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Modeling the span of control of leaders with different skill sets

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Abstract In leading a team doing routine engineering design, two orthogonal skill sets can be distinguished: domain-specific or technical skills, and interpersonal "managerial" skills which are more general. This paper presents a computational model of team performance that relates these two types of skills to the amount of managerial and communication work generated given a certain team size (i.e. span of control). This model can be used to derive the optimal managerial profile for any team size, or the optimal team size for the skill set of a specific manager, provided the nature of the work remains fixed. The analysis of the model reveals several interesting insights. First, managerial skills are found to increase team performance up to a point after which it starts to decrease again. Second, a manager needs to compensate for low domain knowledge with high people skills, so optimal managerial skill level increases with lower domain knowledge. Third, both abilities have a significant impact on the manager's allocated time for his/her group; however, more influence is noticed for managerial skills. Finally, the manager was found to be more essential to large teams.

Keywords Span of control · Manager skills · Leadership traits · Engineering project team · Routine design

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1 Introduction

Since the rise of modern quality management methods, firms have focused on the importance of teamwork as a way to improve decision making, coordinate complex activities, and speed up execution (Katzenbach and Smith 1992; Haddad 1996; Scholtes 1998). For example, Chrysler has dramatically improved its performance since the early 90s primarily due to the use of platform teams (Ashley 1997), as did GM and Ford (Marton 1999).

The design of complex products and services increasingly requires teams of technical experts to collaborate on routine specification and configuration tasks. Different professionals on the team specialize in narrow fields of expertise within their domain, and team managers combine basic technical knowledge and generic managerial skills to make the work of the whole team more efficient.

Although some teams function well when they are self-managed (Nasrallah 2006; Hamel 2011), most teams are typically composed of a team manager and subordinates. A good team manager, who might, depending on the setting, carry the title of "coordinator", "facilitator" or "team leader", is able to communicate with the environment, infuse energy to enhance his/her team's capabilities, handle disturbances, and carry out many other functions to reach the team's goals (Mintzberg 1973). Subordinates are selected depending on the project needs and nature of work.

The team manager's formal authority makes him/her a key player in reaching optimum team performance. His (or her, but henceforth "his" for brevity) success as a manager, and subsequently his contribution to the team's success, depend on two factors: understanding of specific business or engineering topics, Sects. 4.2 and 4.3. Managerial skills include interpersonal, communication, and leadership skills, in addition to project and time management skills. Domain knowledge includes technical or financial knowledge (depending on the nature of work), strategic thinking and decision making (related to work). Since this type of knowledge is very specialized, the richest research literature on it tends to be in detailed case studies, e.g., Carindal et al. (2004) for logistics or Jones (1977) for construction . Managerial skills are transferrable and mostly related to people, while domain skills are specific to each industry (Bailey and Helfat 2003).

One important aspect of the team is its size. A naïve view of team size assumes that an increase in team size means less work per person, but this neglects the coordination time required among team members and the complexity of the relationships associated with large membership (Goldberg et al. 2004). Managing a team, particularly a large one, poses the challenge of coordinating among members, including the team leader. Coordination affects communication time, work efficiency and effectiveness, and team performance in general.

As modern businesses have focused on the role and importance of teams, researchers have written volumes extolling the virtues of teamwork. This research has tended to be either empirical in orientation or qualitative in methodology. Engineering by its nature seeks quantitative understanding of its subjects, even those involving human beings. Engineers seek to understand not only whether, but also how and why changes in one variable affect the outcome.

In this paper, we attempt to build a quantitative model of team size by trying to balance a small subset of factors critical to a team's success. In particular, the aim of this paper is to combine the effects of team size with the effects of the team leader's managerial and domain skills to compute an estimate of the time needed to reach a pre-determined level of quality in an engineering design project. The importance of this model resides in capturing the effects of these two factors, team size and team leader skills, on a one-dimensional view of team performance. Different team sizes require different managers; the classification of skills into "Domain" and "Managerial" skills highlights each type's advantages and disadvantages, relative to team size.

The following section illustrates, through a motivating example of a typical engineering firm, the need for a model of team performance as a function of team size and team leader skill set. The proposed model enables top management to increase the performance of its teams. Depending on each specific work process and group internal communication, the model provides optimal combination(s) of team leaders' skills and team size to complete the project on time and within a certain number of work hours. This combination could be reached through several means: varying team size, modifying work process, assigning/hiring appropriate managers for the selected teams, or sending managers to appropriate training programs.

1.1 Motivating example

The example comes from the second author's employer, an EPC (Engineering-Procurement-Construction) firm that constructs and manages power plants based on reciprocating engines and gas turbines across the Middle East, Africa, and Central Asia. We will refer to the company by its actual initials, SPP (for Solution Power

