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Matching of Resources and the Design of Organizations for Project Management

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Abstract. This paper addresses a problem common to many high-technology firms. How can firms select and resource appropriate projects while balancing the needs of management as well as technologists? We argue that such problems result in social dilemmas for organizations, requiring practical institutional designs for management and resolution. We relate this project resourcing problem to the well-known "problem of stable marriage." Both material as well as knowledge-based resources are needed for project success. The formalization of the problem affords us to borrow existing theorems from the literature on matching. We conclude that the potential for social dilemmas inside the firm are fairly severe, directing institutional solutions into a relatively narrow set of choices for project selection and resourcing. We relate efficient outcomes of project resource matching to several well-known organizational forms including the functional form, the project matrix, and the project-based organization. The paper concludes that, while efficient, the project matrix organization pays a heavy cost for its compromise.

Keywords. Organizational design, project management, stable matching, resource-based perspectives of the firm

1 Introduction

The problem with which we shall be concerned relates to the following typical situation: A firm is considering developing k projects. A successful project requires a matching of i managers, who are gatekeepers of the resources of the firm, with j engineers whom provide the technical know-how to carry the project to a successful completion. The project permits a venue whereby organizational resources meet engineering requirements. A fundamental problem of this scheme becomes the appropriate resourcing of the respective projects given finite resources. And of course, the resource decision is subject to strategic uncertainty whereby actors inside the firm lobby for additional resources under a claim of need. This problem has been addressed by Williamson (1967) in a classic study of transaction cost economics. A further problem involves developing a consensus regarding the placement of the engineers. Gale and Shapley (1962) address the mathematical fundaments of what has now become known as the "matching problem."

We contend that the difficulties here described can be addressed by the appropriate selection of institutional form. The paper outlines a set of design variables, the standard choices made for organizational form and project management. We relate these choices to a class of matching problems (Gale and Shapley 1962). We conclude by considering the adequacy of these organizational forms given various managerial or technical imperatives.

2 Analysis

Gale and Shapley (1962) set forth the basics of the matching problem. The original case concerned the matching of students to university in university admissions. They also considered the matching of men and women, for instance in marriage. We now define the setting more formally (c.f. Shoam and Leyton-Brown 2009). We further elaborate the formalism in the context of engineering project management.

2.1 The Stable Matching Problem

These and subsequent authors model the *stable matching problem* with a graph G, where the agents are represented by vertices, and two vertices are linked by an edge if the agents are both acceptable to each other. Let M be a set of managers, let E be a set of engineers, and let P be a set of projects. We need not assume that $|M| = |E| = |P|$; thus there can be a pool of managerial or engineering talent which is currently underemployed in the firm. Likewise there may be more projects than there are managerial or engineering resources. We begin with the assumption that there is a one-to-one relationship between manager, engineer and project.

At this point, we must make some stylized assumptions regarding the organizational preferences of managers and engineers. For the purposes of discussion, let's examine the idea that managers are primarily motivated by resource-based concerns. Some authors argue that management is largely about the effective management of such resources. In contrast, let engineers be primarily motivated by knowledge and know-how in selecting projects. There may be little overlap between material resources and engineering know-how; the institutional problem is made worse by knowledge asymmetries inherent in engineering projects.

Every agent *s* (both engineer and manager) has their own preference ordering $\succ_s$ over projects. These orderings are likely to be different within agents. The organizational origination and structuring of these preferences is not discussed here, although this is a classic issue of institutional economics (c.f. Williamson 1967). With regard to these preference orderings we write $a \succ_i a'$ to mean that manager i prefers project a to project a'. We further use the null set $\emptyset$ to indicate when a manager or engineer would prefer to be assigned no project at all rather than receive assignment to project a. This is to say that project a is *unacceptable* to i, or $\emptyset \succ_i a$. We require the preferences to be strict; that is to say all agents must be able to choose a preferred option when given any two projects. Of course if a project is unacceptable, than all projects which are unacceptable are equally unacceptable.

DEFINITION 2.1 (Project Matching). An assignment of managers or engineers to a project is called a *project matching.* The project matching is such that each manager is assigned one or fewer projects. Likewise all engineers are assigned one or fewer projects. Let S be the set of engineers and managers. The following are requirements of a project matching, $\mu_p(S)$: $S \cup P \rightarrow S \cup P \cup \{\emptyset\}$. The matching is reflexive. Staff are mapped to project, and project are mapped to staff: $\mu_p(s) = p$ if and only if $\mu_p(p) = s$. All staff members must be matched to a project $\forall s \in S$, such that either $\exists p \in P$ and thus $\mu_p(s) = p$, or that staff member is underutilized $\mu(s) = \emptyset$.

A project matching also implies a matching between engineers and managers.

