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On Interdependence and Modularity: How to Divide a Team

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Abstract

This research addresses how worker interdependence combined with individual performances affect management's decision on how to modularize an organizational team that is evolving over time through replacements. A mathematical model is developed for determining how individual and team performances change when a team is split. Through computer simulations, managerial insights are provided on three fundamental decisions pertaining to dividing a team: (a) when to divide a team in terms of the team's "maturity," (b) how many workers to put on each team, and (c) which workers should move to the new team. With regard to the first of these decisions, the number of pre-division replacements is used as a measure of team maturity. Computer simulations are used to compare the short-term and long-term effectiveness of two team-splitting policies for determining which workers are assigned to the two new sub-teams.

1 Introduction

A classic management challenge is determining how to divide tasks among workers. In Adam Smith's (1776/2003) seminal work "The Wealth of Nations", he described the importance of the division of labor and drew attention to the value of increasing the specialization and simplification of work tasks. The outcomes of Frederick Winslow Taylor's (1911/1998) Scientific Management and Henry Ford's implementation of the assembly line constitute early powerful examples of the gains to efficiency available from splitting up tasks. Now, new challenges related to work specialization have surfaced in the form of modularization of product design and building its complementary organizational structure. Where once efficiency alone was the goal of splitting up tasks among workers and assigning workers to appropriate groups, now innovation and flexibility are also objectives.

Modular product design generally involves taking a product whose parts were once integrated and separating them. The separation process creates parts—modules whose outputs are predefined, but that are otherwise independent in their functioning. Designers try to reduce module size so that each module encompasses the smallest number of interdependent physical parts or processes.

As a result of the division, the functioning of each partition will no longer be constrained by the design process of the other partitions. The design of the modern personal computer is a prominent example of this changing architecture (see Baldwin & Clark, 2000), although many other products from automobiles, airplanes, consumer electronics, household appliances, and power tools have moved increasingly toward modularity in their product design (Sanchez & Mahoney, 1996). Indeed, modularity is a precursor to outsourcing and off-shoring, channels for substantial cost-savings for firms (see Schilling & Steensma, 2001).

Pressures arise to increase the modularity of tasks when inputs could be configured in many heterogeneous ways or customer demands are highly heterogeneous (Schilling, 2000). These two forms of heterogeneity offer the most opportunities for gains through modularity. The greater the variety of ways that a product could be built or a task completed, the more modularity pays. When recipients want flexibility in their products—different customers have different demands or a single customer wishes to make changes to their product or services over time—modularity provides gains. These gains allow managers to take advantage of the flexibility and innovation produced by work broken into modules.

Modularity, however, is not restricted to product architecture; the underlying modularity of tasks is a natural criterion for dividing workers into teams. In team design, modularity exists when teams work independently of each other while members of each team are highly interdependent. Usually, the work of the various teams is then pooled to achieve a finished product or service.

For the purposes of this research, "interdependence" includes any form of interaction among team members that affects a member's individual performance, such as task dependence, resource and information dependence, and dependence on sequencing of work (see Wageman, 1995 for an overview of types of interdependence and Krackhardt and Carley, 1998 for a formalization). Interdependence has also been characterized by the sequencing of obligations (Thompson, 1967). Modular designs embody pooled interdependence among teams. In this case, sufficient resources are provided independently for each team, all tasks are completed within teams and outcomes are pooled only after completion. While the purpose of modularizing a team's tasks and resource use is to create pooled interdependence among teams, the optimal team boundary demarcates the minimum sequential or reciprocal interdependence necessary for successful task completion within the team. In sequential tasks, one or more tasks must precede the others for completion. In contrast, reciprocal interdependence involves simultaneous dependencies across tasks and individuals. From here on, interdependence is used to refer to these sequential and reciprocal dependencies within teams.

One important example of task modularization comes from the computer software industry. Software developers designed object-oriented programming to modularize coding tasks previously written in a structural form. The product of each team is invisible to the other modules except for the predetermined output. Breaking the writing of code into modules written by small teams limits the impact of any one programmer's errors. An error affects only components within the module rather than all of an integrated piece of software. Moreover, breaking the work into modules increases the ability of teams to complete modules while working in parallel rather than sequentially, substantially speeding up the coding process.

Managers may embrace modularity in order to limit the uncertainty that complicates coordination and to allow controlled variation in products or services. Further, modularity may create clarity in goals and tasks for team members sufficient to limit the need for management attention (see Sanchez & Mahoney, 1996 on information structures replacing managerial authority). Managers generally achieve independence between teams by establishing external coordination arrangements prior to the point in time when the teams begin their work. They may achieve this coordination in a number of ways including creating greater group cohesiveness (Kerr & Jermier, 1978), using design rules (Baldwin & Clark, 2000), or information systems (Sanchez & Mahoney, 1996).

1.1 The Process of Modularizing

Modularity is viewed by some as a general property of complex systems (Holland, 1995), whether those systems are physical, biological, or social (Simon, 1962). Complex systems can be intentionally decomposed into loosely coupled subsystems each composed of tightly-coupled parts (Simon, 1962, Weick, 1976). Simon (1962) argues that these systems composed of many sub-parts evolve faster than systems of comparable size without sub-parts (p. 468). They do so because intermediate sub-parts may stabilize and allow other parts to adapt. Innovation or changing speed-to-completion demands changes in other sub-parts. Adaptation of all parts to each other simultaneously, as is necessary in an integrated system, requires a much larger number of experimental variations.

The key decisions in modularizing work processes include 1) separating the task into relatively independent modules, 2) creating the coordination mechanisms among the task teams, 3) testing the performance of modularized teams with emphasis on consequences of unforeseen interdependencies, and 4) enhancing the performance of the independent work teams (Baldwin & Clark, 2000; Narduzzo & Rossi, 2003).

When managers intentionally decompose task systems, they try to minimize interdependencies between teams while building teams around already interdependent task groupings (Baldwin & Clark, 2000; Langlois, 2002; Schilling, 2000). Yet, neat divisions do not always exist. Managers must find a way to navigate among interdependent relationships to support the necessary and eliminate the least essential, while creating more than one effective team. In addition, since the ability to produce output well evolves more rapidly within a system split into sub-parts, managers must decide when to split the teams and when to reconfigure their membership.

Evolution via changing team membership is a standard feature of organizational life. People join the organization and people leave. Modularization works as part of a dynamic process rather than as a static design principle (Narduzzo & Rossi, 2003). Most modularized work systems begin with a group of people performing a somewhat integrated set of tasks. As people come and go, managers identify opportunities for improvement through separation of these tasks. Yet, modularization rarely occurs as a one-time event. Turnover as well as subsequent testing generates opportunities for improvements within the teams and refinements in the choice of teams and membership.

Given interdependencies between tasks and thus among the people doing them, there may be a large variety of combinations of these people into sub-teams that could produce the desired final output. Because of this variety, it remains challenging for managers to determine how to split their people into teams for maximum performance. Little research exists on the best policies in varying circumstances for splitting groups of interdependent people into relatively independent teams.

1.2 Contributions of this Research

The contribution here is a mathematical model that focuses attention on certain factors that a manager should take into account when modularizing a team. The proposed model, based on the *NK* model of Kauffman and Levin (1987) originally used to study complex interactions in the evolution of chromosomes, includes a controllable parameter representing the degree of interdependence within a team, that is, the number of other workers that affect each focal worker's individual performance. When a team is split into two sub-teams, the model provides a mechanism for assessing each focal worker's new performance contribution that results from lost and newly formed interdependencies as well as the performance level achieved by pooling the work of the sub-teams.

Through computer simulations, managerial insights are provided on three fundamental decisions pertaining to modularizing a team: (a) when to divide a team in terms of the team's "maturity," (b) how many workers to put on each team, and (c) which workers should move to the new team. With regard to the first of these decisions, the number of pre-division replacements is used as a measure of team maturity. For example, when a new team is formed, the initial configuration of workers that has not benefited from a substitution would be considered *immature*. The team then matures as members are replaced, eventually resulting in a team that functions well as a unit due to the strengthening of interdependent relationships through smart employee substitutions.

When splitting a team, the manager has new decisions to make, for example, *when* to divide the team during the replacement process. A second decision often includes the number of employees to assign to each new team, for instance, when dividing a large hospital unit that comprises discrete tasks or a management team engaged in knowledge-based tasks into smaller functioning units. In other groups where this cannot be controlled—for instance, in an inflexible assembly process—team sizes are determined by the work processes. Once team sizes are decided (or given), the most important decision remains: how should employees be reassigned to the new sub-teams?

Regardless of how mature the team is when divided and how large the two resulting sub-teams are, the manager's key decision is which workers to move to the new team. This decision is based on many factors, such as job skills, prior experience at a task, leadership and other role abilities, demographic composition, history of working together, salaries, project or relocation costs, and managerial preferences. Because the objective here is to gain understanding into how worker interdependencies affect such decisions, two interdependency-based *policies*—that is, rules that identify which members move to the sub-teams—are proposed. While implementing these policies may be challenging, results from computer simulations nevertheless provide intuition about interdependencies—which are assumed to be inherent in the types of activities undertaken by a team and not controllable—that a manager should keep in mind when faced with such a reorganization.

The proposed model is developed in Section 2 together with a brief description of the *NK* model, on which the model is based. Results of computer simulations with two policies for dividing a team are discussed in Section 3 and sensitivity analysis with regard to several of the key model assumptions is presented in Section 4. Conclusions, limitations of the model, and future potential areas of investigation are presented in the final section.

2 The *NK* and Bounded *NK* Models

The model proposed in Section 2.2 is based on the *NK* model introduced by Kauffman and Levin (1987) and Kauffman (1993). Since then, the *NK* model has been used to study a variety of organizations in the social sciences that exhibit evolutionary behavior due to complex interactions. Examples include firms, economies, political systems, technologies and teams [see the introduction of Rivkin and Siggelkow (2002) for a review]. With respect to teams, the *NK* model mathematically captures how relationships among coworkers lead to emergent, difficult-to-predict group performance. By replacing the "right" worker taking into account these interdependencies, a manager can enhance the productivity of other group members. Managerial insights into the best replacement strategy and can be gleaned from studying the *NK* model (e.g., Solow et al., 2002).