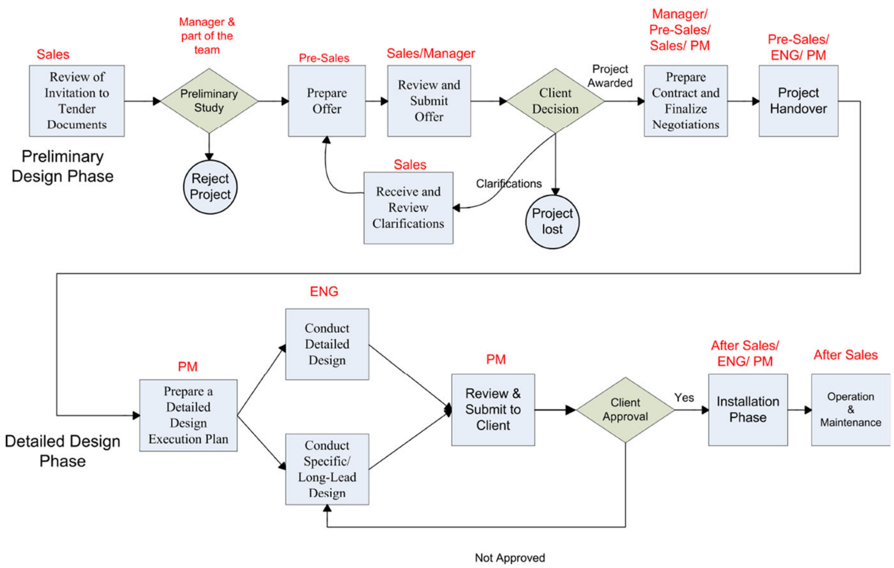

Fig. 1 Process flowchart for typical SPP project

Partner), but the individual managers and projects will be referred to by numbers at the request of the company's management.

The company's design process for each new project follows the general template shown in Fig. 1. The SPP process is quite typical of pre-bid phase of similar engineering firms (Cheng et al. 2006; Cooper et al. 2008).

The scope of work is divided into five work areas: pre-sales, sales, engineering, project management, and after-sales. Team members communicate within and across these work areas to finish the project. The communication dependencies among the different specialized engineering sub-teams (i.e., clusters) are illustrated in the Design Structure Matrix (DSM) shown in Fig. 2 (Eppinger and Browning 2012).

Due to the relatively large size of the engineering teams working on SPP projects (e.g., 15–20), and the interdependence of their work, a considerable amount of time is spent on communicating. In addition, each team leader has a different skill set, matching this to the requirements of each job is a challenge. As a consequence, SPP overhead costs are sometimes high, and project schedule targets are not always met. Many engineering companies involved in routine technical or engineering design and configuration share this problem (Chang 2002).

In this paper, the preliminary study phase is assumed to last enough to reach a certain level of quality independently of the manager's skills or number of people selected to participate in the preliminary study. In other words, if a highly skilled manager needs a certain time T_1 to finish the preliminary study, then a lower skilled manager will need time $T_2 > T_1$ to finish the preliminary study with the same quality. The question of how the team leader knows when the level of quality is reached is outside the scope of this paper: either the manager has the skill to make that determination in zero time, or a higher manager makes the call.

The team members are assumed to have the knowledge to cover the project at hand, so no technical assistance from outside the group is required in the preliminary phase. In the detailed design phase, any input from outside is considered part of the project work volume. Teams are also assumed to have been around long enough that the skills

	PS1	PS2	PS3	S1	S2	S3	E1	E2	E3	PM1	PM2	PM3	AS1	AS2	AS3
PS1		3	3			2	1				1				
PS2	3		3		1									1	
PS3	3	3		2					1						
S1			2		3	3							1		
S2				2		3				1					
S3				2	2										
E1								3	3	2					1
E2							3		3	1		1		2	
E3							3	3		3					
PM1									3		3	3	1		
PM2							1		1	3		3			
PM3							2			3	3		1		
AS1	1				1									3	3
AS2										1			3		3
AS3				1							1		3	3	

1: Low level of dependency 2: Medium level of dependency 3: High level of dependency
PS = Pre-sales S = Sales AS = After-Sales E = Engineering PM = Project Management

Fig. 2 Team-based DSM for typical SPP project of the members are within a common range, with members whose background or aptitudes are not compatible with the rest of the team eliminated over time.

This study focuses on the team leader's inward-facing time, which is defined as the time allocated for interaction with team members. This time, which affects team performance, can be divided further into general management time and domain specific time. We hypothesize that the combination of managerial and domain abilities will greatly improve team performance by giving support to the right people and directing the team to reach the project goals. The model presented in this study allows for testing this hypothesis and investigating the effect of team size on project duration in the context of engineering firms such as SPP.

2 Background

The literature on teams is voluminous and diverse. It spans areas ranging from theoretical work in management and organization sciences (Graicunas 1937; Marks et al. 2001; Millhiser et al. 2011; Neilson and Wulf 2012), to experimental work in social psychology (Stasser and Dietz-Uhler 2001; Kerr and Tindale 2004; Hastie and Kameda 2005; Laughlin et al. 2006), to the applied and empirical investigations of the value of teams in product and software development (Kim and Clark 1992; Kraut and Streeter 1995; Sawyer 2004; Nembhard and Edmondson 2006; Wheelan 2009).

These studies consider team size and composition, team dynamics, characteristics of successful teams, selection of team members, and roles and characteristics of successful team leaders. Furthermore, this literature could also be classified as either qualitative and empirical in nature (Klenke 2008), or mathematical and computational (Hazy 2007). We focus on a subset of this literature that specifically addresses the leaders role in affecting the outcome of the team.

2.1 Theories of teams and team leaders

Many studies of the performance of a team and its manager/leader focus on the importance of the span of control (SOC) (Neilson and Wulf 2012). As team size increases, difficulties arise in agreeing on common objectives and carrying out any decision making process (Curral et al. 2001; Wheelan 2009). The role of the team leader is especially important for large teams; he uses various skills and methods to set structure and direction, identify, communicate and administer goals, and define the work atmosphere. Mintzberg (1973) defined the ten working roles of a manager, which are divided into three groups: interpersonal, informational, and decisional. By properly filling the interpersonal roles defined by Mintzberg, the manager can have an indirect "effect on team performance via team climate" (Pirola-Merlo et al. 2002). His "people skills" encourage subordinates to collaborate with each other and strengthen bonding inside the team (Norrgren and Schaller 1999; Quinn et al. 1998). Teams that collaborate well are often capable of achieving more whether or not the team leader contributed to the quality of the collaboration (Baiden and Price 2011), but the existence of good teams with bad leaders does not detract from the value that a manager with good people skills can bring to a team (Dionne et al. 2004).

