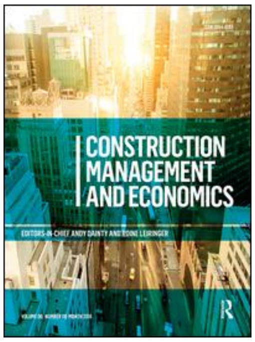

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Modelling the dynamics of design error induced rework in construction

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Rework that is experienced in construction projects is often caused by errors made during the design process. Factors that contribute to design errors are identified and used to design and develop a systems dynamics model, which is used to simulate a number of practical scenarios that can be used to reduce design errors and rework. The model presented in this paper can enable design and project managers to understand better the process of design documentation and how design errors occur in construction projects.

Keywords: System dynamics, design management, time boxing, design errors, rework

Introduction

Rework is the unnecessary effort of re-doing a process or activity that was incorrectly implemented the first time. It is an endemic feature of the construction procurement process and is a primary factor that contributes to time and cost overruns in projects. The direct costs of rework in construction projects are considerable and have been found to be 10–15% of contract value (CIDA, 1994; Burati *et al.*, 1992). Such costs could be even higher as they do not represent the latent and indirect costs and disruption caused by schedule delays, litigation costs and other intangible aspects of poor quality. The primary sources of rework in construction, naturally, are the documentation on which the construction activity is based. These largely consist of design changes, errors and omissions (O'Connor and Tucker, 1986): Burati *et al.*, 1992; Love *et al.*, 1999a). Thus, in order to understand the origins and causal nature of rework it is necessary to model the design process in order to determine why and how rework originates, so that it can be prevented through integrating design management with project management.

This paper builds upon the earlier work of the authors reported in Love *et al.* (1999a), which used case studies to determine the causal nature of rework. Using the findings from the author's previously reported research, this paper uses the methodology of system dynamics to model those factors that were found to cause design error induced rework. A model is developed and used to simulate a number of practical scenarios that can be used to reduce design errors and rework. The model aims to provide an insight into and better understanding of the factors that influence the occurrence of design errors in contract documentation. It is suggested that a reduction in design errors and rework can improve the profitability and competitiveness of a design firm and the performance of construction projects.

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The design process and systems dynamics

Systems dynamics modelling is useful for managing complex processes that involve changes over time and are dependent on the feedback, transmission and receipt of information (Coyle, 1996). The design process relies upon construction project feedback for its effective management (Coles, 1992; Sawczuk, 1992). The design process in a construction environment is extremely dynamic and complex. Invariably it consists of multiple interdependent components, which have multiple interacting feedback processes, and nonlinear relationships (Sterman, 1992; Ogunlana *et al.*, 1998). Moreover, it is a specialized and highly demanding form of problem solving (Pressman, 1993; Lawson, 1997; Pena, 1977). Some researchers and practitioners view it prescriptively (Broadbent and ward, 1969; Wade, 1977; Jones, 1980). Others take a less rule-driven approach and recognize the difficulty of placing boundaries on it by quantifying and describing the activities that take place (Schön, 1993). Although the creative *vision* of the design may be separated from the practical imperative of converting it into a working model of a project, there is an intimate and continuing link between the creative and the documentation process. The documentation process (as distinct from the design process) is the focus of the research presented in this paper. A common term for this activity is 'design management'. For a number of years now, this aspect of a project's development has received greater attention (Palmer, 1981; Cornick, 1990; White, 1991; Gray *et al.*, 1994).

It must be acknowledged that construction projects are also essentially human enterprises, and cannot be understood solely in terms of technical relations among components (Love *et al.*, 1999c). Most of the data required to understand the evolution and dynamics needed to determine the variables that cause rework are concerned primarily with managerial decision-making and other so called 'soft' variables, which contributes to the complex nature of the problem at hand (Sterman, 1992; Coyle, 1996; Li and Love, 1998; Smith *et al.*, 1998) According to Hogarth (1980), people generally have difficulty inferring accurately the behaviour of complex dynamic systems. Simon (1957, p.198) in his famous 'principle of rationality' states: 'The capacity of the human mind for formulating and solving complex problems is very small compared with the size of the problem whose solution is required for objectively rational behaviour in the real world or even for a reasonable approximation to such subjective rationality'.