The *NK* model has also been extended to study the value of leadership in an organization. For example, Solow et al. (2003 and 2005) modified the *NK* model to include the role of a manager as one who motivates and instills cooperation among interacting workers. In a different direction, Rivkin and Siggelkow (2002, 2003 and 2005) show how managerial ability, incentives and control influence firm performance when it is necessary to make interrelated choices in two coevolving departments with conflicting objectives. The work proposed here also requires a model involving multiple teams, but differs in the assumption that the interdependence between workers assigned to different teams will be negligible after the split due to the goals of modularization.

2.1 The *NK* Model

The *NK* model is described now in the context of a team. A team consists of N positions labeled 1 through N. Managers choose among several candidates to staff each position, and for the sake of simplicity, it is assumed that candidates are eligible for only one position. Solow et al. (2000) showed that many insights from the model are essentially the same if each position is restricted to two candidates, and this binary choice conveniently allows the candidates for a particular position to be labeled candidate 0 and 1. Variable x_j represents the label 0 or 1 corresponding to the candidate selected for position j and $\mathbf{x} = (x_1, \ldots, x_N)$ identifies the members of the team.

Assessing the performance of interdependent individuals and their teams can be quite challenging in practice (Solow et al., 2002, Sec. 1.1). The performance of worker x_j is therefore modeled as a number p_j between 0 and 1, with values closer to 1 indicating better performance. This performance depends on the person in position j as well as the contributions to the focal person of people in K other positions—say, the K positions to the right of position j, wrapping around if necessary. Anytime one of these K contributing workers is replaced, the *NK* model captures the uncertainty of new interdependent relationships by updating p_j with a new $0-1$ random number drawn from a uniform distribution.

The overall team performance is taken to be the average of the worker contributions, that is, $p(\mathbf{x}) = \frac{1}{N}\sum_{j=1}^{N} p_j$. The objective is to choose a candidate for each position so that the resulting team $\mathbf{x}$ maximizes $p(\mathbf{x})$. With 2^N possible team configurations, Kauffman proposed a computationally efficient local search that uses replacements to find a productive team. Starting with a randomly organized team, this search moves to successively better teams by replacing the worker in one position at a time, until no further improvement by such a replacement is possible. The final resulting team is called a *local maximum team.*

Kauffman computes the expected performance of local maximum teams when $K = 0$ and $K = N - 1$, as the team size N gets large. He also uses simulations to show that, for large teams, local maximum performance benefits from small $(0 < K < 8)$ amounts of interdependence but then degrades as the number of interdependent relationships K approaches saturation $N - 1$, a phenomenon known as the *complexity catastrophe.* The catastrophe results from the effects on individual performances that result when all components of a system are so tightly connected.

2.2 The Bounded *NK* Model

While the *NK* model captures many desirable properties of teams, it cannot be used directly to study team modularization. One reason is that when a team is divided, individual worker contributions change when interdependent relationships are lost and reestablished. The issue of how to compute the performance of a focal worker x_j when moved to a sub-team is now addressed.

Consider first a worker x_j who, when moved to a sub-team, loses an interdependency with only one of the K co-workers who previously affected that worker's performance and subsequently establishes one new interdependency with a member on the sub-team. Exchanging an old relationship with a new connection can be thought of as replacing one of the K co-workers who originally interacted with the focal worker x_j. In the *NK* model, when one of those K co-workers is replaced, a new $0-1$ random number is generated for the performance of the focal worker x_j. Doing so can result in a significantly different performance level for worker x_j on the new team. Such a radical change in performance may occur when either the one new interdependency drastically affects the performance of worker x_j or the task of worker x_j on the sub-team changes completely—possible but unlikely events. A more realistic assumption is that an employee's performance changes little if contact is maintained with most of the K co-workers and changes more substantially as the number of new interdependencies that must be formed increases. Incorporating this assumption requires a departure from the standard *NK* model and is one contribution of the model proposed now.

When a worker x_j is reassigned to a sub-team along with all K of the original co-workers, it is reasonable to assume that the performance p_j of the worker x_j is virtually unaffected. At the other extreme, if all K co-workers are assigned elsewhere, then the worker x_j must form entirely new relationships and the worker's performance p_j would vary most widely, as low as 0 or as high as 1. When contact is broken with *some* of the K co-workers, the new performance is assumed to vary within limits that are proportional to the number of lost co-workers, with these limits being closer to 0 and 1 as the number of disrupted interdependencies approaches K.

The *bounded NK model* captures this feature in the following way. Let d_j be the number of the K original co-workers with whom the focal worker x_j loses contact when the team is split. Consider first the case when the worker x_j is able to establish connections with d_j new workers after the reorganization. When $d_j \geq 1$, the worker's performance p_j is updated with a new performance p'_j that is a random number between lower and upper limits, denoted l_j and u_j, around the worker's performance p_j. If worker x_j severs interdependencies with all K co-workers, then, when $d_j = K$ new interdependencies are reestablished in the sub-team, the new performance contribution p'_j of worker x_j can be anything between lower-bound $l_j = 0$ and upper-bound $u_j = 1$. At the other extreme, if $d_j = 0$, none of the workers that interact with x_j is being replaced, and so the bounds $l_j = u_j = p_j$. The following formula, based on the number of connections lost d_j, is used to determine the values of the lower and upper bounds in a linear way:

$$l_j = p_j - \frac{d_j}{K} p_j \quad \text{and} \quad u_j = p_j + \frac{d_j}{K}(1 - p_j). \tag{1}$$

Note that lower-bound l_j and upper-bound u_j are the fraction of the number of lost connections divided by the number of original connections, d_j/K, times the distance from the original worker's performance p_j to 0 and 1, respectively.

It can happen that worker x_j loses d_j connections during a reorganization and is unable to reestablish the same number of interdependencies on the new team. To see how this might happen, consider a team of 8 workers in which each worker x_j interacts with the $K = 3$ workers to the right of x_j if the workers were arrayed in an imaginary circle. In a reorganization where sub-team 1 consists of workers 1, 2, and 3 and sub-team 2 consists of workers 4, 5, 6, 7, and 8, worker 1 loses one interdependent relationship with worker 4 but cannot establish a new relationship on sub-team 1 because this sub-team consists of only three workers, two of whom already interact with worker 1. In this case, d_j in equation (1) is taken to be the number of severed interdependencies, regardless of the number of new interdependencies that worker x_j can reestablish after the reorganization.

Equation (1) captures another aspect of human performance in that when poorly working interdependencies are disrupted for a poor performer, on average, that person's performance on a new team is likely to improve. Similarly, more often than not, performance of stronger employees is harmed by team division due to lost interdependencies with key people. Using equation (1), it is possible to prove that if the performance of worker x_j is below average ($p_j < 1/2$), then the new performance p'_j of worker x_j is expected to be better than the old performance p_j. Likewise, if the performance of worker x_j is above average ($p_j > 1/2$), then the new performance p'_j of worker x_j is expected to be worse than the old performance p_j. For this reason, this property of equation (1) is referred to as the *average performance reverting property.* Team research suggests that people who are poor performers may have low skills, but alternately the group itself may be limiting a member's success by, for example, scapegoating, bullying, or stereotyping. The diversity literature (e.g., Cox, 1993) and the minority influence literature (e.g., Schachter, l951) document the type of rejection faced by people who differ from the majority.

What is needed now is a way to combine the performances of two split teams into the performance of the resulting group as a whole, called *two-team performance.* Here, to incorporate varying sub-team sizes, two-team performance is taken to be the average of the updated individual worker contributions: $P' = \frac{1}{N}\sum_{j=1}^{N} p'_j$. Because the performances of the sub-teams use the same formula as that of the undivided team—namely, the average performance of the workers on the team—each worker's contribution is equally important before and after division. The important distinction is how interdependencies are altered by the division and what impact this has on an individual's performance contribution. Other schemes for computing two-team performance are considered in Section 4. (See Section 3.2 for a description of replacements in the bounded *NK* model.)

In addition to the "bounding" process described above, this model is distinct in other important ways from earlier applications of the *NK* model. We do split the landscape, reducing the number of interdependencies. But, the existence of a landscape and the process of groups of agents exploring that landscape searching for the peaks are identical to the processes represented in earlier papers.

We assume, consistent with the goals of modularity, that the teams will be divided so that productive interdependent relationships are sustained. If the underlying task, resource, and information flow and the sequencing of events in these working relationships remain substantially unchanged, we can reasonably presume that the key components of interdependence are the same or very similar in the partition as in the original team. People tend not to "mess with success (Audia, Locke, & Smith, 2000) and routinized behavior locks people in both cognitively and motivationally as people "know what to do" from experience (Nelson & Winter, 1982). It is certainly possible that some productive relationships change, but we expect these to be minor relative to the core determinants of the interdependencies.

3 Managerial Implications of Policies for Dividing a Team

The bounded *NK* model can now be used to gain insights into the impact of team member interdependencies on three managerial decisions regarding team division, namely, (a) when to divide a team in terms of the team's "maturity," (b) how many workers to put on each team, and (c) determining which workers should move to the new team. As mentioned in Section 1.1, the number of pre-division replacements is used as a measure of team maturity. When dividing a team, a manager might be concerned with both the short-term effects—that is, what happens to team performance immediately after division—and the long-term effects—that is, what happens to performance after the divided teams are allowed to mature through additional replacements. The short-term consequences of dividing an immature team using two policies are investigated in Section 3.1 and the short-term and long-term effects of dividing more mature teams are studied in Section 3.2. Throughout, it is assumed that the original team consists of N members, of which N_1 stay on the current sub-team 1 and the remaining N_2 members move to the new sub-team 2.