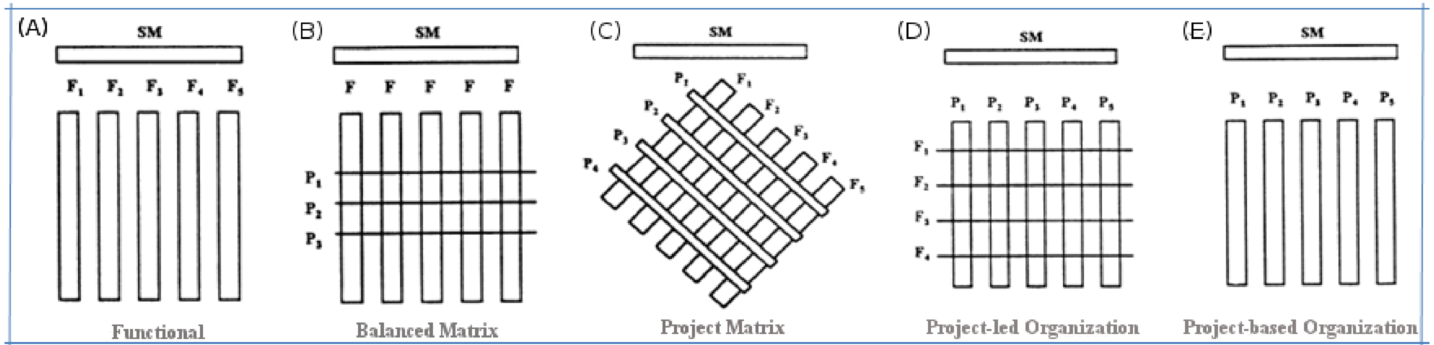
DEFINITION 2.2 (Matching). An assignment of managers to engineers via projects is called a matching. The project matching is such that each manager is assigned one or fewer projects. Likewise all engineers are assigned one or fewer projects. The following matching occurs because of project matching $\mu(M)$: $M \cup P \rightarrow M \cup P \cup \{\emptyset\}$. The matching is reflexive. Managers are mapped to engineers, and engineers are mapped to managers: $\mu(m) = e$ if and only if $\mu(e) = m$. All managers must either be matched with an engineer, or be underutilized $\forall m \in M$, either $\exists e \in E$ such that $\mu(m) = e$, $\mu(m) = \emptyset$. The same is reflexively true of engineers.

For completeness we consider the role of under-resourced projects.

DEFINITION 2.3 (Matching Projects). We define a matching project p to be those projects with both a manager and engineer. Matched projects q are therefore those projects such that $\mu_q(m)=q$ and $\mu_q(e)=q$. All projects in the set P are either matched q or unmatched $\neg$ q. We assume that unmatched projects map to the null set $\neg q \rightarrow \{\emptyset\}$, and any corresponding staff is underutilized. This definition permits us to use the three-fold distinction of engineers, managers and projects, with a generalized two-mode graph framework used in matching problems.

2.2 Organizational Design Choices

We consider a range of engineering project organizations as stated in the literature (Figure 1). The prospective designs range from the fully *functional form,* whereby management is allocated according to traditional functions of the firm such as engineering, finance, or human resources. Engineering may be further divided into separate divisions according to product lines. This is illustrated in 1A.



Key:

* F_1 - F_5 = various functional departments of the organisation (eg Marketing, Finance, Human Resources, Engineering, Manufacturing, R&D)
* P_1 - P_5 = major projects within the organisation
* SM = senior management

Fig 1. Design choices for functional and project-based organizations. Figure is adapted from Hobday (2000).

In the intermediate *project matrix* organization (c.f. Galbraith 1973), every project has full commitment of management resources across all functions of the firm. Further every project has a dedicated staff of engineers who work to provide the project with suitable interfaces with other projects, and to provide suitable design iterations to meet specifications. This is illustrated in 1C. Team-members in the project matrix organization face dual responsibilities to both their project as well as functional organizations.

The fully *project-led* organization consists of vertically integrated teams of management and engineering and other staff dedicated to the needs of the specific project. The resultant organization gains considerable flexibility for the needs of the specific project, but abandons the synergies which can occur across divisions of the company. This is illustrated in 1E.

In short, organizations can be arrayed in a continuum from functional to project-led organization. There are also intermediate organizational forms, of which we choose two of those known to the literature for further discussion. A mixed matrix-functional form is known as a *balanced matrix.* A mixed matrix-project form is known as a *project-led organization.* The intermediate forms have somewhat of a mixed reputation among organizational designers as they are believed to create greater role ambiguity and conflict among staff members (Butler 1973).