The bounded rationality of human judgement means that the best-intentioned mental analysis of a complex problem, such as the rework, cannot be accounted for accurately because of the myriad of interactions that jointly determine its outcome (Richardson, 1991, Sterman, 1992). Fundamentally, no mental model can adequately assess the impact of externally imposed changes or allocate responsibility for the delay and disruption caused by rework. According to Richardson (1991), Sterman (1992), and Coyle (1996) computer models based on systems dynamics can be used to overcome the limitations of mental models as they: (i) are explicit and their assumptions are open to review; (ii) are able to interrelate many factors simultaneously; and (iii) can be simulated under controlled conditions, allowing analysts to conduct experiments which are not feasible or ethical in the real system.

To enable practitioners to manage effectively the complexity associated with rework in a project system, a model that is capable of representing the systems characteristics needs to be developed. In this paper a model of the dynamics of design error induced rework is developed and tested using a number of hypothetical scenarios. The authors' proffer that the model developed can be used to help design managers and the like to understand why and how error induced rework occurs in projects.

Modelling approach

Typically rework originates in the design stage of a project (Burati *et al.*, 1992; Love *et al.*, 1998). Therefore, this paper focuses on modelling and analysing those factors that influence its occurrence during the design process. This paper uses the generic term 'designer' to mean both architects and engineering consultants, and focuses on the practices of the design firm. The methodology used to develop the model presented in this paper can be found in Love *et al.*, (1999a).

The model was presented to a number of practising architects and engineers to test its validity. The factors that were used in the model were considered representative of practice and therefore adequate for the purposes of modelling. Estimates for the model's parameters, that is, project duration, contract value, were derived from the case studies presented in Love *et al.*, (1999a). In addition, practitioners provided estimates for designer salaries, and design fees, ranging from 5–8%. However, it was stressed that project type and method of procurement significantly influence the fee charged (Rawlinsons, 1998, p.760).

The model developed consists of the following interrelated sub-systems: 1. process of inducting/recruiting design personnel; 2. process of designing tasks; 3. error proneness during design; and 4. re-designing design tasks. Influence diagrams are used to highlight the main features of the model in Figures 1–4.

Process of inducting/recruiting design staff

Typically, the composition of personnel within a design firm will vary with the firm's workload. Essentially, there are three different types of designer: (a) experienced; (b) newly recruited; and (c) inducted (i.e. an experienced designer working on other projects within the design firm but may be seconded to a new project). It is noteworthy, that the productivity and accuracy of tasks undertaken during the design process will vary from one group to another (Abdel-Hamid and Madnick, 1991). Thus, when determining staffing levels within a design office the model assumes that the partner(s)/office manager takes a rational approach to selecting and recruiting new staff. Thus, based on their design schedule, the partner(s)/office manager will determine the number of designers needed for a project and then compare those who are available. The difference between the number of designers needed and those available is referred to as the shortfall (–) or surplus (+). If there is a shortfall for a new/current project, the partner/office manager may decide to either recruit additional staff or internally induct staff (refer to Figure 1). Whether a designer is recruited or inducted they have to become familiar with the project's characteristics, requirements and history. Consequently, a delay is experienced before they become 'experienced designers'. The time delay between new designers and experienced designers and between inducted designers and experienced designers is shown by double barred lines in Figure 1.

The mechanisms explained above (see also subsequent influence diagrams) have been expanded further in developing the overall computer model of error in design. The Powersim CONSTRUCTOR® 2.5 package has been used to convert the influence diagrams into flow diagrams and the writing of computer codes. A description of all the major equations used to develop the model is considered to be beyond the scope of this paper. However, an example of the flow diagram and major equations pertinent to the process of inducting/recruiting design staffs are given in the Appendix. A full list of the equations used to develop the model is available upon request to the authors.