3.1 Short-term Consequences of Dividing an Immature Team

Whenever a collection of N people join forces for the first time, one would expect average performance from the group. For example, the first-year performance of any expansion team in professional sports is usually average at best. The same is true of the *NK* model where the expected performance of the workers on an immature team is 1/2. In fact, it can also be shown that the expected performance of randomly dividing an immature team is 1/2 for any size of sub-team 1 and sub-team 2, so there is no expected benefit from doing so.

In contrast, one might hope for improved performance when a more intelligent policy is used to divide a team. Motivated by the "Sorted First Come, First Serve Based on K" policy introduced by Solow et al. (2002) for deciding the order in which to replace members of a team, the following interdependency-based policy is now proposed for modularizing a team:

Policy 1: Eliminate the worker with the worst performance taking into account interdependencies. This policy seeks a worker x_j who, on being moved, will have the most beneficial impact on the collective performances of the remaining K workers who depend on x_j. Thus, for each worker x_j, the sum of the performances of x_j and the K co-workers to the left in the imaginary circle who are affected by x_j is computed, and referred to as the *total contribution* of worker x_j. Workers are sorted in increasing order of their total contribution and the first number N_2 of such individuals (i.e., those with the lowest contribution) is moved to sub-team 2.

For example, consider an eight-member team with $K = 2$ interdependent relationships and the following performances as an individual as well as their total contributions:

position	1	2	3	4	5	6	7	8
individual performance	0.1	0.9	0.4	0.7	0.5	0.6	0.2	0.7
total contribution	1.0	1.7	1.4	2.0	1.6	1.8	1.3	1.5

When the size of sub-team two is $N_2 = 3$, the three workers moved to sub-team 2 by this policy are those in positions 1, 7, and 3 because their respective total contributions are the three smallest.

3.1.1 Dividing an Immature Team Based on Eliminating the Worst Relationships

The short-term effects of dividing an immature team using Policy 1 for different numbers of interdependent relationships K and sub-team 1 sizes N_1 are illustrated in figure 1, where it is observed that for small numbers of interdependencies, the partition sizes of the sub-teams, N_1 and N_2, significantly impact team performance immediately after the division. For example, when the number of interdependencies per worker is $K = 1$ and the size of sub-team one N_1 is small (that is, most members are moved to sub-team 2), average performance decreases immediately after division. In contrast, average performance increases when N_1 is large (that is, few members are moved to sub-team 2). To see why the latter is true, consider what happens when only one member of the original team, say, worker x_j, is moved to sub-team 2. By definition of Policy 1, that worker's total contribution (which includes interdependencies) is the smallest. Hence, worker x_j and the $K = 1$ worker x_{j-1} who is affected by x_j are each likely to have below-average (less than 0.5) performances (this, however, is less likely to be true when dividing more mature teams—see Section 3.2). According to equation (1) with $d_j = K = 1$, the performance of worker x_j on sub-team 2 is generated as a new $0 - 1$ random number that is likely to be greater than the original performance of the worker x_j since the original performance is below average. Simultaneously, the new performance of x_{j-1} who remains on sub-team 1 is generated as a $0 - 1$ random number that is also likely to be greater than the original performance of x_{j-1}. The remaining workers are retained on sub-team 1 with their performances unchanged. The net result is that the performance of each of the two sub-teams—and hence the two-team performance—is likely to improve over the original team, as seen in figure 1 for the number of interdependencies $K = 1$ and a sub-team 1 size of $N_1 = 19$.

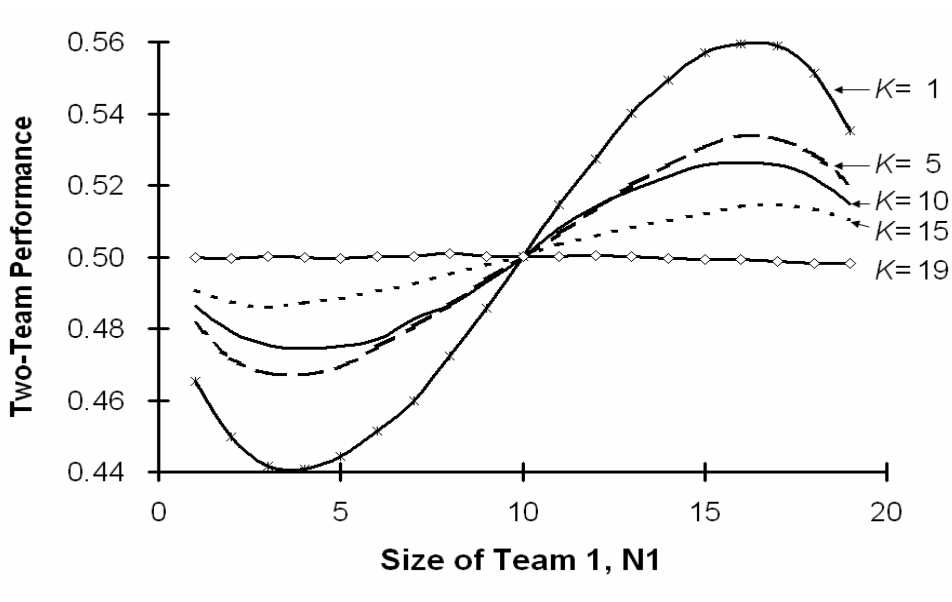

Figure 1: Simulated performance of dividing immature teams using Policy 1 when $N = 20$ and $K = 1$.

The foregoing explanation leads to the most important insight about interdependencies when dividing an immature team: *to improve two-team performance, give the lowest performing employees the largest opportunity to improve while maintaining the performance of the best workers.* And the way to give the lowest-performing workers the largest opportunity to improve in the bounded *NK* model is to disrupt more of their interdependencies. To be successful, a policy must also minimize the disturbance to the relationships of workers who are performing well so that their performance decreases minimally. In general, this is achieved by assigning the majority of the high-performing employees with their most supportive teammates to the larger team. In terms of the model, a strategy that disrupts as many interdependencies as possible of the workers with the lowest total contributions is referred to as the *minimum performance, maximum change rule* (mpMC rule).

This mpMC rule also provides the basis for an explanation as to why the curve for $K = 1$ in figure 1 first increases as the size N_1 of sub-team 1 decreases from its maximum value of 19 and then decreases below $N_1 = 16$. To illustrate, consider what happens when two members of the original team, say x_i and x_j, are moved to sub-team 2 and suppose that x_i and x_j are not interdependent prior to division. According to Policy 1, these two workers' total contributions to the team are smallest, hence, x_i and x_j and the two other workers who depend on them are each likely to have below-average performances. Since x_i and x_j do not interact with each other and they each interact with $K = 1$ other original team members, their performances on sub-team 2 as well as the performance of the two affected workers on sub-team 1 will each be new $0 - 1$ random numbers that are likely to be greater than their original performances. At the same time, the performances of the other 16 workers who are retained on sub-team 1 remain unchanged. So, increasing the size of sub-team 2 from $N_2 = 1$ to $N_2 = 2$ results in increasing the number of disrupted interdependencies from 2 to 4. Had workers x_i and x_j been interdependent prior to division, then only three workers realize change and likely improvement through division. Either way, in accordance with the mpMC rule, additional improvement is achieve when the size of sub-team 2 is $N_2 = 2$, as seen in figure 1.

However, as the size N_1 of sub-team 1 decreases further, more low-performing workers are moved to sub-team 2 with increasing likelihood of having interdependencies with each other. Thus, according to equation (1) in the bounded NK model, the new performances of these workers are likely to improve less than if those workers who move to sub-team 2 had no interdependent relationships among themselves. At the same time, equation (1) implies that the fewer remaining workers on sub-team 1 will realize a more drastic downward change in their performances because they are most likely above-average performers prior to division who are losing an increasing number of beneficial interactions with co-workers who move to sub-team 2. In summary, as the size N_1 of sub-team 1 decreases from its maximum value, two-team performance initially improves but then starts to decrease due to an increasing number of retained interdependencies from the original team on sub-team 2 and a simultaneous increase in lost interdependencies from those remaining on sub-team 1, as seen in figure 1 when N_1 decreases from its maximum value of 19.

To validate the foregoing explanation, simulations were conducted by dividing an immature team of 20 workers with $K = 1$ relationship per worker and a controlled number of workers going to sub-team 2 under Policy 1. Because the number of relationships per worker is $K = 1$, the new performance of each worker x_j who moves to sub-team 2 is either unchanged if the interdependent co-worker x_{j+1} also moves to sub-team 2, or changed to a new $0-1$ random number if interdependent co-worker x_{j+1} remains on sub-team 1. According to the preceding discussion, the fewer the number of workers who move to sub-team 2 with unchanged performance, the better the two-team performance should be. This intuition is confirmed by the results in figure 2, in which the x-axis represents the number N_2 of workers moving to sub-team 2 and the y-axis represents the average two-team performance after splitting the team with N_2 workers moving to sub-team 2.

