Chapter 2

Background and motivation

In this chapter, we provide general information on three essential elements of the environment in which our three problems are embedded. These elements are multi-project management, multi-skilled workers, and teamwork. In Section 2.1, we elaborate on multi-project management, which is concerned with managing a portfolio of parallel undertakings. We emphasize the importance of multi-project management, explain its main tasks, and give an overview of contributions that address the main tasks. Two of these main tasks, namely, project selection and staffing, are part of our approach. In Section 2.2, we turn to multi-skilled workers. Here, we describe advantages of cross-training and give a brief overview of methods to determine skill levels, which are required as input data for our models. Furthermore, we describe the flexibility design problem that is associated with a multi-skilled workforce. Later, we make a novel contribution to this design problem in Section 7.2. Eventually, we address teamwork in Section 2.3 where we give reasons why small teams are advantageous.

2.1 Multi-project management

In this section, we briefly review principles of multi-project management. First of all, we stress the importance of multi-project management. Then, we elaborate on its three main planning tasks, which are portfolio selection, scheduling, and staffing of projects (cf. Heimerl and Kolisch, 2010a, p. 344). All three tasks are affected by the availabilities and capabilities of (human) resources whose crucial role is emphasized throughout this section.

The importance of multi-project management has increased over the last decades and is still growing. In the middle of the last century, project and multi-project management gained momentum; the share of project work has increased since then and the penetration of firms by corresponding management methods has not stopped at the beginning of this century (cf. Kerzner, 2013, pp. 47–63). The ongoing growth of multi-project management and its still increasing relevance is reflected in the currently growing need for portfolio and project management software (cf. Figure 2.1).

The rise in project work has been a response to several developments. Accelerated technological progress and faster changing consumer needs have led to shorter product life cycles and have rewarded shorter product development times. This in turn put time pressure on organizations and caused shorter life spans of the respective organizational structures. Intensified national and international competition rewarded customer orientation, i.e., customized and thus unique solutions. Shorter life spans of organizational

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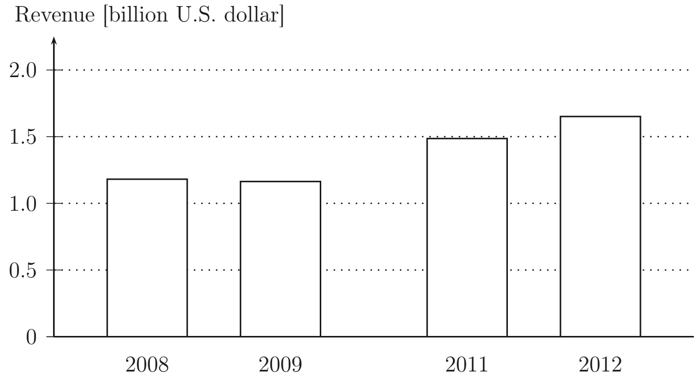

Figure 2.1: Global revenue from project and portfolio management software from 2008 to 2012 (data provided by Statista (2013), original source: Gartner, Inc.)

structures and customer orientation favor project work, which is temporary and unique by nature. The increase in project work has amplified the importance of multi-project management, which is concerned with planning, executing, and controlling. In the realm of planning, the major management tasks are selecting, scheduling, and staffing projects. We elaborate on these main tasks because they overlap with our approach.

The first main task of multi-project management is selecting projects. The resulting project portfolio contains both external and internal projects. External projects originate outside a firm, whereas internal projects come from within the firm. Examples are a customer order and a process improvement project, respectively. Common criteria for project selection are strategic fit, urgency, and profitability of a project amongst others (cf. Pinto, 2010, pp. 90–125; Rüdrich, 2011). The strategic fit expresses how well the project contributes to overall long-term goals of the organization, whereas urgency relates to the operational need for the deliverables of the project. The criterion profitability measures the economic advantage of the project. In our approach, we condense information emerging from several criteria into a single benefit value for a project.

Two variants of project selection problems are distinguished: static and dynamic project selection. The static variant, which we consider in our approach, considers a set of candidate projects from which only a proper subset can be selected for implementation. A decision is made only once. If resource constraints are taken into account, this variant is related to the knapsack problem where a subset of items must be chosen such that their total weight does not exceed the capacity limit of a knapsack and their total utility is maximized. The dynamic variant of the project selection problem considers the situation where project proposals arrive over time (cf. Herbots et al., 2007). Every time when a project arrives, a decision has to be made whether the project is selected or not.

When such a decision must be taken, details of future arrivals, e.g., resource requirements, benefits, and arrival times of the projects arriving next, are not known.

Static project selection problems are formulated either as single- or multi-period problems. In the case of multi-period formulations, the planning horizon is divided into periods. Hence, the temporal process of a project can be taken into account. A multi-period approach is advantageous especially if scarce resources are considered because the schedule of a project—whether already fixed or still flexible—does not result in a constant load over time for all resources in general. The following example demonstrates the advantage of a multi-period model when resource requirements vary over time.

Example 2.1 Let two candidate projects that last one year each have a resource demand for 4 man-years while 8 workers are available. Then, both projects can be selected in a single-period model as they do not violate resource constraints. However, if each project requires 6 full-time workers in the first half of the year and only 2 workers in the second half, it is not possible to implement both projects given 8 workers. Nevertheless, the portfolio containing both projects would be a feasible portfolio in the single-period model. □

Since changes in resource requirements over time, e.g., the dynamic requirements stated in Example 2.1, cannot be captured by a single-period model, we opted for a multi-period formulation. A multi-period model allows to take non-constant resource demands and supplies into account.