Process of designing tasks

In Figure 2 design tasks are assigned among the three different groups of designers. Figure 2 suggests that there are two possible design outcomes: the design is completed correctly or the design is done erroneously. Depending on the error proneness of the designer, (that is the likelihood of the designer to make mistakes) the number of correctly designed and erroneously designed tasks can be determined, although this will vary between each designer type (Abdel-Hamid, 1989). The model identifies the number of tasks designed correctly and incorrectly by each type of designer. It assumes that the design firm undertakes quality checks/design reviews to identify any erroneous tasks so the contract documentation can be corrected before contractors price and tender for the project.

Error proneness during design

The factors that contribute to error proneness are identified in Figure 3. The authors have assumed that the identified designer types will each be subject to different degrees of error proneness (Abdel-Hamid and Madnick, 1991). Therefore, a nominal value for committing error is determined in the model, which can be seen in Table 1. This error value is deemed to rise as schedule pressure increases, when design fees

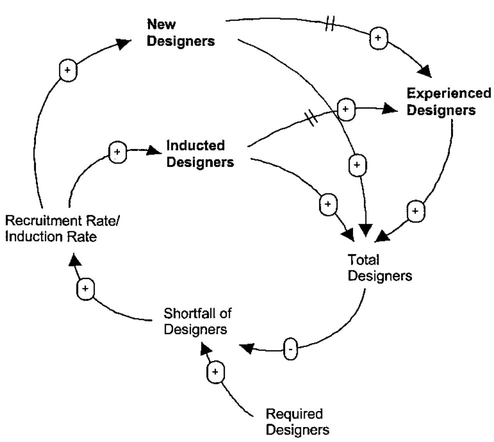

Figure 1 The process of inducting/recruiting design staff

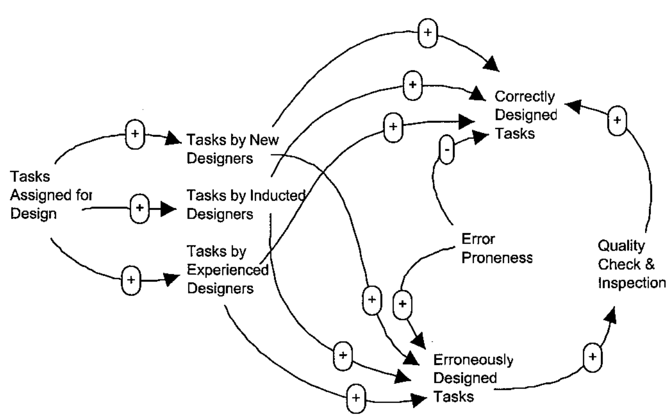

Figure 2 The process of designing tasks

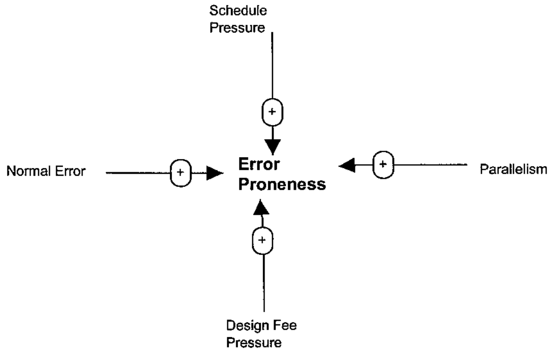

Figure 3 Factors affecting error proneness during design

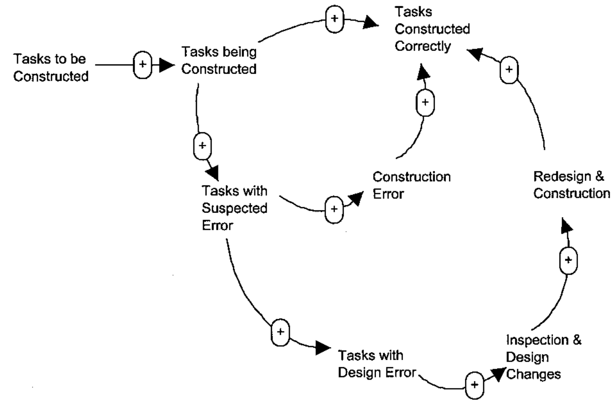

Figure 4 The process of re-designing design tasks

are low, and when the degree of parallelism between tasks carried out by different designers increases. In other words, as tasks are performed concurrently the number of interactions increases and the likelihood for errors occurring also increases (Williams *et al.*, 1995). Low salaries can act as de-motivators, which in turn may also contribute to the incidence of errors (Abdel-Hamid, 1989; Olomolaiye and Price, 1989; Ogunlana, 1993). Similarly, when a firm submits a low design fee for a project, it may 'time box' tasks. That is, only a fixed time is allocated to complete each task, irrespective of whether the documentation is complete or not. In turn this can also cause errors being made by other parties who rely on the designers' curtailed information.

Re-designing design tasks