The Leader-Member Exchange (LMX) theory suggests that the quality of the relationship between manager and subordinates, characterized by "trust, respect, and obligation", results in several positive outcomes for the organization (Winkler 2009). Therefore, this mature relationship has a powerful impact on team performance (Graen et al. 1982; Scandura and Graen 1984; Graen et al. 1986). One important finding by Kacmar et al. (2003) is the link between the frequency of communication (between manager and subordinate), LMX, and performance, through factors such as team climate (Pirola-Merlo et al. 2002) and group confidence (Pearce et al. 2002).

Beyond the interpersonal and informational roles, a manger's decision making also affects team performance by creating a task structure that, if well designed and understood, can positively influence the performance of multidisciplinary teams (Wilemon and Thamhain 1983). Task structure is the set of tasks in a specified process and the procedures for coordinating them (Sarin and McDermott 2003). By setting a task structure and making sure it is followed, the manager reduces communication and conflict inside his team (Muczyk and Reimann 1987).

Recent empirical research by Sauer (2011) has shown that new leaders who are perceived as having low status, be it due to age, education, or experience, perform better in a directive leadership role (i.e. telling team members exactly what needs to be done and how). Such leaders can successfully transition to a more collaborative leadership style only after they have established their authority among team members.

Teams are understood to possibly consist of managers who themselves lead teams or division, and not just of individual contributors. The model developed in Sect. 3 connects the different roles of the manager discussed above to the different ways in which team size drives combinatorial growth in communication volume. The focus is on a team of individual contributors who are specialized engineers grouped into self-organizing technical clusters.

2.2 Mathematical models of teams and team leaders

Mathematical modeling and computer simulation are valuable tools in studying organizational behaviors (Ilgen and Hulin 2000; Rouse and Boff 2005). The core tradeoff in all these models is to strike a balance between the time spent on working versus the time spent communicating with other team members (Goldberg et al. 2004). Often the objective function is to reduce project lead-time (or cost) by choosing the optimal team size or composition, or even the optimal number of interactions between team members.

Millhiser et al. (2011) argue that previous research on team member selection has focused only on the abilities of individual team members rather than on the relationships among members, but the focus is shifting to skills related to working well together. Accordingly, they offer a simple model of a team. In their model, team output is a function of both individual outputs and peer effects. Peer effects are the contributions each individual makes to the output of fellow team members. Without peer effects, a teams output is simply a sum of individual outputs. The model provides insights to managers for harnessing interdependence when forming teams, whether the managers are familiar or unfamiliar with how well their people work together.

Similarly, Solow et al. (2002) applied the NK model (Kauffman 1993) to the process of replacing members of a team. The NK model contains no concept of leadership, but Solow and Leenawong (2003) developed an extension that includes the role of a leader in achieving cooperation among team members. This resulted in a collection of models that shows the impact of a co-operational leader on the teams performance. These models include controllable parameters whose values reflect the amount of interaction among team members as well as the skill and variance of the leader in achieving cooperation. Computer simulations with these models show that having a leader with no co-operational skill is the same as having no leader at all. Also, average team performance increases as the skill level of the leader increases, regardless of the amount of interaction among the members. In a subsequent work, Solow et al. (2005) investigated the role of motivational leadership on team performance. Their results showed that having a skillful leader can be more important for team performance than controlling the amount of interdependence among team members.

Jacobsen and House (2001) described six phases in the charismatic leadership process: Identification, activity arousal, commitment, disenchantment, depersonalization, alienation. Then they use a system dynamics modeling to analyze the process of charismatic leadership in organizations. They were able to duplicate longitudinal data collected for six leaders, each of whom was generally considered to possess charisma.

Schreiber and Carley (2006) used data from field observations and dynamic network analysis to study how the flow of information within teams impacted performance. They found that multiple network hubs in the flow of information, rather than a single one, that is, a single "leader", led to better performance when complex functioning was required. Similarly, Batallas and Yassine (2006) determined optimal composition for multi-disciplinary team using social network analysis.

Computational approaches to organizational theory are often characterized by the use of sophisticated simulation and optimization requiring the setting of large numbers of parameters, and hence tend to be case specific. Additionally, these models require significant restrictive assumptions to maintain computational traceability, while others are too detailed and difficult to experimentally test and verify, such as computational organizational theory models.

This paper builds upon the aforementioned research to develop a relatively simple model of time allocation by teams performing complex but routine engineering projects, defined by Baccarini (1996) as an interrelated set of tasks that are non-novel yet technically non-trivial, and interdependent but not ambiguous. The goal of the model is to capture the performance effects of managerial and domain abilities in the team leader. The model is used to test the hypothesis that team performance is improved when the team leader gives support to the right people and directs the team to reach project goals, but this effect is diminished with increasing team size. The model assumes (1) a predictable list of tasks with a known amount of specialized work content, (2) design process that consists of a preliminary design and a detailed design phase (as in Fig. 1), and (3) prior knowledge of the communication map between sub-teams in charge of these tasks (as in Fig. 2).

