Formal Theories of Engineering Management

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Abstract: - What is the key underpinning factor that determines the efficiency of group work? How does human group provide a mechanism for enabling the exchange between labor and time? This paper presents a coordinative work organization theory for explaining the fundamental mechanisms of engineering organization and management. The coordinative work organization theory is derived based on analyzing the nature of group workload and the exchange mechanisms between labor and time in team work. The human error mechanisms in task performance in groups are explored in order to develop a formal quality assurance theory in engineering management. Applications of the formal engineering organization theory have been demonstrated in efficient engineering project organization and optimization in supplement to traditional empirical practices in engineering management.

Key-Words: - Engineering management, group mechanisms, cooperative work organization, human factors, workload, effort, labor allocation, duration determination, quality assurance, project optimization, software engineering, system engineering

1. Introduction

Engineering is originated as a concept of industrial organization emerged from the industrial revolutions [29, 32]. It seeks solutions for complicated problems and large-scale systems that could not be done by individuals. Engineering is also a process that converts theoretical concepts into useful applications to satisfy human needs. Therefore, engineering may be deemed as an organizational methodology to repetitively plan, design, develop, produce, maintain, and/or use complicated artefacts in systematic, efficient, and optimal processes. Contrary to the traditional individual-based production process, engineering methodology enables a group of people work together to produce a complex product, or to achieve a common goal, which could not be reached by individuals due to physical, technical, and/or economical constraints. Therefore, the essence of engineering is an organizational mechanism for enabling efficient group work.

Because of the involvement of multiple people or groups in engineering projects, management becomes a necessary need for coordination and synchronization of groups when people worked together to achieve a result not possible by individuals acting alone. Therefore, management is a coordination process that organizes group activities and efforts towards a synergic output. Management science is the discipline that studies organizational behaviors, executive decision making, and resource optimization in engineering, which provides classic thought on how organizations may be operated efficiently, effectively, and profitably on certain constraints of resources and environments [16]. The objects under study in management science are work, people, resources, and processes. The basic principles of management science are organization, coordination, planning, forecasting, scheduling, and quality assurance.

The development of management as a scientific discipline can be traced back to the work of Frederick Taylor on the improvement of operations in production in the 1890s [31]. Henry Gantt studied project scheduling and developed the control chart in the 1900s known as Gantt Chart [9] for minimizing interrelated job completion times. In the 1920s, William Shewhart introduced statistics into management and developed the control charts for statistical process and quality control [27]. In the 1950s, project scheduling was well studied and the Program Evaluation and Review Technique (PERT) [7, 10, 25] and Critical Path Method (CPM) [15, 26] were developed. Queuing theory was proposed by

E. Erlang and John Little in the 1910s and the 1960s, respectively [17, 22]. Various programming methods were proposed to solve optimization problems for a given objective and a number of constraints such as linear programming in the 1940s [20], nonlinear programming and dynamic programming in the 1950s and later [1, 6, 25]. Philip Crosby, Edwards Deming, Genichi Taguchi, and Joseph Juran worked on quality systems and developed a number of quality control principles and methodologies in the 1970s and the 1980s [3, 4, 5, 11, 12, 13, 14, 30].

This paper explores the group mechanism and management gains in engineering as well as the coordinative work organization theory for engineering management. In the remainder of this paper, the coordinative work organization theory is rigorously developed in Section 2 based on a long chain of reasoning on the mathematical model of group workload, laws of coordinative workload organization and optimization in engineering management. Then, the human error mechanisms in group task performance are introduced to model the basic theory of quality assurance in engineering management in Section 3.

2. The Coordinative Work Organization Theory for Engineering Management

In order to explain the fundamental problems of engineering management, the mechanisms of group coordination need to be rigorously studied. This section explores how human group work provides a layout for the exchanges between labor and time, and explains what the key underpinning factor is that determines the efficiency of group work in engineering projects.

2.1 Mathematical Model of Coordinative Group Work

There are a number of myths on the relationship between labor and project duration in empirical engineering management, and on the nature of the hybrid product of workload in person-month (PM) [2, 21, 35]. For example, how many persons and how many months are needed for carrying out a certain workload? Is 1P • 10M = 10P • 1M = 10PM? Brooks presented an empirical study on the myths of the relationship between labor (number of persons) and time (duration) in software engineering [2]. This section creates a mathematical model for formally analyzing the mechanisms and behaviors of coordinative work and their engineering organization.