Once the design and contract documentation is complete it is passed on to the contractor to price. At this point, the authors assume the contract has been let to a selected main contractor and construction has commenced on site. As construction on-site progresses inevitably errors are found in the contract documentation. Similarly, some elements are constructed incorrectly (Figure 4). If the suspected error is proved to be the responsibility of the contractor or the subcontractors, then the error may be rectified (rework) with no added cost to the client of the project. On the other hand, if the architect or engineer caused the error then they will be responsible for solving the problem. Unless it is a simple problem a particular item or selection of work may need to be re-designed. The design firm may have to recall the designer(s) responsible for that part of the design and documentation process to undertake the necessary rework. If the original designer(s) have left the firm the process of recruiting/inducting may well commence again, as shown in Figure 1. However, for the purpose of this paper, the authors have assumed that the designer(s) can be easily recalled to the project.

It is assumed that as construction progresses on-site, errors in the contract documentation will be identified by the contractor/subcontractors. As they are identified the process of confirmation and redesigning of tasks will commence as shown in Figure 4.

Table 1 Data and assumptions of the model.

Characteristics	Assumption
Designer's average salary	\$1 000 per week
Scheduled design completion time	40 weeks
Project cost	\$10 960 000
Design fees (in percentage of project cost)	5%
Estimated effort in the design stage	548 person-weeks
Construction start time	40th week
Available designers (initially)	10 persons
Construction time	43 weeks
Design error proneness	
by expert designers	10% of tasks
by designers inducted from other projects	20% of tasks
by newly recruited designers	25% of tasks

Model simulation and analysis

In conjunction with industry practitioners, the authors have determined the parameters used to model the influence of design errors. Table 1 identifies some of the data and assumptions made in the model for the purpose of generating a series of possible scenarios for a given project. The process of model validation is multifaceted. The model has been examined for structural validation inasmuch as the major factors identified in Love *et al.* (1999a) have been used and the values used in the model validated by industry practitioners. The model is tested for behaviour prediction so as to assist practitioners with particular scenarios