3 Model

Consider an engineering design process which consists of two sequential stages: a "preliminary design" phase (duration P_1) and a "detailed design" phase (duration P_2). The total time of the engineering process (TT) consists of the sum of the durations of the two phases $(TT = P_1 + P_2)$. The different contributors to each phase are mutually interdependent. The proposed model takes as inputs the managerial skills (M) and domain knowledge (D) of the team leader, as well as the team size (N). Managerial skill (M) is measured as a percentage of the level of competency of the most expert manager; i.e. the manager who can always pick smallest representative subset of his team for the preliminary design stage. Domain knowledge (D) is measured by the number of work areas in which the manager has enough knowledge to be able to function in place of his team members, if necessary, divided by the total number of work areas. The different parameters used in the model are shown in Table 1. These include, in addition to the above, various calibration parameters that are used to bring the model's output in line with observations, for example by modulating the presumably monotonic effect of a higher M on the motivation of the team.

Table 1 Model parameters

Project parameters	
V	Volume of direct engineering work in preliminary design phase
W	Volume of direct engineering work in the detail design phase
C	Number of specialization clusters used to group tasks and people
$\overline{DSM}$	Matrix of communication relationships between clusters
Team parameters	
N	Number of engineers in the team
$\overline{K}_W$	Vector of number of engineers in each of C clusters
Manager parameters	
M	Manager level of competency $(0 \leq M \leq 1)$; $= \frac{\text{Size of smallest representative subset}}{\text{Size of preliminary design subset picked by manager}}$
D	Domain knowledge of the manager $(0 \leq M \leq 1)$; $= \frac{\text{Areas known to manager}}{\text{All areas in team}}$
Calibration parameters (monotonically increasing functions)	
f_1(M)	Manager-to-subordinate communication multiplier
f_2(M)	Manager-to-team communication multiplier
f_3(M)	Subordinate-to-subordinate communication reduction factor
f_4(D)	Inter-cluster communication reduction factor

3.1 Preliminary design phase

In the preliminary design phase, the team leader must choose the number of team members (N_D) who need to be involved. The leader's domain knowledge allows him to perform the work of certain specializations from his own time allocation, while his managerial skills gives him the ability to recognize the best candidate for a "key" team member to represent each remaining specialization cluster.

Preliminary design is all about coordination, so any work not completely taking place inside the head of a multi-skilled manager requires a meeting. Figure 3 describes the different kinds of possible meetings. Key members are essential to this phase, but other team members who are not essential may also be present if the team leader includes them due to his poor understanding of the team dynamics.

The team leader selects N_D members to participate in this stage based on his skills and his perceptions of the team's structure and abilities. The team leader's managerial skills help choose the right member inside each cluster. The highest level of skill leads to C members, one from each cluster, and the lowest level leading to all N members participating in preliminary design.

We assume that the worst case scenario is to have all N members on the preliminary design meetings. The degenerate case, when the manager chooses an incomplete and inappropriate subset, will not reach the level of design quality needed to move on until the official participants realize that they need to confer with other team members. This scenario therefore devolves into about the same number of communications needed as if all N members were participating.

If the team leader has domain skills in a specific specialization cluster, then this eliminates the need for a separate representative from that cluster. This leads to Eq. (1), which is a linear extrapolation from 0 for a manager who has enough domain skills to complete the preliminary design on his own, to N for a manager who has neither domain skills to contribute nor managerial skill to enable selection of the smallest sufficient subset of the team to help with preliminary design.

$$N_D = (1 - D)(MC + (1 - M)N) \quad (1)$$

We calculate the expected total communication time T using the Graicunas (1937) approach of enumerating possible subsets of the members present:

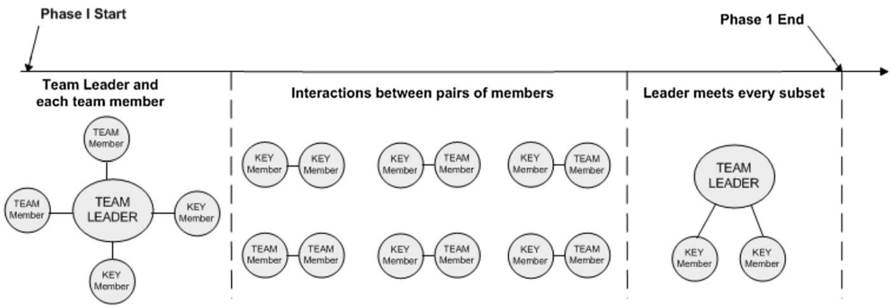

Fig. 3 Three types of communication in the preliminary design phase

$$T = N_D + \left\lfloor \frac{N_D}{2} \right\rfloor + 2^{C(1-D)} - 1 - C(1-D) \tag{2}$$

Equation (2) represents the three communication stages shown in Fig. 3, where N_D is the number of possible interactions (meetings) between the team leader and each team member, $\lfloor \frac{N_D}{2} \rfloor$ is the number of pairs, and $2^{C(1-D)} - C(1-D) - 1$ is the number of communications between the manager and all the different subsets of key members. The term $C(1-D)$ is the number of key members, whose meetings actually matter. Clearly the expression will be dominated by the polynomial term for larger teams. The preliminary design phase ends when the key members have participated in enough meetings to reach the required level of design quality.

$$\begin{aligned} P_1 &= U + T \\ U &= D \times V \end{aligned} \tag{3}$$

Finally, Eq. (3) gives the total time (P_1) spent on the preliminary design, which is the sum of team time (T) and the manager's own work (U), obtained by multiplying manager domain knowledge ratio (D) by the volume (V) of direct engineering work in this phase. This linear relationship defines the scale of the variable M, so calibrating functions f_1, f_2 and f_3 are used in the three other places where M enters into an equation.