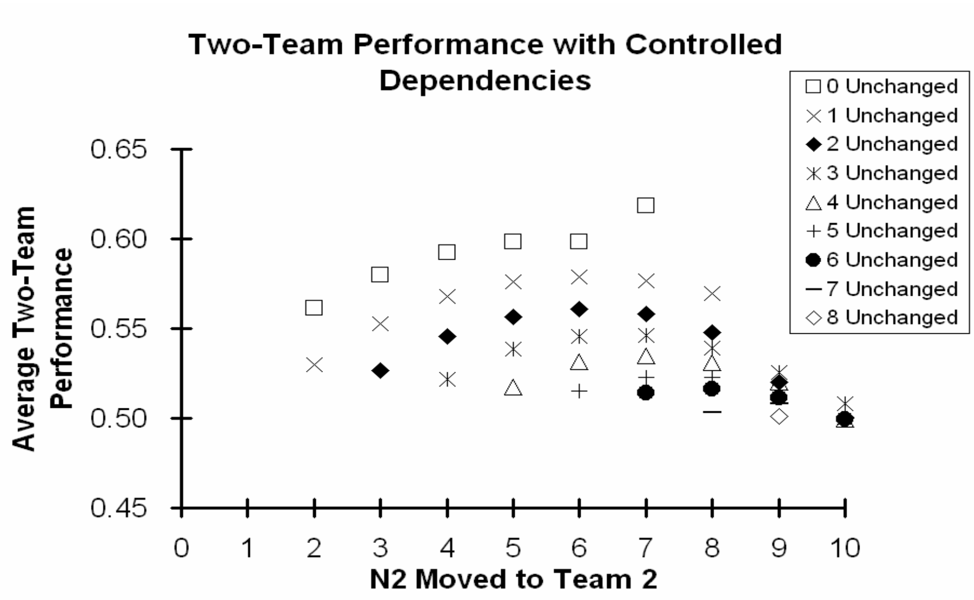

Figure 2: Simulations controlling the number of workers who move to sub-team 2 with unchanged performance when the number of workers $N = 20$ and the number of interdependencies per worker $K = 1$.

For example, the three points plotted directly above the value of $N_2 = 3$ in figure 2 represent the average two-team performance when the number of the N_2 workers moving to sub-team 2 with unchanged performance is 2, 1, and 0, respectively. More generally, for each value of N_2, 100,000 immature teams were generated and split using Policy 1 and then put into groups, depending on how many of the N_2 workers moving to sub-team 2 had their performance unchanged. The average two-team performance for all teams in each group was computed and plotted as a single point in figure 2. As seen there, for any size N_2 of sub-team 2, the fewer the number of workers who move to sub-team 2 with unchanged performance, the better the average two-team performance is.

Returning to figure 1, observe that as the size N_1 of sub-team 1 decreases below one-half, the foregoing performance benefits of division are eventually offset by workers with above-average performance being moved to sub-team 2. In summary, as the size of sub-team one N_1 decreases, two-team performance immediately after the division first increases and then starts to fall from its maximum and, if more than half of the workers are moved to sub-team 2, the result is a net decrease in two-team performance when compared to the original team. This sinusoidal pattern for the curve associated with the number of interdependent relationships $K = 1$ is also evident for the other values of K in figure 1, but to a lesser degree.

Another observation from figure 1 is that the curves flatten out and approach 0.5 as the number of interdependencies K between workers increases. This means that as the number of interdependencies increases, the maximum amount of performance improvement that can be obtained immediately after division decreases to the point where dividing a fully-interacting team yields virtually no improvement, even with the best partition sizes. The decrease in two-team performance to 0.5 for a fully-interacting team ($K = N - 1$) can be explained as follows. When workers have interdependencies with all other workers on their team, the total contribution of each worker x_j is that person's contribution plus the sum of the performances of all other workers. In other words, when $K = N - 1$, each worker's total contribution is identical. Thus, the N_2 workers that are moved to sub-team 2 are, for all practical purposes, chosen randomly. As mentioned previously, it can be proved that the expected two-team performance of dividing a team randomly with any partition sizes N_1 and N_2 is 0.5, which explains why the curve for team sizes $K = 19$ in figure 1 is approximately flat.

3.1.2 Dividing an Immature Team Based on Exploiting the mpMC Rule

As just seen, the immediate benefit of dividing an immature team with the best possible partition decreases as the number of interdependencies of each worker increases. It is therefore worthwhile to seek a policy that overcomes this drawback. Such a policy should be based on the mpMC rule in which one would ideally disrupt many interdependencies of low-performing workers, in the hope that new relationships will lead to better performance, while maintaining most interdependent relationships of high-performing workers. To maintain desirable interdependencies, the proposed policy divides the team into two adjacent groups and the point of division is determined by the employees who collectively would benefit most by having their relationships severed. To identify such a split, for each possible partition of the team into two contiguous sub-teams, a measure is now proposed with the property that the smaller that measure, the more likely such a division will, collectively, benefit weak performers by disrupting many of their interdependencies while not hurting strong performers, by disrupting few of their interdependencies.

To understand this measure, consider the team in figure 3 where workers 1, 2, 3, 4, and 5 remain on sub-team 1 and workers 6, 7, and 8 move to sub-team 2. As seen, after division, workers 5 and 8 lose all their prior $K = 3$ connections, workers 4 and 7 lose all but one of their prior 3 connections,

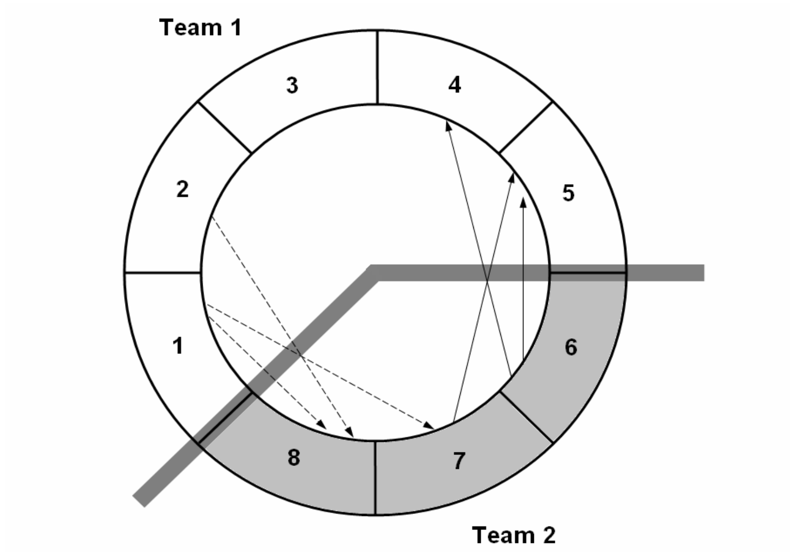

Figure 3: An example of lost connections when a team is split into two contiguous teams and $N = 8$, $K = 2$ and $N_1 = 5$.

and so on. According to the mpMC rule, it would be best if the workers in the ending positions 5 and 8 have the worst performance, those in positions 4 and 7 (one position in from the end) have the next worst performance, and so on. While this cannot be guaranteed, an appropriate measure can be obtained by adding up each worker's performance weighted by the fraction of that worker's K connections lost in the division. The smaller the value for this sum, the more likely such a division will benefit weak performers removed from sub-team 1 by disrupting many of their interdependent relationships while not hurting strong performers on sub-team 1 by disrupting few of their interdependencies. Similarly for sub-team 2. In summary, the following policy is proposed.

Policy 2: Disrupt weak collective interdependencies. Given desired team sizes N_1 and N_2, divide the team into two adjacent sub-teams in such a way that when workers are numbered so that $1, \ldots, N_1$ are on sub-team 1 and $N_1 + 1, \ldots, N$ move to sub-team 2, the following *total weighted performance* is as small as possible:

$$TWP = \sum_{j=1}^{N_1} \frac{d_j}{K} p_j + \sum_{j=N_1+1}^{N} \frac{d_j}{K} p_j \tag{2}$$

To demonstrate Policy 2, recall the previous example where a team of $N = 8$ workers and

$K = 2$ interdependencies each with initial performances $p = (0.1, 0.9, 0.4, 0.7, 0.5, 0.6, 0.2, 0.7)$ is partitioned so that the size of sub-team 2 is $N_2 = 3$. Under Policy 2, there are eight ways to move $N_2 = 3$ adjacent workers in an imaginary circle to sub-team 2, and hence eight TWP measures to compare. One such division, depicted in figure 3, retains workers $1, \ldots, 5$ and moves workers 6, 7 and 8 to sub-team 2. The dashed lines in figure 3 indicate that, as each worker depends on $K = 2$ other workers, worker 7 loses one connection with worker 1 and worker 8 loses connections with workers 1 and 2. Similarly, workers 4 and 5 lose one and two connections, respectively, as indicated by the solid lines in the figure. Workers 1, 2, 3 and 6 realize no disrupted interdependencies. Thus,

$$TWP = \left(\frac{0}{2}p_1 + \frac{0}{2}p_2 + \frac{0}{2}p_3 + \frac{1}{2}p_4 + \frac{2}{2}p_5\right) + \left(\frac{0}{2}p_6 + \frac{1}{2}p_7 + \frac{2}{2}p_8\right) = 1.65$$

The next division considered would be to retain workers $2, \ldots, 6$ on sub-team 1 and assign workers 7, 8, and 1 to sub-team 2 with the following measure:

$$TWP = \left(\frac{0}{2}p_2 + \frac{0}{2}p_3 + \frac{0}{2}p_4 + \frac{1}{2}p_5 + \frac{2}{2}p_6\right) + \left(\frac{0}{2}p_7 + \frac{1}{2}p_8 + \frac{2}{2}p_1\right) = 1.30. \tag{3}$$

Under Policy 2, the second partition with the smaller TWP is preferred to the first because the strongest three workers (2, 4 and 8) maintain the same or better interdependent relationships and the worst worker (worker 1) increases from zero to two severed connections. In fact, this particular division provides the lowest TWP of the eight divisions considered by Policy 2, and hence is the partition that takes maximum advantage of the mpMC rule.