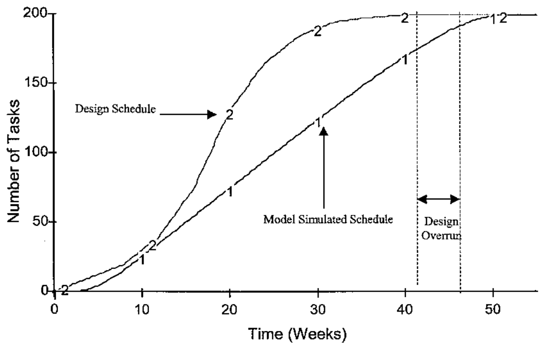

Figure 5 Simulated completion of design tasks versus the actual schedule

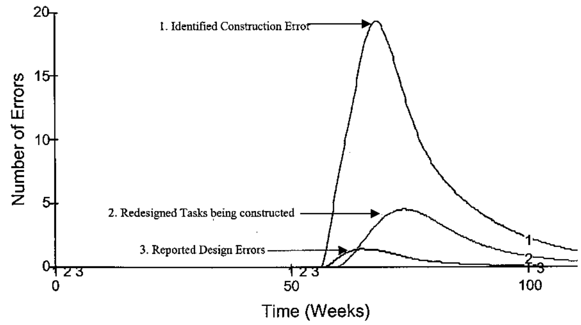

Figure 7 Occurrence of errors in the construction stage

they may be faced with. Figure 5 depicts the simulated behaviour for the time allocated for the design and documentation process in comparison with the design schedule.

For the example used in this paper, the model shows a simulated design completion time of 45 weeks (for the completion of 95% activities) compared with a scheduled design completion time of 40 weeks (Table 1). Figure 5 shows the behaviour of actual design activities completion against the forecast schedule. The actual progress always remained below the scheduled design activities. This is explained by the fact that the design firm takes time to recruit and train design personnel. However, design firms often neglect this factor when planning their design schedule for projects (Ogunlana *et al.*, 1988; Love *et al.*, 1999a) Figure 6 exhibits the allocation of design staff during the documentation process, and shows that more design staff are allocated to design and documentation processes during the early stages of the project. Similarly, the number of design staff decreases as tasks are completed.

The actual effort (measured in person-weeks) in the documentation process is marginally above the estimated effort, that is, 556 person-weeks against the target of 548 person-weeks. At least 43 activities in total have been modelled are designed erroneously in this example. It is assumed that of these, 28 errors are design based, which are detected on-site and therefore have to be redesigned. Figure 7 shows the time dependent behaviour of identified errors and their rectification. The period for amending the errors (redesigning of activities) takes 14 person-weeks effort (refer to Table 2). With a 40-week period for documentation and 43-week construction period, the simulation indicates that at the 105th week only 95% of activities will be completed. 'Time boxing' may occur at or even before this point is reached. The number of designers that need to be recalled during construction for correcting errors identified in the contract documentation was simulated and calculated. Though a small fraction of a single designer's time is utilized, over the whole project time the redesign time was equivalent to a designer working full time on correcting errors for 14 weeks.

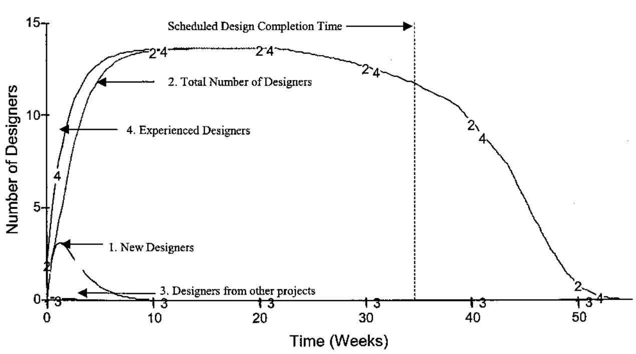

Figure 6 The number of design staff required during the documentation process

Testing of alternative scenarios

To understand further the dynamics of error induced rework in a project system the following scenarios were tested.

1. Continue with the present situation.
2. *Drastically reduce design time.* Due to external pressure, a project manager could accelerate the design and documentation process of the project. For example, the design schedule could be compressed from 40 weeks to 25 weeks. No other change is affected: salary is $1000 per person per week, available design personnel from other projects are 10.
3. *Drastically reduce design time with engagement of experienced design personnel.* It is assumed that paying an additional salary (in terms of

overtime payments) will be attractive to experienced design staff. The salary is increased by 50% to $1500 per person per week. The scheduled design completion time is kept at 6 weeks.

4. *Recruiting a high proportion of design personnel from external sources*. In the event of awarding a new contract, design firms in normal circumstances use their existing personnel, as this may be less disruptive. However, if there is a shortage of internal design staff the design firm may have to recruit design staff externally. Reducing the number of available design staff from 10 to 5 can test this scenario. Salary is set at $1000 per person per week and the scheduled design completion time is 6 weeks.
5. *A combined policy incorporating a design fee reduction, short design delivery period and reliance on external supply of design personnel*. Design fee (% of project cost) is reduced from 5% to 4%. Design completion period is 25 weeks and the available design personnel from internal sources are only 5.