Definition 1. The *workload W* of a coordinative project is determined by a product of the number of labor L and the duration T needed or spent in the project, i.e.:

$$W = L \bullet T \quad [\mathrm{PM}] \tag{1}$$

where the unit of labor is *person* (P), the unit of duration is *month* (M), and as a result the unit of workload is *person-month* (PM).

Almost all empirical questions on the nature of group workload can be reduced to the fundamental question: Whether labor L or duration T is arbitrarily determinable for a given workload W? Or more generally, are labor L and duration T freely interchangeable for a given workload W in coordinative work organization? The following lemma introduces answers towards the above questions. Formal analyses of them are elaborated in a chain of reasoning in the following.

Lemma 1. The generic form of *workload W* carried out by a group with more than one person is always supplemented by an inevitable overhead h for collaboration, i.e.:

$$W = L \bullet T = W_1 \bullet \left(1 + h\right) \quad [\mathrm{PM}] \tag{2}$$

where h is called the *interpersonal coordination overhead* in a group, and W_1 is the *ideal workload* when only one person is allocated for the project.

The ideal workload W_1 in Eq. 2 can be determined on the basis of the size of a given engineering project and the productivity benchmarks of the industry or a specific organization.

Definition 2. The *ideal workload* of an engineering project is determined by the ratio of the estimated project size $\overline{S_s}$ and the productivity ρ in terms of 1/PM, i.e.:

$$W_1 = \frac{\overline{S_s}}{\rho} \quad [\mathrm{PM}] \tag{3}$$

According to Lemma 1, the role of the interpersonal coordination overhead h is the key to answer the fundamental problems about collaborative workload in engineering organization and management. The *interpersonal coordination activities* are tasks that cannot be done by an

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individual, such as management, communications, task synchronizations, meetings, work product reviews, standardization, training, and quality assurance.

Definition 3. The *average rate of interpersonal coordination* r is the average ratio between the time spent on group coordination t_r and the total working time T in a given project, i.e.:

$$r = \frac{t_r}{T} \tag{4}$$

The rate of interpersonal coordination r is ranged in [0, 1.0] where $r = 0$ means there is no coordination and $r = 1.0$ means all time has been spent on collaboration. The typical range of r in the field of software engineering is $0.1 \le r < 1.0$, or r is between 10% to 99%. Real-world project data collected in recent surveys in the software industry show that r is between 12.5% to 47.8% [34]. Higher rate of r is also reported up to 70.0% at IBM [19].

Theorem 1. The *overhead of interpersonal coordination, h* , in a multi-person project ($L > 2$) is proportional to both the number of pairwise relations n and the average interpersonal coordination rate r, i.e.:

$$\begin{aligned} h &= r \bullet n \\ &= r \bullet \frac{L(L-1)}{2} \end{aligned} \tag{5}$$

Theorem 3 indicates that h is the efficiency of transformation between labor and time. The more the persons involved in a collaborative project, the higher the overhead spent in interpersonal coordination in the project. Typical overheads of interpersonal coordination as a function of r and L, $h(r, L)$ can be simulated by a family of curves as shown in Fig. 1. Note that the first curve $h(0.001, L)$ is very close to zero.

Substituting h in Eq. 2 by the expression derived in Eq. 5, the actual workload of a group project can be obtained as follows.

Theorem 2. The *actual workload W* of a project with the overhead of interpersonal coordination is the product of number of persons L and the actual time spent in the project T, i.e.:

$$\begin{aligned} W &= L \bullet T = W_1(1+h) \\ &= W_1(1 + r \bullet \frac{L(L-1)}{2}) \\ &= 0.5W_1\ (rL^2 - rL + 2) \quad \text{[PM]} \end{aligned} \tag{6}$$

where W_1 is the ideal workload without overhead or that of a single person project.