3.2 Detailed design phase

During the detailed design phase, the manager no longer carries out design work, so the communications are divided into the following categories.

1. Dual communication (S), which is one-to-one meetings or other communications between the manager and one of his subordinates,
2. Multi-party communication (R) between the manager and a group of subordinates, and
3. Communication among team members (Q).

Dual communication (S) is mostly initiated by the team leader to establish a high Leader-Member Exchange (LMX) relationship with each of his subordinate. S increases with managerial skill M: this can be viewed as a short-term expenditure of additional time that leads to a long-term gain. The scaling function f_1 is used to isolate the effect of M on S from the definition of $M = \frac{C}{N}$ from phase 1.

$$S = Nf_1(M) \tag{4}$$

Multi-party communication with the manager (R) is a function of the number of clusters in the team. We consider one person per meeting per cluster, and enumerate the different sets of clusters, dividing by a monotonically increasing function of the manager's skills to account for increased motivation to finish meetings on time.

$$R = \frac{2^C - 1}{f_2(M)} \tag{5}$$

Team member communication (Q) consists of two types of communication: inter-cluster and intra-cluster communication. Both are reduced by higher M, but inter-cluster communication is also reduced by higher D since the manager with domain skills can do the coordination for those clusters he understands. Eq. (6) gives the full expression for the value of Q.

$$Q = \frac{1}{f_3(M)}\left(\sum_{a=1}^{C}(2^{K_a} - K_a - C) + 2^{C(1-f_4(D))} - C - 1\right) \tag{6}$$

Figure 4 shows the different types of communication and work (W) encountered during a typical second phase. Waiting/idle time is minimized by simply scheduling meetings so that those that can happen in parallel do so. Nevertheless, it is possible (Case 1) for the manager's communication time with members is less than the communication and work time of members without him, or conversely (Case 2) for manager-mediated communication to require more time than inter-team

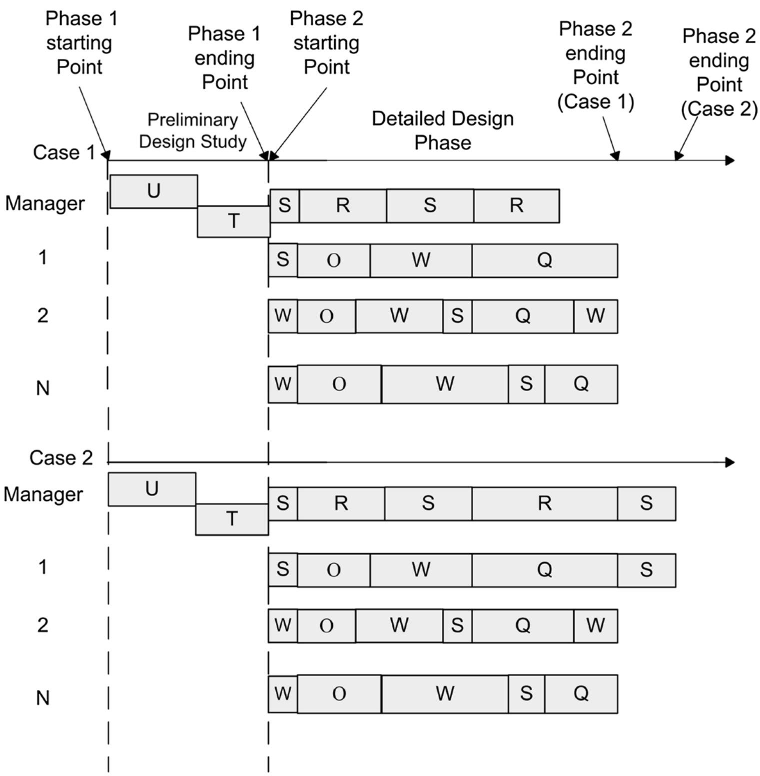

Fig. 4 Snapshot of simultaneous meetings in a typical project

communication and work time. Equation (7) shows how the total duration of phase 2 is the maximum of the two cases.

$$P_2 = \max\left(S + R, \frac{S + CR + Q + W}{N}\right) \quad (7)$$

In addition to duration, the model also gives the total number of engineer-hours (*TC*) required, by adding *T* from Phase 1 to the sum of *S*, *Q* and *R* from phase 2. Similarly, the total number of manager-hours (*T*)M can be found as follows.

$$TC = T + Q + R + S \quad (8)$$

$$TM = U + (T - N_D) + S + R \quad (9)$$

4 Numerical results and discussion

This section illustrates the application of the proposed model to a real-world case study. As mentioned earlier, SPP is a power generation firm which manufactures products and provides engineering services related to the power sector. The team studied includes fifteen engineers in the following different work areas (as shown in Fig. 2): pre-sales (proposal), sales (business development), engineering, after-sales (construction), and project management. Some of the clusters overlap, so $\sum K_n$ add up to more than *N*. The complete set of input parameters used are shown in Table 2.

Table 2 Numerical parameters for SPP case

Project parameters	
V	12 work hours
W	1000 work hours
C	5
Team parameters	
N	15
K_1	3
K_2	4
K_3	4
K_4	3
K_5	3
Manager parameters	
M	0.5
D	0.6
Calibration parameters	
f_1(M)	7 M
f_2(M)	5 M
f_3(M)	3 M
f_4(D)	$\frac{2}{3}$ D

The project duration (*TT*) is computed as approximately 11 days and 1 h (assuming 8 working hours per day). The preliminary study phase constitutes 17 % of the total duration (15 h taking into account the quality of the study), while the remaining time is for detailed design phase (74 h). The total communication effort (*TC*) during the project is 101 engineer-hours. The team leader allocated (*TM*) 77 h for his team during the project, which is equivalent to 86 % of the project time. The following sections present a sensitivity analysis how project duration responds to changes in team size in team leader domain knowledge and managerial skills. The results are intended to demonstrate how this particular model with the specified (linear) calibration functions produces changes consistent with what is expected in this type of company.