In scenario 2 the design schedule is reduced from 40 weeks to 25 weeks. Consequently, this requires designers to raise their productivity without an increase in salary, which may have a demotivating consequence and contribute to more errors being made. In this scenario, the effort to design has risen by 5% and the number of erroneously designed activities increased by almost 100%. To complete the design activities in a shorter period, the design firm may have to recruit a large number of inexperienced personnel, but due to their high error proneness errors may increase. As a result, the number of redesigned activities and the effort required would increase by 90% and 85%, respectively, when compared with scenario 1.

Scenario 3 appears to be a reasonable approach as a reduction in the design and documentation period would require the design firm to pay higher salaries for better qualified personnel. The implications of implementing this scenario are that the design and documentation period would be completed within 390 person-weeks and the required effort would be 30% less than that in scenario 1. The number of errors in both the initial design and redesign stages is similar to that found in scenario 1 (Table 2). The behaviour observed in scenario 4 is very similar to that in scenario 2. In scenario 4, due to the lack of available in-house design staff, the design firm could be compelled to recruit inexperienced design staff from external sources. In effect this may increase the number of committed errors and, consequently, more effort may be required during the design and documentation process. Moreover, as errors occur increased effort may be needed to re-do erroneous activities. Scenario 5 may be considered to be the most inappropriate policy. A reduction in the design fee from 5% to 4% as well as a reduced design and documentation period may force the design firm to produce contract documentation within minimum effort, which can lead to higher levels of error being experienced.

Conclusion

The system dynamics model developed has enabled the authors to unravel a series of complex problems into more manageable interrelated components. Although this version of reality may not capture the mass of complexity, the authors suggest the model presented in this paper can enable design and project managers to better understand the process of design documentation and how design errors occur in construction projects. To reduce the likelihood of design errors occurring in a project, practitioners need to have a mechanism to test various alternative scenarios so that the design and documentation process can be managed more effectively. The analysis of the interrelated factors in the design scenarios tested can assist industry professionals in making rational decisions as to which factors need the most attention in reducing their rework.

The scenario analysis demonstrated that short term measures such as recruiting from external sources to cope with sudden rises in demand for design personnel, submitting low design fees to win a contract and subsequently paying low salaries to designers are considered ineffective management practices in

Table 2 Summary of scenario tests

Scenario	Number of tasks designed erroneously	95% Design completion (weeks)	95% Project completion (weeks)	Number of activities redesigned	Effort spent on re-design (person-weeks)
Scenario 1	43	45	105	28	14
Scenario 2	82	30	98	53	26
Scenario 3	48	29	98	35	17
Scenario 4	84	30	98	54	27
Scenario 5	59	30	98	41	21

the long run. Notably, each of these options may contribute to an increase in design errors and therefore rework, especially if inexperienced staff are subject to 'time boxing'. In some cases, rework will demand a significant amount of additional time for rectifying design errors that are identified during construction. It must be acknowledged that only those responsible for managing a design firm can make the decision as to which design management strategy they adopt to help them with their decision-making. Without an understanding how errors affect a firm's overall performance, design fees will be perceived to be low as additional resources undertake rework. Clearly, a reduction in design errors will project a better professional image of the firm, lead to more effective design management, but more fundamentally it will improve the profitability and competitiveness of a design firm.

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Appendix

Description of flow diagram and equations for process of inducting/recruiting design staff sub-system

Figure A 1 identifies the major levels and rate variables associated with inducting and recruiting and recruiting new and experienced designers.