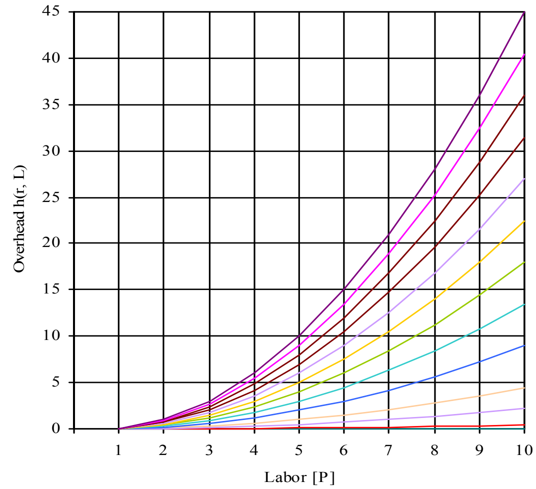

Fig. 1. Overhead of interpersonal coordination $r \in \{0.001 \ldots 1\}$

2.2 Principles of Coordinative Work Organization

Observing Theorem 2 it can be seen that the ideal workload of a group project is the minimum workload in collaborative tasks, and it cannot be further reduced no matter how many persons are involved via any kind of task allocation.

Theorem 3. The *law of interchangeability of labor and time* states that labor L and duration T in a group project are transformable with respect to a given workload W under the following condition:

$$\begin{aligned} T &= \frac{W}{L} = \frac{W_1}{L}(1 + r \bullet \frac{L(L-1)}{2}) \\ &= \frac{W_1}{L}(\frac{1}{2}rL^2 - \frac{1}{2}rL + 1) \\ &= \frac{1}{2}W_1(rL - r + \frac{2}{L}) \end{aligned} \tag{7}$$

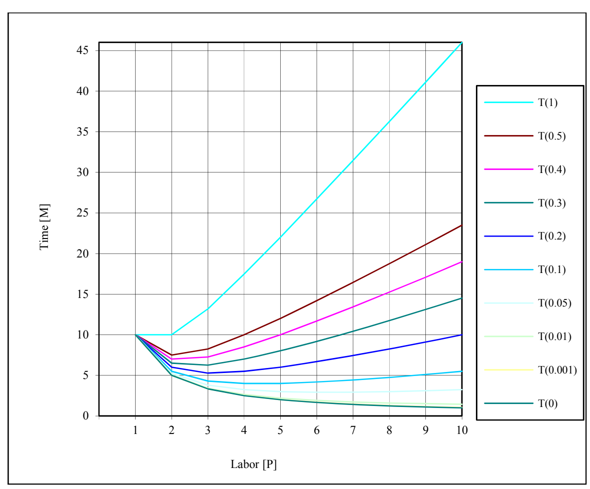

Fig. 2. Project time against number of labors in the layout of an engineering project ($W_1 = 10PM$)

Theorem 4. The *law of* the *shortest duration* of collaborative group work states that there exists the *shortest duration* T_{min} determined by the *optimal labor allocation* L_0 for a given workload W_1, i.e.:

$$\begin{cases} T_{\min} = T(r, L \mid L = L_0) = \frac{1}{2} W_1 (r L_0 - r + \frac{2}{L_0}),\ L_0 \neq 0 \quad [\mathrm{M}] \\ L_0 = \left\lceil \sqrt{\frac{2}{r}} \right\rceil,\ r \neq 0 \quad [\mathrm{P}] \end{cases} \tag{8}$$

Proof. Given r as a constant, Eq. 8 obtains the minimum when its first derivative reaches zero, $T_{\min} = \frac{dT(L)}{dL} = 0$, i.e.:

$$\begin{aligned} &\text{Given } T = \frac{1}{2} W_1 (rL - r + \frac{2}{L}) \\ &\quad \frac{dT(L)}{dL} = \frac{d}{dL}(\frac{1}{2} W_1 (rL - r + \frac{2}{L})) = \frac{1}{2} W_1 (r - \frac{2}{L^2}) \\ &\text{Let } \frac{dT(L)}{dL} = \frac{1}{2} W_1 (r - \frac{2}{L^2}) = 0 \\ &\quad \text{Obtain } L_{\min} = L_0 = \left\lceil \sqrt{\frac{2}{r}} \right\rceil,\ r \neq 0 \\ &\quad \text{and} \quad T_{\min} = \frac{1}{2} W_1 (r L_0 - r + \frac{2}{L_0}),\ L_0 \neq 0 \end{aligned} \tag{9}$$

■

Theorems 2 and 3 reveal that the optimal labor allocation in a group project is not directly related to the size or the project's workload as conventional empirical studies suggested. However, it is solely determined by the key interpersonal coordination rate r in the given project determined by $T_{\min}(r, L_0)$.