Results of computer simulations comparing short-term performances of Policies 1 and 2 on immature teams are shown in figures 4, 5 and 6. Several properties of Policy 2 are first identified and explained. For example, as seen in figure 4, two-team performance under Policy 2 is symmetric about the division where sub-team 1 is half the size of the original team ($N_1 = N/2$). To understand why, consider the foregoing numerical example in which there are $N = 8$ workers and the size of sub-team two is $N_2 = 3$. As computed in equation (3), the division that minimizes the TWP has workers 7, 8, and 1 moving to sub-team 2 and the other five workers remaining on sub-team 1. According to the way the TWP is computed in equation (2), when the size of sub-team 2 is $N_2 = 5$, the TWP of the division in which workers 7, 8, and 1 stay on sub-team 1 and the remaining five

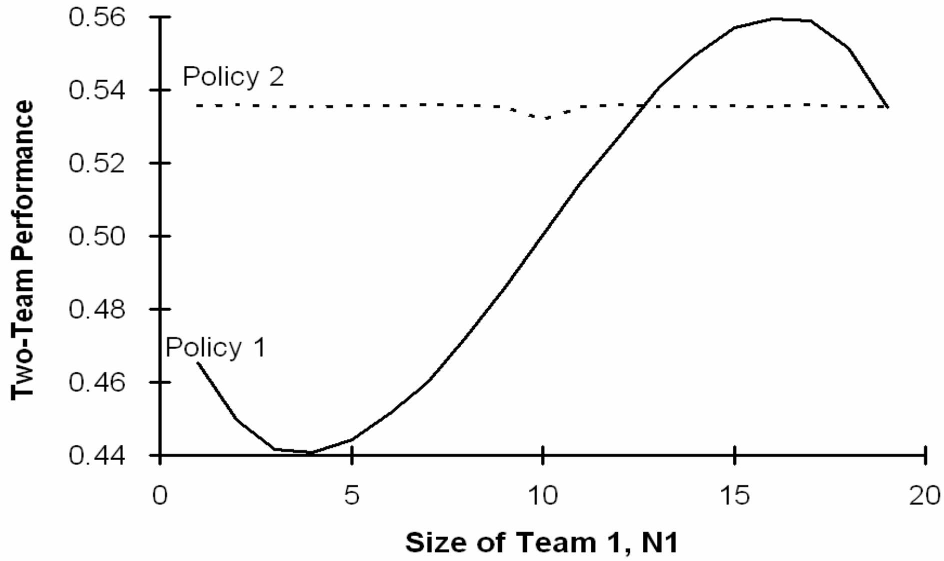

Figure 4: Comparing Policies 1 and 2 when $N = 20$ and $K = 1$.

workers move to sub-team 2 has the same (minimum) value of 1.30. Thus, under Policy 2, the same two sub-teams result when the size N_2 of sub-team 2 is 3 or 5. Note also from figures 4-6 that this symmetry is independent of K because, regardless of K, the TWP for any value of the size of sub-team 1, say, $N_1 = M$, is the same as the TWP when $N_1 = N - M$.

Another property seen in figure 4 is that the two policies perform identically when the number of interdependencies per worker is $K = 1$ and the size of sub-team 1 is $N_1 = 19$. This is because of the way TWP is computed in equation (2). Specifically, consider the single worker moved to sub-team 2, say, x_j. Since $K = 1$, the only workers affected by the division are x_j and x_{j-1} and the associated TWP is $p_j + p_{j-1}$. Thus, the division that minimizes the TWP is the one in which position j minimizes $p_j + p_{j-1}$, which is precisely the same criterion used in Policy 1 when the number of interdependencies is $K = 1$ and the size of sub-team two is $N_2 = 1$.

However, when the number of interdependencies is $K = 1$, Policies 1 and 2 yield different results as the size of sub-team 1 decreases. Specifically, as seen in figure 4, two-team performance remains constant under Policy 2 for all sizes N_1 of sub-team 1 except for a slight dip when the size of sub-team one is half of the number of workers ($N_1 = N/2$) while performance under Policy 1 is sinusoidal as the size N_1 of sub-team 1 changes. The reason for the constant two-team performance of Policy 2 is that, for any size N_1 of sub-team 1, the division that minimizes the TWP requires finding the position $j = 1, \ldots, N$ that minimizes the joint performance $p_j + p_{j+N-N_1}$. Regardless of the value of the size N_1 of sub-team 1, doing so involves finding the minimum of N sums of two individual performances, $p_j + p_{j+N-N_1}$, for $j = 1, \ldots, N$. To illustrate, consider a team of size $N = 5$. Finding the TWP for this team for each different size N_1 of sub-team 1 requires finding the minimum of the $N = 5$ possible values of $p_j + p_{j+N-N_1}$ for $j = 1, 2, 3, 4, 5$ shown in the following table:

TWP

N_1		$j=1$	$j=2$	$j=3$	$j=4$	$j=5$	
1	min{	$p_1 + p_5$,	$p_2 + p_1$,	$p_3 + p_2$,	$p_4 + p_3$,	$p_5 + p_4$	}
2	min{	$p_1 + p_4$,	$p_2 + p_5$,	$p_3 + p_1$,	$p_4 + p_2$,	$p_5 + p_3$	}
3	min{	$p_1 + p_3$,	$p_2 + p_4$,	$p_3 + p_5$,	$p_4 + p_1$,	$p_5 + p_2$	}
4	min{	$p_1 + p_2$,	$p_2 + p_3$,	$p_3 + p_4$,	$p_4 + p_5$,	$p_5 + p_1$	}

Observe from the foregoing table that for all sizes N_1 of sub-team 1, finding the value of j for the TWP involves finding the minimum of 5 sums of distinct pairs of performance measures, each pair being the sum of two independent $0 - 1$ random numbers. The expected value of these sums, and of the new performances of the two workers affected by the division, are the same regardless of the value of N_1, thus explaining why the curve for Policy 2 is flat when the number of interdependencies per worker is $K = 1$. But why does this curve dip slightly when the size of sub-team 1 equals half the number of workers ($N_1 = N/2$)? The answer lies in an anomaly that arises when N is even. When the size of sub-team 1 is half the number of workers and the number of workers N is even, only $N/2$ (instead of N) of the sums are distinct.

Turning to figures 5 and 6, it is seen that sizes of the sub-teams impact the results under Policy 2. To understand why, consider what happens when the number of interdependencies per worker is $K = N - 1$ and the size of sub-team 2 is $N_2 = 1$. In this case, the performance of a worker, say, x_j, who moves to sub-team 2 changes significantly, based on losing $N - 1$ connections while the performances of the remaining $N_1 = N - 1$ workers staying on sub-team 1 change based on losing only the one connection with worker x_j. If the performance of worker x_j is below average, the net result is that two-team performance after the division improves over the original undivided team, as seen in figure 6 when the size of sub-team 1 is $N_1 = 19$. However, when the size of sub-team 1 is $N_1 = 18$, the performances of, say, workers x_j and x_{j+1}, who move to sub-team 2 change based

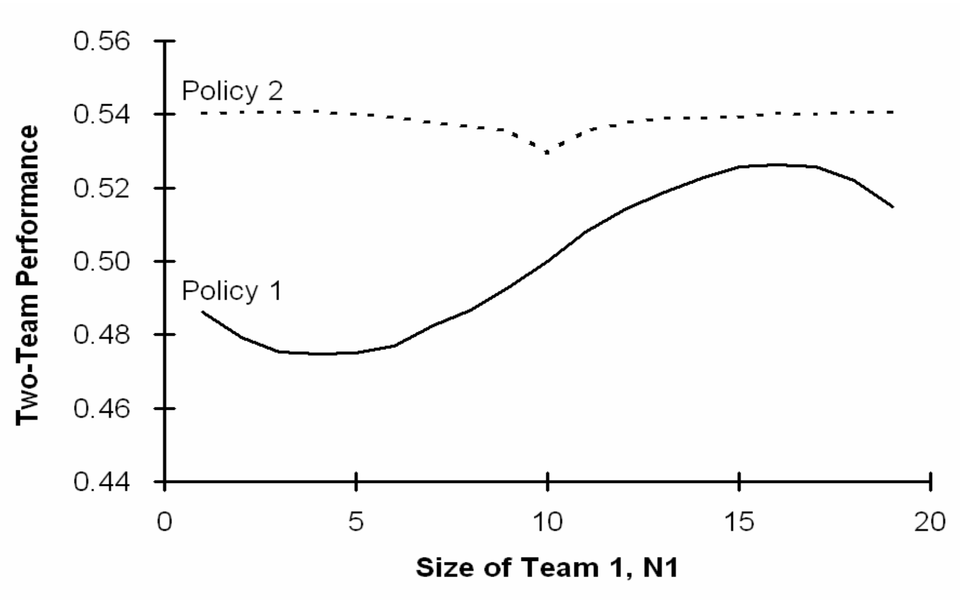

Figure 5: Comparing Policies 1 and 2 when $N = 20$ and $K = 10$.

on losing $N - 2$ connections, which is not as much as when only one worker moves to sub-team 2. Likewise, the performances of the $N - 2$ workers who stay on sub-team 1 change based on losing two connections, which is more than when $N - 1$ workers stay on sub-team 1. If the performances of the two workers x_j and x_{j+1} are below average, the net results is that two-team performance after the division improves over the original undivided team, but not as much as when the size of sub-team two $N_2 = 1$, as seen in figure 6 for sub-team 1 of size $N_1 = 18$. This degradation in two-team performance under Policy 2 continues as the size N_1 of sub-team 1 increases to half the total number of workers $N/2$.