4.1 Team size

Modifying team size *N* while maintaining the same output quality results in a trade-off between calendar time and engineer-hours. As shown in Fig. 5, the decrease in time with each additional member reaches an optimal point, beyond which having extra members increases time slightly and raises costs significantly (the left axis is in hours and the right is in dollars at the rate of 10 dollars per engineer-hour).

Depending on project priorities and objectives, team size can increase or decrease between 5 (minimum needed members as number of different areas in the work is 5) and 16 (optimal number of members for TT as shown in Fig. 5). That is, if the company is not interested in minimizing the cost (as the total cost difference between a team of 16 and a team of 5 is 21 %), and its only goal is to deliver the project with the minimum time, then N is equal to 16 (optimal team size for time). However, a company aiming to reduce its cost by 9 %, for example, at the expense of time will reduce its team size to 11 (from initial size N = 16).

Figure 5 also shows a decreasing slope as the team size increases, where the total time is decreasing at a smaller rate with each additional team member. For example, (TT) decreased by 9.6 % when Team Member 9 was introduced while it decreased

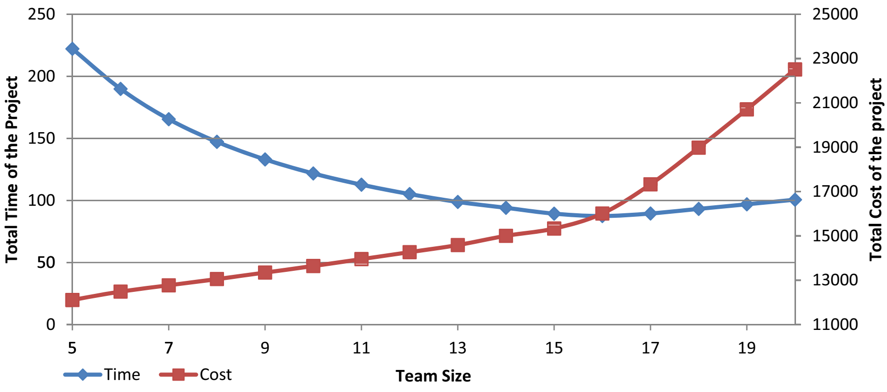

Fig. 5 Total time (TT) and total cost of the project as a function of team size (N)

by only 2.1 % with Team Member 16. This supports the argument of slow team development with larger teams (Wheelan 2009). With each additional member, the communication time increases exponentially up until the total time starts increasing. The increase in project duration at the time where team size is large results in a sharp increase of the cost shown in Fig. 5 (after N = 16). This means that the team has a certain limit (in this case 16) where each extra member lowers the performance.

4.2 Domain knowledge

Higher domain knowledge decreases duration as shown in Fig. 6. Total engineering time (TT) and manager time (TM) are measured in working hours. Candidates with higher domain knowledge are more valuable to the team, unless that higher domain knowledge comes with a much higher salary requirement or lower number of hours available for the project. Other roles of the manager which exclude his team are well documented in the literature (Mintzberg 1973). These roles, such as figurehead or liaison, limit the time allocated for the team.

4.3 Managerial skill

As shown in Fig. 7, managerial skills improve team performance up to a certain level, after which performance starts to deteriorate. This means that a manager who seeks to build close relationships with team members will, after a certain threshold, cut into the performance of the current project. The manager's time is even more sensitive to managerial skills. When managerial skills are high, the manager spends almost all of his time building relationships with his subordinates and reinforcing team climate, leaving him with no time for other roles. The extent of this effect