Example 1. Given a project with an expected workload W_1 = 10PM and r = 10%. The optimal labor allocation L_0 and the shortest expected duration T_{min} for this project can be formally determined according to Theorem 4 as follows:

$$\begin{aligned} L_0(r) &= \left\lceil \frac{1.414}{\sqrt{r}} \right\rceil = \left\lceil \frac{1.414}{\sqrt{0.1}} \right\rceil \\ &= \lceil 1.414 \ / \ 0.316 \rceil \\ &= 5.0 \ [\mathrm{P}] \end{aligned}$$

$$\begin{aligned} T_{\min} &= \frac{1}{2} W_1 (r L_0 \text{ - } r + \frac{2}{L_0}) \\ &= 0.5 \bullet 10.0 \bullet (0.1 \bullet 5.0 \text{ - } 0.1 + 2 \ / \ 5.0) \\ &= 4.0 \ [\mathrm{M}] \end{aligned}$$

Although, Example 1 results in a workload, W = 5.0P • 4.0M = 20.0PM, in the optimal group organization form for the project, the gain is that the project duration has been reduced from 10 to 4 month. In other words, the time-oriented project optimization has enabled an interchange from 5-persons to 6 months by the optimal allocation of group size under the constraint of a given interpersonal coordination rate r.

2.3 Optimization of Project Organization in Engineering Management

According to the coordinative work organization theory as developed in preceding sections, the workload of a given project is dominated by the property of interpersonal coordination rate r inherited in group coordination. Further, the allocations of labor and time for a group project cannot be determined arbitrarily because they are interlocked by the rules as stated in Theorems 3 & 4.

After the ideal workload W_1 and the optimal labor allocation L_0 are determined, the duration of a group project or subproject (if multi-groups are needed) can be determined according to Theorem 6. When the optimal labor allocation and shortest duration of the project is determined, the expected real workload of the project can be rigorously derived.

Definition 4. The *optimal workload* of group project, W_0, is determined by the product of the optimal labor allocation L_0 and the shortest project duration T_{min}, i.e.:

$$\begin{aligned} W_0 &= L_0 \bullet T_{\min} \\ &= L_0 \bullet \frac{1}{2} W_1 (r L_0 - r + \frac{2}{L_0}) \\ &= \frac{1}{2} W_1 (r {L^2}_0 - r L_0 + 2) \quad [\mathrm{PM}] \end{aligned} \tag{10}$$

It is noteworthy that in conventional practice, a subjective and empirical project organization strategy without observing the optimal work allocation principle, i.e., $W_0(L_0, T_{min})$, may result in a significant loss of effort and/or time as shown in the following example.

Example 2. As given in Example 1, the optimal organization of a group project $W_0(L_0, T_{min})$ = W_0(5P, 4M) = 20PM with W_1 = 10PM and r = 10%. However, if the project is subjectively organized by using L = 9 persons, the resulted duration and workload of this project will be T = 5.1M and W = 45.9PM, respectively. This irrational project organization will result in a waste of effort as follows:

$$\Delta W = W - W_0 = 45.9 \text{ - } 20.0 = 25.9 \ [\mathrm{PM}]$$

This result reveals that a non-optimal organization of projects in engineering management is one of the hidden reasons or the black-holes that resulted in a failure in large-scale engineering project organization where the higher the r, the severer the risks in non-optimal project organization. This also explains why 2/3 of large-scale software engineering and system engineering projects had failed in the history according to statistical data [2, 34].

It is noteworthy that Theorem 4 applies to the optimal organization of any sized projects. In the case of large-scale projects, the following divide-and-conquer strategy will be adopted where each subproject still obey the same project optimization rule based on Theorem 5.

