort and duration are limited. They are biased, and sensitivity analysis is not easily performed on them. Therefore, the emphasis should be directed to methods with a more quantitative basis. This paper has outlined a number of estimation models. These models constitute a complete quantitative estimation methodology which can provide initial as well as updated project estimates from feasibility study until project completion. These estimates address the following questions.

- How much design effort is needed?
- How much will the project cost?
- How much manpower is needed at any time?
- How long will the project take?
- What will happen if changes in design requirements or resource allocation are carried out at a certain point of time while development is still in progress?
- Is the project feasible?

The estimation methodology presented here has been extended for different applications. For more details contact the authors.

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