Note from figures 4, 5, and 6 that Policy 2 performs worse as the number of interdependencies K approach saturation at $N-1$ because, as K increases, the workers on the larger team experience more disruptions of their working relationships. Finally, the differences across figures 4, 5, and 6 show the advantage of Policy 2 over Policy 1 for all but the smallest number of interdependencies K. For example, as seen in figure 4 where interdependence is low ($K = 1$), the best immediate two-team performance is achieved with Policy 1 when the size N_1 of sub-team 1 is large (that is, few members are moved to sub-team 2) and exceeds any performance that can be achieved with Policy 2, regardless of team sizes. However, as seen in figure 5 where interdependence is moderate ($K = 10$), immediate two-team performance generated by Policy 2 dominates that of Policy 1 for all partition

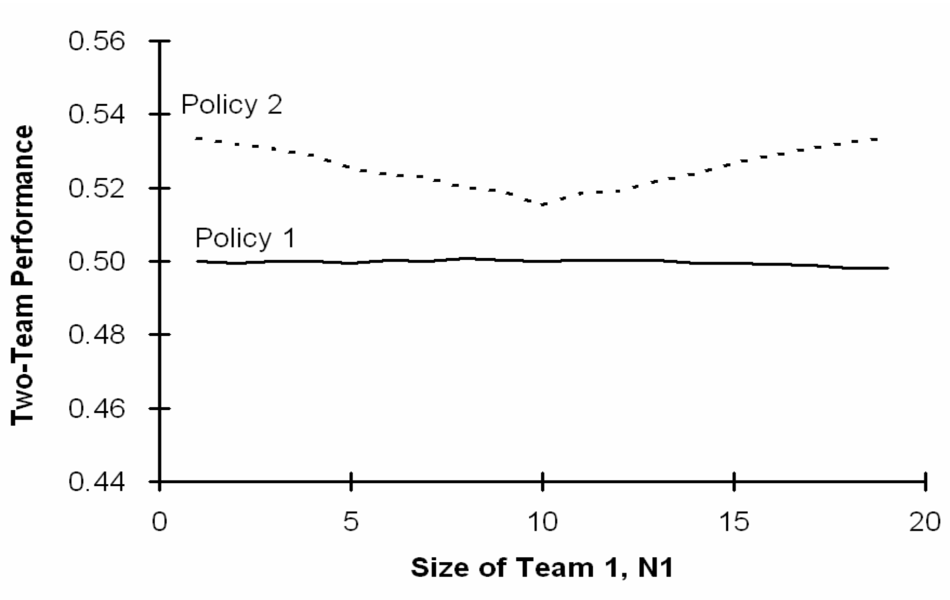

Figure 6: Comparing Policies 1 and 2 when $N = 20$ and $K = 19$.

sizes of sub-team 1. Similar advantages are obtained with Policy 2 when interdependence is high ($K = 19$), as seen in figure 6, where both curves have moved down compared to the corresponding curves in figure 5. The dominance of Policy 2 when there are more than a few interdependencies is due to the fact that Policy 2 exploits the mpMC rule better than Policy 1.

Will: cleanup. To summarize, the average performance of policy 2 exceeds that of policy 1 for dividing immature teams, regardless of the amount of interdependencies and the size of the split teams. This is because Policy 2 exploits the mpMC rule more effectively than Policy 1. Note that the average performance of the split teams using Policy 2 exceeds that of 0.5 for the undivided team in virtually all scenarios of immature teams. However, as will be seen in Section 3.2, the immediate improvement that results from dividing a team decreases as the number of pre-division replacements increases, and may even result in an overall decrease in two-team performance when compared to the undivided team.

3.2 The Effects of Worker Replacements Before and After Division

The results in Sections 3.1.1 and 3.1.2 pertain to the immediate two-team performance after dividing an immature team using Policies 1 and 2. It is now explored how replacements both before and after dividing a team affect the benefits of using these policies. A mature team is modeled as one that strengthens through employee replacements. Other senses of the term "maturity"—such as individual or group learning—are ignored to focus on working interdependencies. The presumption is that the act of replacing workers supports healthier relationships so that team performance grows overall, but raises the key questions of how many replacements should occur before the team is divided and how quickly the team strengthens with replacements after the division. These questions are answered by starting with a single immature team that experiences a number of worker changes until being divided with one of the two policies from Section 3.1, after which subsequent replacements improve team performance once again.

Worker replacements before division: As in the *NK* model, the one-replacement heuristic in the bounded *NK* model changes workers one at a time until no worker can be replaced for team improvement. In an undivided team, when focal worker $x_j = 0$ is replaced with candidate $x_j = 1$ for the first time, the performance of the new worker is assumed to be a $0 - 1$ random number because the candidate has not been evaluated previously. This replacement also affects K others, and the performance of each such worker x_i (for $i = j-1, \ldots, j-K$) is represented by a new random number between lower bound l_i and upper bound u_i determined by equation (1) using the number of disrupted relationships $d_i = 1$, since worker x_i has an interdependency disrupted with the one worker replaced in position j. If at some future time the original worker $x_j = 0$ returns to replace $x_j = 1$, how should performance p_j be recomputed? If the configuration of the original worker's dependent relationships $x_j^K = (x_j, x_{j+1}, \ldots, x_{j+K})$ was evaluated in a previous iteration, then the performance p_j of the focal worker x_j is already known. However, if the configuration x_j^K has not appeared, then one can show that the one-replacement heuristic has the property that a configuration that differs from x_j^K by only one worker in positions $j+1, \ldots, j+K$ has already been examined, say $x_j'^K$ with performance p_j'. Therefore, the focal worker's performance p_j would be computed by again modifying the new performance p_j' based on the bounds in (1) and the number of disruptions $d_j = 1$. The replacement process is continued until a team with a local maximum performance is reached.

Worker replacements after division: When a team with K interdependencies per worker is divided, there is a question as to what the number K_i of interdependencies per worker is for each sub-team $i = 1, 2$. For example, consider the team $\mathbf{x} = (1, 0, 0, 0, 1, 1)$ with $K = 3$ interdependencies per worker being divided into sub-team $1 = (1, 0, 0, 0)$ sub-team $2 = (1, 1)$. While each worker on sub-team 1 can still have $K = 3$ interdependencies per worker after the division, the workers on sub-team 2 cannot. In fact, each of the two worker on sub-team 2 can have at most one interdependency. In this example, after dividing the original team with $N = 6$ workers and $K = 3$ interdependencies per worker, sub-team 1 would have $N_1 = 4$ workers with $K_1 = 3$ interdependencies per worker and sub-team 2 would have $N_2 = 2$ workers with $K_2 = 1$ (the most possible) interdependencies per worker. More generally, for $i = 1, 2$, if the number N_i of workers on sub-team i after division is at least $K + 1$, then each member on sub-team i can have as many interdependencies after division as before division, so $K_i = K$. If, however, the number N_i of workers on sub-team i is K or fewer, workers on sub-team i can have at most $N_i - 1 < K$ interdependencies. In this case, the number K_i of interdependencies per worker on sub-team i is taken to be as large as possible, that is, $K_i = N_i - 1$. Therefore, each replacement prior to division affects K workers while each replacement on sub-team i after division affects K_i workers.

Furthermore, when a team is first divided, note that the candidates for replacing the workers on the sub-teams may have interacted previously with some of the workers on the sub-team prior to division. To avoid the complications this can cause in computing the candidate's performance when replacing a worker on a sub-team, it is assumed here that, for all practical purposes, those candidates are in a new working environment when first entering a sub-team. As a result, immediately after division, each candidate to be considered for replacing a worker on a sub-team i is viewed as a new person whose performance, when put onto a sub-team for the first time, is assumed to be a new $0 - 1$ random number. The performances of subsequent replacements on the sub-team are then computed using the approach of the bounded NK model.

Computer simulations are used with the foregoing pre-division and post-division replacement processes to find local performance maxima staring with undivided teams of sizes $N = 10$ and $N = 20$ and each number of interdependencies $K = 1, \ldots, N - 1$. After a controlled number of pre-division replacements, each such team was divided by Policy 1 into sub-team 1 with $N_1 = 1, \ldots, N - 1$ workers and sub-team 2 with $N_2 = N - N_1$ workers and the appropriate number of interdependencies K_1 and K_2 for each sub-team. Then the individual, if any, on either sub-team whose post-division replacement resulted in the best improved two-team performance was identified. Workers on the sub-teams were replaced one at a time in this post-division fashion until no further two-team improvement was obtained. The same simulation was repeated using Policy 2. Specifically, the thick solid line ("undivided team") in figure 7 shows the performance of a team after 0, 1, . . . , 9 pre-division replacements as well as the results of dividing that team by Policy 2 after each of these replacements. For example, when the team is divided after two replacements, performance increases slightly, with further improvement being realized as additional replacements are made on the divided team (as seen by the dashed line that starts on the solid line at the point corresponding to the performance of the undivided team after two replacements). In contrast, if the original team is divided after four replacements, two-team performance initially decreases below that of the undivided team but again increases as additional replacements are made on the divided team.

More generally, the observation from these simulations is that *as more workers are replaced prior to division, the immediate relative improvement of each policy strictly decreases.* For example, figure 7 shows that dividing an immature team after zero replacements helps performance at first (as is expected for Policy 2), but after three or more pre-division replacements, the division harms overall performance initially. This is because each pre-division replacement strictly improves team performance, so pushing the average performance of the member p_j higher above $1/2$ and disrupting interdependencies on better performing teams will tend to have negative consequences due to the average performance reverting property. The better the average performance p_j, the greater the average performance degradation caused initially by dividing the team. Thus, it is most difficult for the policies to improve the performance of local maximum teams. However, even if division is initially detrimental, subsequent replacements on the divided team eventually lead to performance that exceeds that of the undivided team.

These observations also hold for Policy 1. In fact, figures similar to figure 7 result for Policy 1 when the number of interdependencies K is small and the size of sub-team 1 is large, that is, scenarios where Policy 1 is expected to improve performance initially. However, since Policy 1 results in an initial performance decrease when the size of sub-team one is less than half the number of workers $N/2$ (see Section 3.1.1), these scenarios harm performance when dividing after any number of pre-division replacement, and the more pre-division replacements, the greater the net performance decay. However, as with Policy 2, subsequent replacements always improve performance above what could be achieved with a single undivided team.