Theorem 5. *Time-oriented optimization for large-scale project organization* states that in order to further reduce the shortest duration T_{min} of an entire large-scale project constrained by Theorem 6, the optimal form of organization is to evenly partition the whole project into n lightly-coupled parallel subprojects that may be conducted by independent subgroups with the average a shortest duration $\overline{T^i_{\min}}$, $1 \leq i \leq n$, so that an average n-fold time deduction can be achieved, i.e.:

$$\overline{T^i_{\min}} = \frac{1}{n}\sum_{i=1}^{n} T^i_{\min} = \frac{1}{n} T_{\min} + \varpi \qquad (11)$$

where ϖ is a positive overhead needed for system integration or composition.

3. The Theory of Quality Assurance in Engineering Management

The previous sections reveal the group mechanisms and project organization in engineering management. This section explores the nature of human errors and the group mechanisms that contribute to the enhancement of quality assurance in engineering management.

It is recognized that individuals work in groups for large engineering projects in order to extend human physical and intelligent capabilities, to incorporate human strengths into complex information processing and decision-making, and to avoid human performance uncertainties due to fatigue, distractions, or non-rigorous actions. Therefore, human factors are not only a constantly important constraint in almost all disciplines of science and engineering, but also the most active and dynamic factors to be considered in project optimization.

3.1 Taxonomy of Human Errors in Group Work

Human factors in engineering management are the roles and effects of humans in a system that introduces additional strengths, weaknesses, and uncertainty. Human factors are the most predominant factor in all systems where humans are part of them. Numerals human factors have been identified in science, engineering, sociology, psychology, and everyday live. The taxonomy of human factors in engineering can be classified into human strengths, weaknesses, and uncertainties as shown in Table 1.

It is a fact that people do make mistakes in both contingent and routine work. Fortunately, most of them may be corrected by additional undo or redo actions. However, in safety- or mission-critical contexts, the impact of human errors can be catastrophic such as in the nuclear and chemical industries, rail and sea transports, as well as aviation.

Table 1. Taxonomy of Human Factors

No.	Category	Basic factor
1	Strengths	Natural intelligence, autonomic behaviors, complex decision-making, highly skilled operations, intelligent senses, perception power, complicated human coordination, adaptivity
2	Weaknesses	Low efficiency, slow reactions, error-prone, tiredness, and distraction
3	Uncertainties	Productivity, accuracy, reaction time, persistency, reliability, attitude, performance, and motivation to try uncertain things

Definition 5. A *human error* is an incorrect operation caused by wrong actions and inappropriate behaviors.

Christopher Wickens and his colleagues identified a long list of reasons that cause operation errors, such as inattentiveness, poor work habits, lack of training, poor decision making, personality traits, and social pressure [37]. The Systematic Human Error Reduction and Prediction Approach (SHERPA) proposed by D. Embry in 1986 identified sixteen potential psychological errors [8]. J. Reason developed a similar system in 1987 known as the Generic Error Modeling System (GEMS) [23, 24]. The set of human behavioural errors identified in SHERPA are: Action omitted, action too early, action too late, action too much, action too little, action too long, action too short, action in wrong direction, right action on wrong object, wrong action on right object, misalignment, information not obtained/transmitted, check omitted, check on wrong object, wrong check, and check mistimed.

A comparative study of the above work indicates that there is still a need to seek a more logical taxonomy of human errors, which will be developed in the following subsection.

3.2 The Behavioral Model of Human Errors

A formal behavioral model of human errors is derived in this subsection based on cognitive categories of human behaviors, which explains the fundamental mechanisms of human errors.

Definition 6. A *human behavior B* is constituted by four basic factors known as the sets of objects (*O*), actions (*A*), space (*S*), and time (*T*), i.e.:

$$\begin{aligned} B &= (O, A, S, T) \\ &= O \times A \times S \times T \end{aligned} \quad (12)$$

Any incorrect configuration in the four factors results in an error in task performance. Therefore, there are 16 modes of human behaviors on the basis of the combinations of the four dimensions as analyzed in the Behavioral Model of Human Errors (BMHE) in Table 2.