1.1 Organizations as Institutions for Stable Matchmaking

Our claim in this paper is organizational designs provide effective institutions for the matching of resources in engineering projects. Allocation of the resources of labor, capital, and capital goods are the typical prerogatives of managers. Equally important for many organizations is the allocation of knowledge – both formal knowledge, as well as learning by doing. These resources are the prerogative of engineering staff. A failure to successfully allocate either material resources or knowledge resources could easily gutter a project.

Institutional theorists see institutions as rules, routines or procedures for the practical resolution of problems. This definition is widely adopted – see for instance Hemke and Levitsky (2004). Technical problems abound in many engineering project firms. Organizations also succumb to social problems when individual decisions are not mediated by collective rules or procedures. Christensen (1997) describes the "innovator's dilemma" many high technology companies face -- yet organizations routinely face other social dilemmas as well. Among the most severe of these problems is surely the appropriate resourcing of internal projects.

The functional organization is a social technology which delivers the unparalleled ability to administer resources in large organizations while holding down opportunism and rent-seeking behaviors. Linstone (2002) argues that the transition from owner operated firms to corporate hierarchies resulted in a dramatic increase in societal wealth, further fueling major waves of economic activity. The functional organization then is an institution furthering the need of owner-operators, and later shareholders and their corporate delegates, to match resources with wealth creation opportunities within the firm. Sosa et al. (2004) describe how traditional organizational forms discourage needed interaction at design interfaces.

What then about the project-based organization? Hobday (2000) and others are quite clear about this. These are the organizations excel at mustering technical knowledge in pursuit of specialized knowledge, or customized product design. Project-based organizations avail projects of the best available technological organization. Thus project-based organizations are institutional solutions to the dilemma of inadequate application of technological knowledge within the firm.

We hypothesize that the functional form of organization affords managers an opportunity to guide the matching process between firm resources and available projects. We further hypothesize that the project-based organization provides the engineer with the opportunity to match their own technical knowledge with firm projects. The mixed forms of organization shown in figure 1 are therefore mixed responsibility organizations which variously allocate the responsibility for defining and resourcing projects between management and engineers. This alignment of institutional form with resource dilemmas raises still further questions concerning the effective resourcing of projects internal to the firm.

2.3 Desirable Institutional Solutions for Matching

Three desirable qualities of a match have been identified by the literature. These qualities can be readily applied to the resource matching problem outlined in this section. The qualities of an effective match are *rationality, lack of blocking,* and *stability.*

DEFINITION 2.4 (Individual rationality). A matching μ is *individually rational* if no staff s prefers to remain unmatched than to be matched to $\mu(s)$.

DEFINITION 2.5 (Lack of Blocking). A matching μ is *unblocked* if there exists no pair (m,e) such that $\mu(m) \neq e$, but $e \succ_m \mu(m)$ and $m \succ_e \mu(e)$.

Definitions 2.4 and 2.5 can be intuitively understood as the following. A solution is well-matched when no staff member is matched to an unacceptable project, and when no pair of managers and engineers would be preferred to be matched to each other than their respective projects. Putting these together we have the definition of a *stable matching.*

DEFINITION 2.6 (Stable Matching). A matching μ is stable if and only if it is individually rational and unblocked.

Given this problem definition, subsequent structuring and definitions, we are now prepared to advance hypotheses concerning the role of an effective organizational design in resourcing projects. In section 3 we build upon existing theorems of matching. In addition we introduce some new corollaries to existing findings, with import for project management. The nature of project “resource buckets” and the likely response of organizations to environmental uncertainty has been considered by

Chao and Kavadias (2008). Project stability and resource appropriation is a matter for serious concern.

3 Organizational Design and the Effective Resourcing of Projects

The following section used a mixed form of reasoning, switching between the applied problem context of project resources, and the formal domain of matching problems. Nonetheless we hope to make it clear how abstract findings relate to the application setting. Our first finding is the conclusion that the matching of resources to projects in organizations is in fact a social dilemma, which cannot be solved using solely informal methods.

THEOREM 3.1. *If there is two-sided opportunism or strategic behavior, the matching problem cannot be solved in absence of a formal institution.*

Proof (Roth 1982). The proof consists of a proof by contradiction showing that individual agents have no incentive to truthfully reveal their preferences for projects given a lack of knowledge of the preferences of others on the staff. If they do truthfully reveal such preferences then this will be exploited by other staff. Furthermore, there is no effective project selection mechanism which can occur in absence of knowing the preferences of others (*ex post* equilibrium).

It is possible to solve the problem if either engineers or managers preferences are common knowledge. This could occur for instance if managers were in a contractual structure to manage resources and effort. This is a common assumption concerning the governance of hierarchies. Such a contractual mechanism would in fact constitute a formal institution. A second conclusion, building upon the literature, is that if you were to design an project organization, it is in fact possible to find a stable matching between engineers and managers using projects.