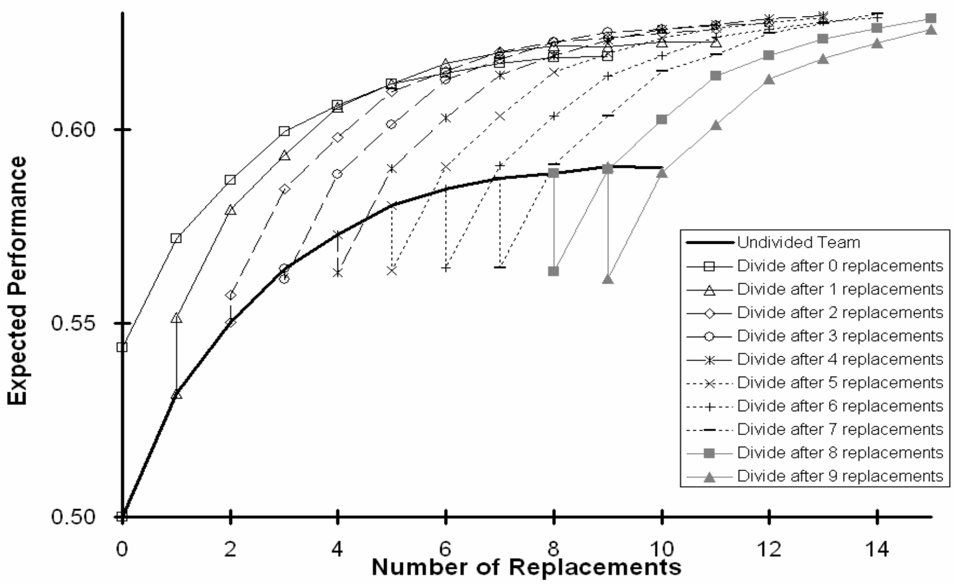

Figure 7: Value of replacements before and after division using Policy 2 when $N = 10$, $N_1 = 9$ and $K = 5$.

It is natural to expect reorganizations to disrupt team performance initially due to losses in coordination (Steiner, 1972) or disruption of shared cognition (Fiore, Salas & Cannon-Bowers, 2001). However, over time, one would hope that the employees adapt to their new interdependent relationships, thus leading to improved team performance. Figure 7 (as well as all other scenarios studied under both policies), shows that worker replacements after division overcome the initial setbacks due to division, if any. In fact, *both policies result in strict improvement over the original local maximum performance of the undivided team if divided and optimized via replacements.* This is due in part to candidates $0-1$ performances when first brought onto a team after division, and is also partly explained by the number of interdependencies on the sub-teams being no more than K. When the number of interdependencies per worker on the sub-teams are less than K, the sub-teams are less prone to the complexity catastrophe.

Replacement strategies to maximize performance: Not only is the local maximum performance of divided teams greater than the local maximum performance of the original team, *the more replacements that transpire prior to division, the greater the local maximum two-team performance after subsequent replacements.* This was evident in most scenarios studied, including the one depicted in figure 7. Because the average performance of the undivided team is better with each replacement, and the candidates are given $0 - 1$ random performances the first time they are engaged after division, the pool of candidates and workers is stronger overall if more replacements occur prior to division. This implies that a manager can achieve maximum group performance by dividing local maximum performance teams, rather than by replacing more workers.

The most economical replacement strategy: Maximizing performance requires many costly replacements, however. A more economical approach that achieves high performance through fewer replacements is to divide an immature team immediately using the best policy given the size of the first new team N_1 and a given number of interdependent relationships K according to Section 3.1, then perform replacements after the division. For example, the scenario depicted in figure 7 shows that dividing an immature team followed by one replacement achieves about as much performance improvement as four replacements to the undivided team.

4 Insights from a Weighted Performance Measure

Measuring team performance as the average worker contribution may not be appropriate when modularizing certain types of organizations. One such scenario is when one sub-team's task is more important or more urgent than that of the other sub-team, for which a *weighted performance measure* might be more appropriate [other possible performance measures, such as the lowest performance of anyone on the team, are identified in Solow et al. (2000)]. Performing simulations with a weighted performance measure not only confirms several observations from Section 3, but also uncovers additional properties of the two policies.

When an organization values the performance of one team more heavily than that of the other, rather than computing the two-team performance as the average of the individual contributions of the workers on each team, it is possible to weight individual performances of each sub-team differently. Specifically, let w_1 and w_2 denote the relative importance of the performance of sub-teams 1 and 2, respectively, where $0 \leq w_1, w_2 \leq 1$ and $w_1 + w_2 = 1$. An appropriate two-team performance measure that combines the average performance of each sub-team using w_1 and w_2 is:

$$P' = w_1 \left(\frac{1}{N_1} \sum_{i=1}^{N_1} p'_i \right) + w_2 \left(\frac{1}{N_2} \sum_{i=N_1+1}^{N} p'_i \right). \qquad (4)$$

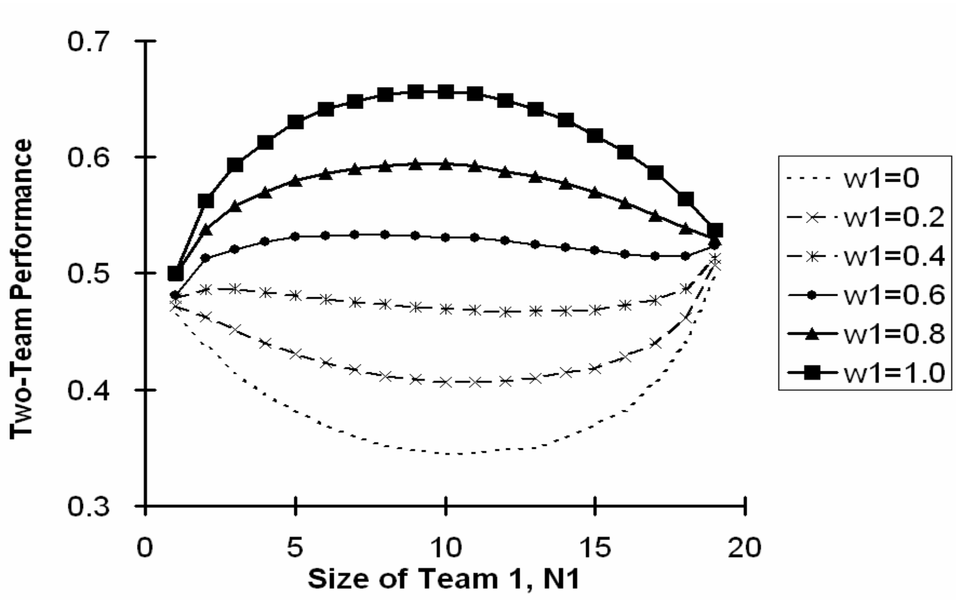

Figure 8: Two-Team Performance using Weighted Performance Measure and Policy 1, $N_1 = 20$, $K = 1$.

Note that the measure introduced in Section 2.2 is a special case of (4) in which the weight given to each team's performance is proportional to the number of workers on each team, that is, $w_i = N_i/N$ for $i = 1, 2$. Insights from simulations of dividing immature teams using Policies 1 and 2 with equation (4) are now presented.

Policy 1: Figure 8 shows the performance that results from dividing an immature team when the number of interdependencies is $K = 1$ and when there are different numbers of workers on each sub-team. Each curve corresponds to a different value of the weight w_1 given to sub-team 1 and used to compute the two-team performance according to equation (4). Specifically, the top curve corresponding to giving all the weight to the performance of sub-team 1 ($w_1 = 1.0$) is the average performance of sub-team 1 while the bottom curve corresponding to giving no weight to the performance of sub-team 1 ($w_1 = 0.0$) is the average performance of sub-team 2 [see (4)]. The fact that the top curve always lies above the bottom curve reveals that with Policy 1, the performance of sub-team 1 is always better than that of sub-team 2, regardless of the size N_1 of sub-team 1.

To understand why, consider first what happens when the size of the sub-team 1 is $N_1 = N - 1$ and that of sub-team 2 is $N_2 = 1$, that is, when only one person, say, x_j, is moved to sub-team 2. Now according to Policy 1 with the $K = 1$ interdependencies per worker, the reason x_j is moved to sub-team 2 is because the combined performance of the two workers x_{j-1} and x_j work is the smallest among all workers. Thus, the performances of both workers x_{j-1} and x_j are likely to be less than 1/2. According to the bounded *NK* model, the performance of the worker x_j on sub-team 2 is computed as a new $0-1$ random number (because $K = 1$ and $\delta_j = 1$) whose value is expected to be 1/2. This expected performance of 1/2 for the one worker moved to sub-team 2 is confirmed in the bottom curve in figure 8 by the point corresponding to $N_1 = 19$.

Turning to sub-team 1, recall that the original undivided team, being immature, has an expected performance of 1/2. Because worker x_j, who moved to sub-team 2, has below-average performance, the remaining $N_1 = 19$ workers on sub-team 1 must collectively have slightly above-average performance. In addition, when worker x_j moves to sub-team 2, the performance of worker x_{j-1} is also recomputed as a new $0-1$ random number that is expected to result in improved performance of that worker. In summary, when worker x_j is moved to sub-team 2, the remaining N_1 workers on sub-team 1, whose performances remain unchanged except for that of x_{j-1} who improves, are expected to have an average performance slightly larger than 1/2. This is also confirmed in the top curve in figure 8 by the point corresponding to sub-team 1 size $N_1 = 19$.

Consider now what happens when the size of sub-team 1 is $N_1 = N-2$ and the size of sub-team 2 is $N_2 = 2$, that is, when the two workers x_i and x_j are moved to sub-team 2. According to Policy 1, the performances of x_{i-1}, x_i, x_{j-1}, and x_j are all likely to be less than 1/2. In the event that x_i and x_j do not interact with each other, both of their performances, when moved to sub-team 2, are generated as new $0-1$ random numbers whose values are expected to be 1/2. However, occasionally, x_i and x_j interact, for example, when $i = j-1$. In this case, only the performance of x_j changes when moved to sub-team 2 while that of x_{j-1} remains unchanged at below 1/2. In this case, the average performance of sub-team 2 is expected to be slightly less than 1/2, which is confirmed in the bottom curve in figure 8 by the point corresponding to sub-team 1 size $N_1 = 18$.