Corresponding to Table 2, a Human Error Tree (HET) is described as shown in Fig. 3. It is noteworthy that the identification of the object is the most important task in the chain of actions, because it is obvious that a correct action in a correct location at a correct time without a right object is obviously an incorrect action. Observing Fig. 3 and Table 2, it may be found that for a human operator, there is only 1/16 chance to get a given action or behavior correct, but there are 15/16 probability to get it wrong. That is, the probabilities of human success p(+) and error p(-) in performing a specific task, respectively, are:

$$\begin{cases} p(+) = \dfrac{1}{16} = 6.25\% \\ p(-) = \dfrac{15}{16} = 93.75\% \end{cases} \quad (13)$$

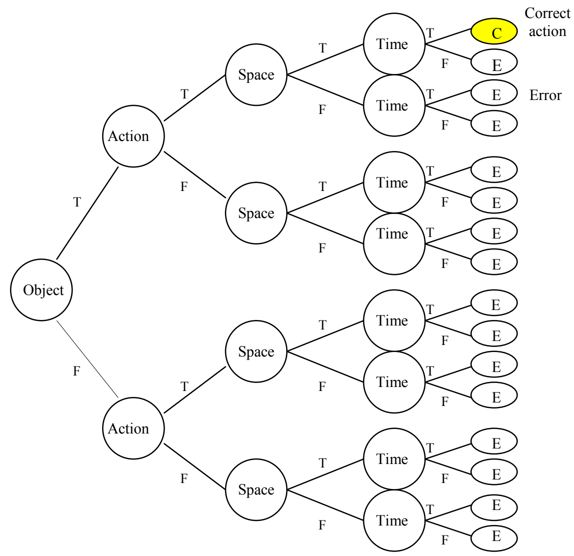

Fig. 3. The model of human error tree (HET)

Both the BMHE and HET models indicate that the natural rate of human errors in task performing would be very high. Fortunately, a well trained professional is fault-tolerant when performing tasks in a well established engineering process. The major means for fault-tolerant in task performing is checking and rechecking. By adopting all checking and monitoring techniques in each step of HET, the error ratio as shown in Eq. 21 can be significantly decreased as formally analyzed in the following subsection.

Table 2. The Behavioral Model of Human Errors (BMHE)

No.	Objects	Action	Space	Time	Error Mode
0	T	T	T	T	Correct action
1	T	T	T	F	Mode 1: Wrong timing
2	T	T	F	T	Mode 2: Wrong place
3	T	T	F	F	Mode 3: Wrong timing and place
4	T	F	T	T	Mode 4: Wrong action
5	T	F	T	F	Mode 5: Wrong action and timing
6	T	F	F	T	Mode 6: Wrong action and place
7	T	F	F	F	Mode 7: Wrong action, place and timing
8	F	T	T	T	Mode 8: Wrong object
9	F	T	T	F	Mode 9: Wrong object and timing
10	F	T	F	T	Mode 10: Wrong object and place
11	F	T	F	F	Mode 11: Wrong object, place and timing
12	F	F	T	T	Mode 12: Wrong object and action
13	F	F	T	F	Mode 13: Wrong object, action and timing
14	F	F	F	T	Mode 14: Wrong object, action and place
15	F	F	F	F	Mode 15: All wrong

3.3 The Theoretical Foundation of Quality Assurance in Engineering Management

On the basis of various fault-tolerant measures, the statistical properties of randomness of human errors may be observed referring to the HET model in Fig. 3.

Lemma 2. The *statistical properties of human errors* are as follows:

a) *Oddness*: Although individuals make different errors in task performance, the chance of making a single error for a given task is most of the cases than that of multiple errors.
b) *Independence*: Different individuals have different error patterns in performing the same task in a group.
c) *Randomness*: Most of the different individuals do not make the same error at the same time in a group.

Properties (a) through (c) reveal the random nature of human errors on object, action, space, and time in performing tasks in a group.

Corollary 1. The *random nature of human errors* during task performance in a group is determined by the statistical properties that the occurrences of the same errors by different individuals are most likely at different times.

The findings as stated in Lemma 2 and Corollary 1 form a theoretical foundation for fault-tolerance and quality assurance in engineering project management. They indicate that human errors may be prevented from happening or be corrected after their presence as soon as possible in a coordinative group context by means of independent inspections and peer reviews.