The actual number of required designers (Req_Desnrs) is calculated based on an estimated number of designers (Est_Reqd_Dgnrs) and a multiplier (Reqd_Dgnr_Mult), as shown in Equation 1. This multiplier is dependent on the percentage of tasks that are to be designed, which is also dependent on the size and complexity of the project, as shown in Equation 2.

$$\text{Req\_Desnrs} = \text{Est\_Reqd\_Dgnrs} * \text{Reqd\_Dgnr\_Mult} \qquad (1)$$

$$\text{Reqd\_Dgnr\_Mult} = f(\text{Perc\_Tasks\_to\_be\_Designed}) \qquad (2)$$

The estimated number of designers depends on two factors: the time available to complete the design tasks and estimated effort (in terms of design hours).

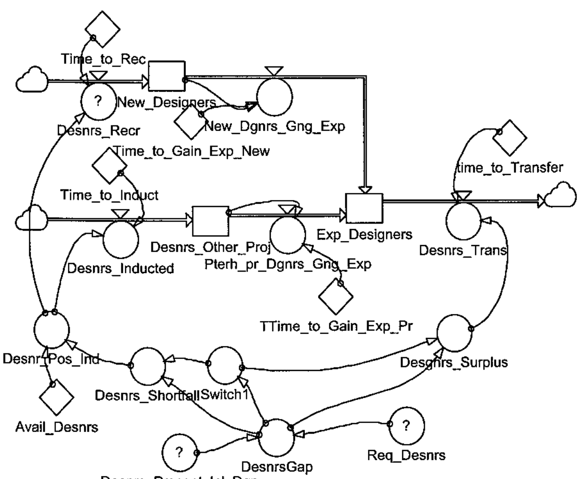

Figure A1 Flow diagram for the process of inducting/recruiting design staff

Thus, if the scheduled time for completing the design process were considered to be short, then the estimated number of designers needed to complete the firm's requirements would be increased proportionally (Equation 3).

$$\text{Est\_Reqd\_Dgnrs} = \text{Estimated\_Effort} / \text{Sched\_Dgn\_Comp\_Time} \qquad (3)$$

$$\text{Estimated\_Effort} = \text{Design\_Fee} / \text{Dgnr\_Salary} \qquad (4)$$

Equation 4 assumes that the firm's design fee (Design_Fee) and the average salary of designers (Dgnr_Salary) determine the estimated effort (Estimated_Effort) needed to conduct a series of design tasks. The model is used to calculate the gap between the required and actual number of designers employed at every simulation interval. The model uses this information to determine whether or not designers need to be hired/inducted from other projects (Equation 5).

$$\text{DesnrsGap} = \text{Req\_Desnrs} - \text{Desnrs\_Present\_Inl\_Dgn} \qquad (5)$$

$$\text{Desnrs\_Present\_Inl\_Dgn} = \text{New\_Designers} + \text{Desnrs\_Other\_Proj} + \text{Exp\_Designers} \qquad (6)$$

Equation 6 assumes the actual number of designers (Desnrs_Present_Inl_Dgn) equals the number of newly recruited designers (New_Designers) plus the designers transferred from other projects (Desnrs_Other_Proj), plus the experienced designers (Exp_Designers). If the actual number of designers were less than required, then there would be a need for additional staff through recruitment or induction of existing designers to the project.

As mentioned above, designers are available from two sources: external recruitment and the induction of existing designers from other projects currently being undertaken by the design firm. The number of new designers decreases as they gain experience through the training/familiarization process (Equation 7). For externally recruited/internally transferred designers there is a time period for recruiting/inducting (Equation 8).

$$d/dt(\text{New\_Designers}) = \text{Desnrs\_Recr} - \text{New\_Dgnrs\_Gng\_Exp}$$
$$\text{New\_Designers} = 0 \text{ (initial value is 0).} \qquad (7)$$

$$\text{Desnrs\_Recr} = (\text{Desnrs\_Shortfall} - \text{Desnr\_Pos\_Ind}) / \text{Time\_to\_Rec} \qquad (8)$$

The model allows a time period for the training or familiarization of designers. The model recognizes that there are different time periods required for each of these designers, which in turn affects its efficiency estimation.