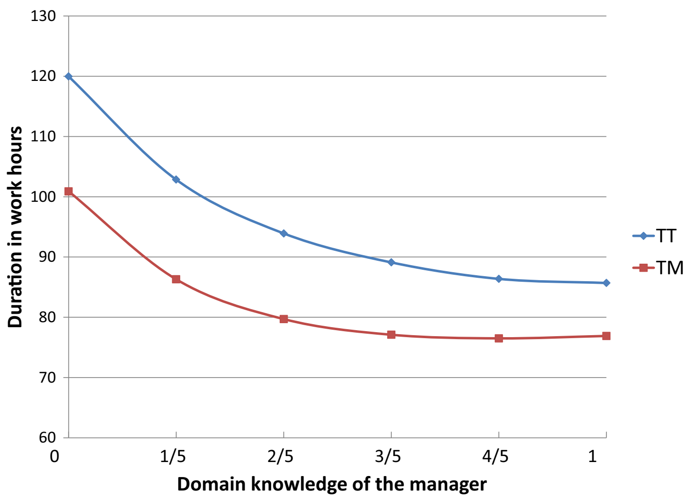

Fig. 6 Effects of team leader's domain knowledge

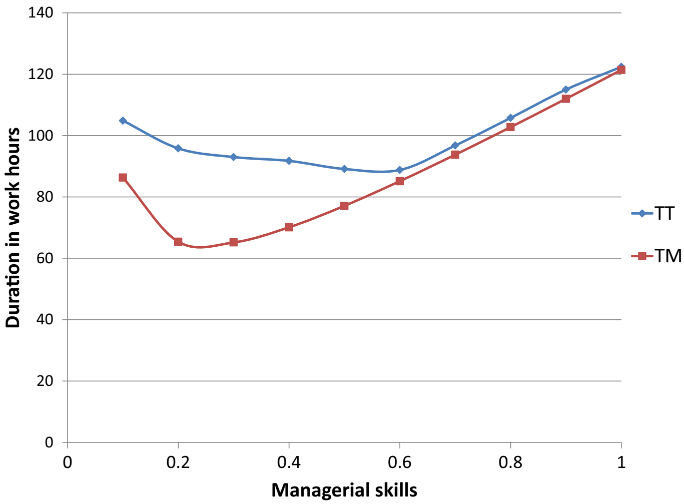

Fig. 7 Effects of team leader's managerial skills

depends on the team size and degree of clustering. In this specific case, the optimal level of managerial skills required is 0.61 (see Fig. 7), which means hiring a manager who establishes high LMX relationships with all of his team members will lower the performance despite his other skills (communication, leadership, etc).

4.4 Two-way sensitivity

A two-way sensitivity analysis of domain and managerial abilities shows that the optimal manager's profile corresponds to having $D = \frac{5}{5}$ and $0.4 \le M \le 0.6$. This optimal managerial skills range was found to increase when domain knowledge decreases. This is in line with literature (e.g., Nasrallah 2006) arguing that if the manager is too democratic, the team's performance can decrease, but it contradicts the LMX theory: the link between LMX relationships and performance is not positive in all the cases. As shown in Fig. 8, the optimal managerial skill level increases when domain knowledge decreases: when a candidate has lower domain knowledge, his people skills must be higher to compensate for it. Finally, domain knowledge has higher effect on duration than managerial skills. This follows from observing how deviation from optimal D for a given M affects performance, compared to the effect of deviation from optimal M for a given D:

- TT decreases by 28 % between $D = 0$ and $D = 1$ for $M = 0.1$, while it decreases by 21 % between $M = 0.1$ and $M = 0.6$ for $D = 0$.
- TT decreases by 22 % between $D = 0$ and $D = 1$ for $M = 0.6$ while it decreases by 14 % between $M = 0.1$ and $M = 0.6$ for $D = \frac{1}{5}$.

This difference shows the higher impact of domain knowledge on team performance compared to managerial skills.

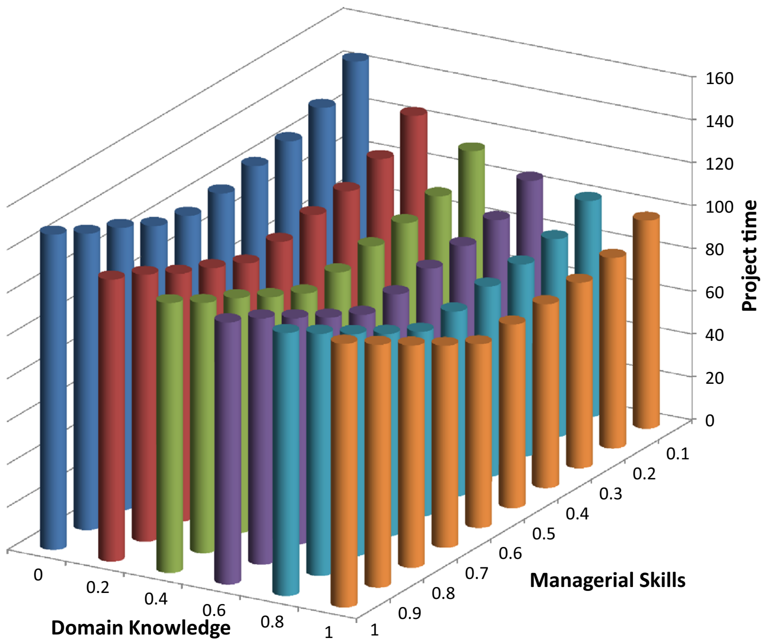

Fig. 8 Project duration at N = 15 for different domain and managerial abilities

Finally, we note that the decrease in TT between a low-skilled and an optimally-skilled manager was higher in large teams (40 vs. 39 %) than in smaller ones (22 vs. 25 %). This follows from remarking that, as communication increases dramatically with large teams, the role of the manager becomes more central to reducing all the time-wasting cross-talk, whether it be by being better able to direct the communications due to better managerial skill or to being able to avoid the need for engineers to coordinate by virtue of his understanding of the multiple domain issues.

5 Cross-project validation

Following the development of this model, we collected additional project data from the same company that had provided the motivating example, and compared the performance with the predictions of the model. Seven projects undertaken by two different managers were examined. Team members and colleagues of the two managers were interviewed to obtain a numerical estimate of the domain knowledge (D) and managerial skill (M) of the two managers (see Table 3).

Table 3 Ratings of the two managers

	M (Managerial skill)	D (Domain knowldege)
Manager 1	0.3	0.4
Manager 2	0.8	0.2

The seven projects were characterized by the following parameters:

Volume of direct engineering work in preliminary design (V).
Volume of direct engineering work in the detail design phase (W).

V and **W** were obtained from the records of the SPP proposal department, which prepares estimates prior to taking on a job.

Design structure matrix (DSM) Interviews with the team members were used to determine the communication relationships between clusters, and these were encoded into a matrix similar to the one in Fig. 2 (All seven had similar communication relationships between clusters).

Number of specialization clusters (C) The number of distinct engineering job disciplines used in each project was obtained from the project documents and mapped one-to-one to communication clusters. (All seven projects had five distinct clusters, with some overlaps).