THEOREM 3.2. *There exist organizational designs which can provide an effective matching of projects to resources.*

A further conclusion is that there may be many such matchings; we may seek further for only those designs which are optimal for either engineer or management.

DEFINITION 3.3. A stable matching μ is optimal if every staff member likes it at least as well as any other stable matching; that is, $\forall s \in S$ and for every other stable matching μ', $\mu'(s) \succcurlyeq_s \mu(s)$.

Recall our hypothesis of section 2.3 that functional forms of organization afford managers their optimal choice of projects. Likewise, consider the hypothesis that project-based organizations afford engineers their optimal choice of projects. The next theorem demonstrates that such institutional forms do exist, and furthermore there is only one such institution possible.

THEOREM 3.4. *There is an institution, which we call the "functional organization" which is capable of achieving a stable matching which furthermore is optimal for managers.*

THEOREM 3.5 (Roth and Vande Vate 1990). *Roth and Vande Vate suggest a proposal rejection algorithm which permits projects to be proposed in any order. Stability can be achieved by a proposal-rejection process.*

Thus institutions capable of effective matching of diverse resources within an organization are definitely possible. Such an institution can also manage the decentralized creating and ranking of projects. The institution can work even as new projects are proposed and are entered into consideration for resource sharing. An optimal institution is as equally feasible for engineers as it is for managers. This leads to corollary 3.5.

COROLLARY 3.5. *There is an institution, which we call the "project-based organization" which is capable of achieving a stable matching which is engineering optimal.*

THEOREM 3.6. *There exists only one engineering optimal and only one management optimal institution.*

Proof. The Gale and Shapley algorithm can be run by either party, resulting in two distinct but singular and stable solutions.

A logical counter-argument would be to ask whether or not a single institution could be both engineering optimal and management optimal at the same time. Here again we have existing proofs from the literature that engineering optimal and managerial optimal solutions are frequently mutually incompatible.

THEOREM 3.6. Any organizational form which is stable and which is optimal from a managerial perspective will necessarily be the worst achievable from an engineering perspective. The reverse is also true.

Proof. An optimum matching is by definition Pareto optimal. If the managers choose the projects, then they will necessarily choose the projects which are best for them, requiring engineers to accept second-best projects. The obverse will be true if engineers are in the lead. The asymmetry of outcome is caused by either managers or engineers taking the first choice of projects.

We are then lead to question whether intermediate forms of organization, such as the project matrix, make sense given a project context.

THEOREM 3.7. Intermediate forms of organization (project matrix) are possible, but result in all projects being second-best from either an engineering or a managerial perspective.

Proof. The proof follows directly from stability concerns. For there to be a stable solution, then all managers must be better off with their current project than with any other project available to them. The same must hold for engineers. Furthermore, if the institution is indeed intermediate between engineering and management, then neither member of staff can be given their first-best choices. Such an organization may be implemented in a decentralized fashion using a project rejection scheme, preventing either engineering or management from dominating the process (Roth and Vande Vate 1990).

Thus, the matrix organization enforces a standard of mediocrity across all projects in the organization. Such uniformity may be still be desirable when mutual losses for management and engineering staff are high for substandard projects.

4 Concluding Remarks

A number of areas for future research are suggested. First, this line of argumentation could provide pay-offs in examining project selection procedures. The existing results concerning appropriate project deferral and rejection might be used in existing project management organizations in pursuit of efficient project selection and funding. Furthermore in the framework considered here, projects are a "meeting point" for resource exchange engineers and managers. A more general framework could permit weighted assignments, given the so-called "stable allocation problem (Biró 2007). " This raises a larger issue concerning the appropriate number of projects, as there is clearly more to the problem than meeting resource-based constraints.

Practical relevance also requires we consider the dynamics of project design and selection. Can an optimal allocation of projects be maintained as the project portfolio grows or changes? Similarly, if organizational designers select a given institutional design, how can they be sure that the design isn't subverted by the awarding of projects? The institutional setting is need not be fixed. Surely one of the more prominent modes of failure of the project matrix organization is when a functional organization permanently acquires resources only temporarily allocated during project resourcing.

As Gale and Shapley (1962) concluded before us "in making the special assumptions needed in order to analyse our problem mathematically, we necessarily moved further away from the original . . . question, and eventually . . . entered the world of mathematical make-believe (p. 15)." Nonetheless we think "the world of mathematical make-believe" has value for considerations of organizational design and project management, if only to remind us of the severity of the choices facing the firm. No informal mechanism exists for project selection, and any formal institutional mechanism must make difficult trade-offs between resources and technical knowledge. Any admixture of both resources and technical knowledge must necessarily result in a hybrid organization adequate at many criteria, but be excellent for very few.

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