Turning to sub-team 1, because the two workers x_i and x_j have below-average performances, the remaining $N_1 = 18$ workers on sub-team 1 must collectively have slightly above-average performance. In addition, when x_i and x_j are moved to sub-team 2, the performances of at least one of the below-average performers x_{i-1} and x_{j-1} is recomputed as a new $0-1$ random number that is expected to improve. When x_i and x_j do not interact, performances of both x_{i-1} and x_{j-1} are recomputed, resulting in an average performance of sub-team 1 that is expected to exceed that of sub-team 1 when only one person is moved to sub-team 2. In summary, when the workers x_i and x_j are moved to sub-team 2, the remaining N_1 workers on sub-team 1, whose performances remain unchanged except possibly for that of x_{i-1} and x_{j-1} who improve, are expected to have an average performance slightly larger than 1/2 and slightly larger than when only one worker is moved to sub-team 2. This is again confirmed in the top curve in figure 8 by comparing the point corresponding to sub-team one with a size of $N_1 = 18$ with sub-team one with a size of $N_1 = 19$.

Continuing the foregoing reasoning explains why the top curve in figure 8 increases and the bottom curve decreases as the size of sub-team one N_1 decreases from its maximum value of 19 $(N - 1)$ to 10 members $(N/2)$. Similar reasoning explains the behavior of those two curves as the size of sub-team one N_1 increases from 1 member to half of the available pool of workers $N/2$. For example, when the size of sub-team 1 is $N_1 = 1$, only one worker, say, x_j, is retained on sub-team 1. By design of Policy 1, that worker and worker x_{j-1} are both expected to have performances above 1/2. After the team is split, the performance of worker x_j in the bounded *NK* model is computed as a new $0 - 1$ random number (because $K = 1$ and $\delta_j = 1$) whose value is expected to be 1/2. This expected performance of 1/2 for the one person retained on sub-team 1 is confirmed in the top curve in figure 8 by the point corresponding to sub-team 1 with size $N_1 = 1$. Similarly, the remaining $N_2 = 19$ workers moved to sub-team 2 collectively have original performances slightly smaller than 1/2, which decreases further when the performance of the above-average performing worker x_{j-1} is recomputed as a new $0 - 1$ random number. This is also confirmed in the bottom curve in figure 8 by the point corresponding to a sub-team 1 with size $N_1 = 1$.

While figures are omitted here, similar "football" shapes result for graphs with $K = 2, \ldots, N-1$ interdependencies per worker. However, the amount by which sub-team 1 outperforms sub-team 2 reduces for all sizes of sub-team 1 as the number K of interdependencies per worker increases until there is no difference at saturation $K = N - 1$. This coincides with the observation in Section 3.1.1 that as the number of interdependencies approaches saturation, Policy 1's selection criterion becomes random.

Policy 2: In the way that studying general weighting factors revealed that Policy 1 creates a stronger sub-team 1 than sub-team 2, similar analysis of Policy 2 shows that the larger team outperforms the smaller team for any number of interdependencies per worker K (except when

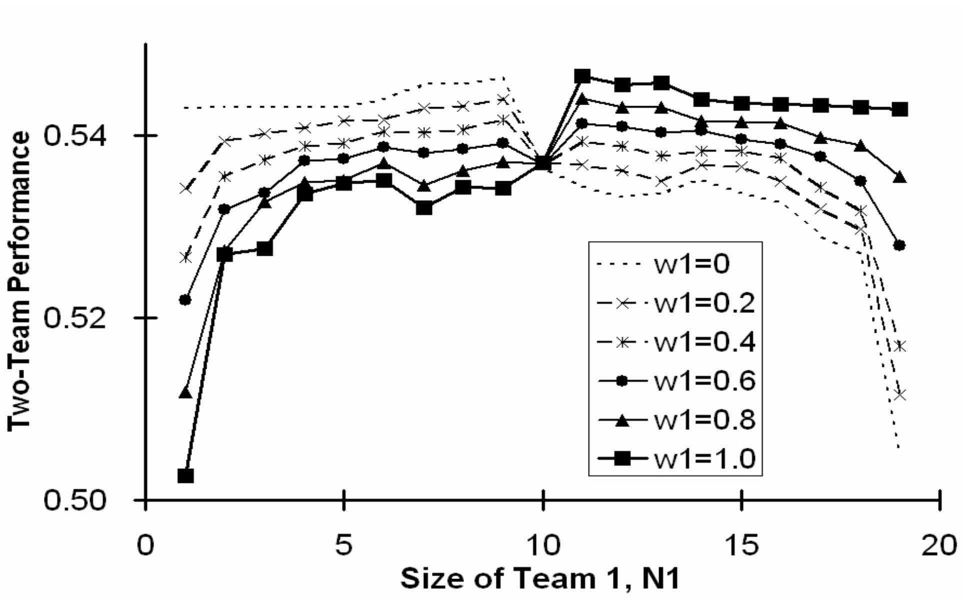

Figure 9: Two-team performance using Weighted Performance Measure and Policy 2, where original team size $N = 20$, number of interdependencies per worker is $K = 1$.

the sizes of the sub-teams are equal, resulting in equal performance). Since the workers who are assigned to the smaller team have no fewer interdependencies disrupted than those assigned to the larger team, the TWP measure of Policy 2 tends to assign the workers with the maximum room for improvement to the smaller team. As a result, the smaller of sub-teams 1 and 2 always performs worse than the other, as confirmed in figure 9 which shows the performance of Policy 2 under various weightings when the number of interdependencies is $K = 1$.

Recall from Section 3.1.2 that as the number of interdependencies K increases, the workers assigned to both teams by Policy 2 experience more disruptions in those working relationships, and hence Policy 2's contribution to performance declines. The same was observed for Policy 2 when weighting factors are used in the performance measure.

In conclusion, for dividing immature teams having few interdependencies ($K = 1$), the weighting scheme in the original bounded NK model of Section 3.1 resulted in Policy 2 dominating Policy 1. However, it is seen from figures 8 and 9 that when the importance of sub-team 1 (w_1) is sufficiently large (roughly, $w_1 \geq 0.7$), then Policy 1 outperforms Policy 2. When there are more interdependencies, Policy 2 dominates as before.

5 Conclusion

Work teams are complex, adaptive systems (Ilgen, Hollenbeck, Johnson & Jundt, 2005; McGrath, Arrow & Berdahl, 2000). One component of the complexity of work groups is the interdependence of their members for completing tasks. Learning how and when to disturb interdependencies and when to leave them intact is an important challenge for managers. Managerial observations about the effectiveness of some connections over others provides a powerful lever for modularizing teams for maximum increases in effectiveness, innovation, and speed.

This paper offers a sensible way of modularizing task teams. Analogously to traditional product modularization processes that focus on features of the product to identify the components with the most interdependence and create maximum separation between these parts, focus here is on similar work-team features and policies for the most effective divisions. The features attended to when dividing a team are the workers performances as a function of their own work and their dependence on others and the number of others a worker's performance affects.

The bounded *NK* model is introduced as a reasonably accurate mathematical descriptor of these complex interdependencies in organizations. Although highly stylized, the *NK* model permitted the proposal and testing of two policies for modularizing one team into two independent work groups. Our work extends the understanding of processes of adaptation by exploring the success of reducing the complexity of the landscape.

The first policy identified team members who appear to affect the performance of other team members most negatively. Studying the effect of this policy on random teams reveals that the policy performs best when the relationships of poor performers are disrupted, and good performers maintain most of their relationships, a property referred to as the *minimum performance, maximum change*, or mpMC, rule. Policy 1 is so effective in some scenarios (particularly, when few poor performers are sent to sub-team 2) that a second policy was developed to exploit the mpMC rule.

The two policies for modularization collectively demonstrate that three principal qualities impact the success of team division: the amount of worker interdependence, the maturity of the team, and which workers are assigned to each sub-team. For example, it was seen that on immature teams that have not benefitted from replacements, Policy 1 improves two-team performance only when the size of sub-team 1 is much larger than the size of sub-team 2, since the workers removed from the original team are poor performers who benefit most from maximum disruption of their poor working relationships. Policy 2, on the other hand, improves performance for any size of sub-team 1 and sub-team 2. Notably, an increase in the number of interdependencies per worker limited the effectiveness of both policies. In the case of Policy 1, increasing the number of interdependencies made the policy's selection criterion more random, to the point where, as the number of interdependencies among teammates approaches saturation, the policy becomes worthless. In the case of Policy 2, increasing interdependencies leads to more disruption of relationships, thus constraining Policy 2's ability to increase performance. In contrast, Policy 2 so effectively harnesses the mpMC rule that it improves immature teams for any number of interdependencies

Using the number of replacements before and after division as an analog for team maturity, it was seen that any policy's performance suffers as team maturity increases. Replacements after modularization were shown to overcome any initial setbacks. However, costly replacements can be reduced by dividing a team as soon as possible using the most effective policy for a particular scenario of team sizes and number of interdependencies, then performing a few replacements after division.

While it may be challenging to implement the policies studied here, the insights suggest that managers should be aware of how interdependent relationships are distributed across a team before any reorganization. The mpMC rule further indicates that a manager should use this knowledge to protect the interdependencies of the top workers while shaking up those of below-average employees. The study of replacements suggests that the longer managers delay reorganization, the more unified and efficient the original team becomes and the more likely division will result in an initial decrease in performance. However, making replacements on the divided sub-teams on average will eventually result in performance that exceeds that of the undivided team.

Sensitivity analysis indicates that the results in this paper hold for team sizes of 10, 20 and 100. Furthermore, insights about the mpMC rule hold if two-team performance is measured by weighted sub-team averages rather than the average of all workers. In fact, various weightings revealed when sub-team 1 is expected to outperform sub-team 2 as a result of each policy.

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