Company cost records were used to obtain the actual time sheets of each team member, and individual interviews were used to determine the phase where the time was expended. Since time sheets provide the total engineer-hours of the project, total actual duration was obtained by dividing total engineer-hour over number of engineers. This was compared to what SPP estimators predicted before the work started, and to the predictions of the model described in this paper (See Table 5).

Six of the seven projects were performed by a 10-person team, and Project 7 had a 9-person team. For all seven, each team member belonged to one or more of the communication clusters. The number of man-hours for various phases of the seven projects are given in Table 4. Actual hours were obtained from cost records and sorted into the two phases by interview. The SPP estimates came from company files.

Table 4 Data for the seven projects from SPP

Project number	Project manager	Actual Ph. 1 h ($\div N_d$)	Actual Ph. 2 h ($\div$N)	Phi estimate ($\div N_d$)	Ph2 estimate ($\div$N)	Model P_1 output	Model P_2 output
1	PM#1	102 (34)	3849 (385)	108 (36)	3250 (325)	57	336
2	PM#1	109 (36)	1848 (185)	116 (39)	2083 (208)	61	219
3	PM#1	66 (22)	6244 (624)	71 (24)	4550 (455)	42	466
4	PM#1	58 (19)	2229 (223)	74 (25)	1925 (193)	44	203
5	PM#2	83 (28)	6824 (682)	133 (44)	5950 (595)	47	604
6	PM#2	68 (23)	2896 (290)	87 (29)	3125 (313)	38	322
7	PM#2	16 (8)	1352 (150)	26 (13)	1250 (139)	26	148

Table 5 Comparison of Model output with actual project data

Project number	Project manager	Estimate/actual (%)	P1 + P2/ actual (%)
1	PM#1	86	94
2	PM#1	112	127
3	PM#1	74	79
4	PM#1	90	102
5	PM#2	90	92
6	PM#2	109	115
7	PM#2	96	110

Table 6 Ratio of the actual, estimated and model output project durations by manager

	Estimate/actual (%)	Model/actual (%)
PMl	85.4	93.5
PM2	95.9	100.3

Table 5 compares the model's outputs to both SPP estimated time and actual time. The model did a better job of approximating duration than the professional estimators at SPP. In general, model predictions were within 15 % of the actual time except for Projects 2 and 3, which were affected by factors outside the scope of the model. Project 2 had a very low incidence of comments and revisions from the project owner, leading to faster overall execution time. Project 3 had a higher communication requirement due to the learning effect of a number of new hires in the company.

When the durations for all of the projects run by the same managers are summed and the ratios of the sums from different managers are compared (Table 6), it can be seen that the model output is closer to the actual value than the SPP estimate. This can be read to indicate that the project managers relationship with the team members, as modeled by this paper's methodology, was a highly influential factor affecting communication work. In particular, this factor overshadows factors such as new team member assimilation and superior client relationship, which are not in the model. This averaging also makes it more clear that SPP estimates for both managers undershoot the actual times, reflecting an estimation process that does not take account of communication slowdowns or project manager skills.

6 Conclusions, limitations and extensions

There has been progress in understanding organizational theory computationally in recent years, but the busy complexity and one-off nature of those modeling efforts makes one wonder whether simpler analytical models can help better guide organizational thinking and design. This paper offers one such model.

This study examined the impact of team size, managerial skills, and domain knowledge on team performance as measured by the time and effort needed to complete conceptual and detailed design for a typical engineering project. The model replicates the well-known fact that the benefits of each additional team member to the group are less than the previous one. Team size can therefore be selected according to the project priorities (e.g., time and cost) within the range where marginal project time savings are higher then the cost of an additional engineer. But even for the lowest-cost inputs, a limit exists where the performance starts decreasing with each added member.

The team leader's managerial skills do increase performance up to an optimal point after which it starts to decrease. This implies that having close relationships with team members must be limited, as it affects the performance beyond that threshold. However, in small teams, the manager can have a closer relationship with his members without affecting the performance. Therefore, high-percentile managerial skills increase in value when team size decreases. In addition, a manager needs to compensate for low domain knowledge with high people skills, so optimal managerial skill level also increases with lower domain knowledge.

On the other hand, domain knowledge is positively related to performance. Higher domain knowledge in the team leader is always better for the team's functioning regardless of size. This means that only the cost of having that more domain-skilled team leader needs to be considered in selecting team leaders, whether that cost is expressed as a higher salary requirement or in reduced level of managerial skill.

Both abilities have a significant impact on manager's allocated time for his group. More influence is noticed for managerial skills which makes sense as more time is consumed from the manager's part. Finally, having a team leader with the right skill set was found to be more beneficial to large teams. As team's size increases, relationships among its members tend to be more complex, so the presence of a good leader is crucial in managing that complexity. The effects of hiring more skilled managers on the cost of the project given a certain range of managerial salaries presents a fascinating area of further study.

The model presented in this paper depends on some limiting assumptions which might present further opportunities for future research. First, by incorporating quality in the time dimension, we were not able to capture the true effect of manager's skills and team size on project quality. Future research may include separate dimension for project quality. Another limitation of this research is that team members competency is not part of the scope, which neglects the manager's ability to transfer his knowledge to members and therefore limits the effect of domain knowledge. Future research can include each member competency in different clusters and compare it to domain knowledge of the manager and their influence on performance. Finally, the effects of using scaling functions $f_n(M, D)$ that are not linear also remains to be studied in future iterations of the model.

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