Theorem 6. The *n-fold error reduction structure* states that the *error rate of a work product* can be reduced up to *n*-fold against the average error rate of individuals r_e in a coordinative group via *n*-ary *peer reviews* based on the random nature of error distributions and independent nature of error patterns of individuals, i.e.:

$$R_e = \prod_{k=1}^{n} r_e(k) \tag{14}$$

Example 3. A software engineering project is developing by a group of four programmers. Given the individual error rates of the four group members as: $r_e(1) = 10\%$, $r_e(2) = 8\%$, $r_e(3) = 20\%$, and $r_e(4) = 5\%$, estimate the error rates of the final software system by adopting the following quality assurance structures, respectively, such as: (a) Pairwise reviews between Programmers 1 vs. 2 and Programmers 3 vs. 4; and (b) 4-ary reviews between all group members.

a) The pairwise reviews between Programmers 1-2 and Programmers 3-4 will result in the reduction of the following error rates R_{e1} and R_{e2}:

$$\begin{aligned} R_{e1} &= \prod_{k=1}^{2} r_e(k) \\ &= 10\% \bullet 8\% \\ &= 0.8\% \\ R_{e2} &= \prod_{k=3}^{4} r_e(k) \\ &= 20\% \bullet 5\% \\ &= 1.0\% \end{aligned}$$

b) The 4-ary reviews between Programmers 1 through 4 will yield the following error rate R_{e3}:

$$\begin{aligned} R_{e3} &= \prod_{k=1}^{4} r_e(k) \\ &= 10\% \bullet 8\% \bullet 20\% \bullet 5\% \\ &= 0.008\% \end{aligned}$$

Theorem 6 and Example 3 explain why multiple peer reviews may greatly reduce the probability of errors in group project. In the software engineering context, a four-level quality assurance system is adopted for mission-critical software projects as shown in Table 3.

Table 3. The Four-Level Quality Assurance System of Software Engineering

Level	Actor	Means
1	Programmer	Self checking, module-level testing
2	Senior engineer	Peer review, module-level testing
3	Tester/ quality engineer	System-level testing, audit, review, quality evaluation
4	Manager	Quality review, deliver evaluation, customer survey

Example 4. For a software project reviewed according to the four-level quality assurance system as shown in Table 3, estimate the quality of the final result of the program assuming the individual error rates are $r_e(1) = 10\%$, $r_e(2) = 5\%$, $r_e(3) = 2\%$, and $r_e(4) = 10\%$, respectively.

According to Theorem 6, the 4-ary quality assurance system may yield a significantly reduced error rate R_{e4} as follows:

$$
\begin{aligned}
R_{e4} &= \prod_{k=1}^{4} r_e(k) \\
&= 10\% \bullet 5\% \bullet 2\% \bullet 10\% \\
&= 0.001\%
\end{aligned}
$$

The results indicate that the error rate of the above system has been successfully reduced from the initial rate of 100bugs/kLOC to the final rate of 0.01bugs/kLOC. It demonstrates that the hierarchical organization structure for group quality assurance can greatly increase the quality of software engineering products and significantly decrease the requirement for individual's capability and error rates in software engineering project management. The fundamental theory of project quality assurance in group work can be applied in a wide range of engineering fields where a group of people are coordinately working together via optimal engineering management structures [38].

4. Conclusion

It has been recognized that the mechanisms of human group work is the key to explain a number of fundamental problems and theories in engineering management. The coordinative work organization theory has revealed the nature and principles underpinning human coordination in group work and the approaches for engineering project optimization. The basic properties and characteristics of coordinative work and their mathematical models have established, which explain the transformability between labor and time in coordinative work as well as the role of the interpersonal coordination rate in engineering projects. It has also explained how the error rate of a work product can be significantly reduced in a group via peer reviews based on the random nature of error distributions and independent nature of error patterns of individuals. The coordinative work organization theory for engineering management has provided a foundation for rigorously analyzing the work duration and effort in coordinative project organization. On the basis of the coordinative work organization theory, a set of decision optimization strategies have been derived towards optimal project organization for the best labor allocation, the shortest project duration, and the lowest effort.

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