In the literature on project selection, however, an explicit consideration of resource requirements and resource availabilities is not a given and often, resources are neglected. Textbooks on project management frequently suggest selection procedures which do not consider resource constraints (cf. GPM, 2008, pp. 447–467; Pinto, 2010, pp. 90–125). Of course, procedures that do not account for resources can be justified, as in some situations resource constraints are not present or because the procedures have another focus. In many situations, though, resources are scarce, and neglecting resource constraints can lead to plans that cannot be implemented.

Many approaches to project selection consider budget constraints, i.e., limited financial resources. Financial requirements of projects may include cost for personnel. Some approaches that consider only budget constraints but no other resource constraints may imply the assumption that workers with the necessary qualification profiles can just be bought. However, such an assumption is risky. Since skilled workers are rather scarce, this assumption is questionable and may lead to failure when projects are carried out.

Table 2.1 gives an overview of contributions to static project selection problems that we reviewed for this thesis. Some of these contributions will be treated in more detail in subsequent chapters, especially in Section 5.1. Table 2.1 distinguishes single-period from multi-period models and whether only budget restrictions or resource constraints including potential budget restrictions are considered. Furthermore, we marked contributions that consider skills, be it in the form of multi-skilled resources or in the form of different skill levels of mono-skilled resources. Some of the listed publications integrate scheduling and/or staffing and some explicitly consider multi-skilled resources. Scheduling is integrated into the models of Chen and Askin (2009), Escudero and Salmeron (2005), Ghasemzadeh et al. (1999), and Kolisch et al. (2008). Kolisch et al. (2005) and Taylor et al. (1982) consider problems with a time-resource trade-off where project start times are fixed but project durations vary with the amount of allocated resources. Both scheduling and staffing is incorporated in the selection models of Gutjahr et al. (2008, 2010). Lopes et al. (2008), Yoshimura et al. (2006), and Taylor et al. (1982) integrate selection and staffing.

Table 2.1: Classification of selected publications on static project selection procedures

		Constraints		
	Multi-period model	Only budget	Resources (incl. budget)	Skills
Fox et al. (1984)		•		
Golabi et al. (1981)		•		
Gurgur and Morley (2008)		•		
Lai and Xue (1999)		•		
Lopes et al. (2008)		•		•
Muralidhar et al. (1990)		•		
Schmidt (1993)		•		
Tavana (2003)		•		
Eilat et al. (2006)			•	
Santhanam et al. (1989)			•	
Santhanam and Kyparisis (1996)			•	
Yoshimura et al. (2006)			•	•
Chen and Askin (2009)	•		•	
Doerner et al. (2004)	•		•	
Escudero and Salmeron (2005)	•		•	
Ghasemzadeh et al. (1999)	•		•	
Graves and Ringuest (2003)	•		•	
Gutjahr et al. (2008)	•		•	•
Gutjahr et al. (2010)	•		•	•
Kolisch et al. (2005)	•		•	
Kolisch et al. (2008)	•		•	
Taylor et al. (1982)	•		•	
Weingartner (1966)	•		•	

Skills are considered in only four of the listed works. In Yoshimura et al. (2006) and Gutjahr et al. (2008, 2010), multi-skilled workers constrain the composition of the project portfolio. Skill levels are static in the model of Yoshimura et al. (2006), whereas Gutjahr et al. (2008, 2010) take learning and forgetting into account resulting in dynamic skill levels that increase through exercising the respective skill and decrease when the skill is not used. In Lopes et al. (2008), projects are selected and assigned to students who must complete a project as part of their curriculum. Here, students exhibit different average grades that can be interpreted as distinct skill levels. A soft constraint requires that the mean skill of each project team is not below a minimum level.

In all contributions, portfolio benefit or value is maximized while occasionally other goals are pursued in addition to benefit maximization. Some authors describe how multiple criteria can be aggregated, whereas Yoshimura et al. (2006), Doerner et al. (2004), Graves and Ringuest (2003), and Gutjahr et al. (2010) consider genuine multi-criteria models with a separate objective function for each criterion. Apart from the objective of maximum portfolio benefit, three models feature additional objectives that refer to skills and worker satisfaction. Lopes et al. (2008) minimize the total deviation of all project teams from the minimum mean skill level. Yoshimura et al. (2006) pursue the aim of maximizing the skill supply for each project and maximizing worker satisfaction. Gutjahr et al. (2010) seek for solutions that lead to an optimal growth in skill levels due to learning.

The second main task of multi-project management is project scheduling, which is concerned with determining a start time for each project and sometimes also for each activity of a project if there is leeway. Start times must be chosen such that resource constraints and temporal constraints are regarded. Since resources are required to perform project activities, a feasible schedule must observe availabilities of renewable resources such as manpower and of non-renewable resources such as budget. Temporal constraints can comprise minimum and maximum time lags between project activities. Frequent objectives for scheduling are maximization of the net present value, minimization of costs, and minimization of project duration, also called makespan minimization. Though, Tukel and Rom (1998) found in a survey among U.S. project managers from various industries that quality was the most important scheduling objective for the respondents; it was more important than time and cost. However, a precise definition of the term quality was not given by Tukel and Rom.

In general, a multi-project scheduling problem can be transformed into a single-project scheduling problem for which a rich body of literature exists that provides different solution approaches for a large number of objective functions (cf. Neumann et al., 2003, for example). To sketch the transformation, assume that each project is represented by an activity-on-node network whose nodes correspond to project activities and whose arcs correspond to temporal constraints. Then, the separate project networks can be merged into one network that represents a meta-project and contains all projects as subprojects. In this case, multi-project and single-project scheduling problems are equivalent.

For the project selection and staffing problem that we consider in this thesis, we assume that the schedule of each project is already fixed prior to the decision about the project portfolio. This assumption holds true for many situations nowadays. Due to increased competition, clients can often demand tight due dates that do not give the freedom to shift activity start times (cf. Kolen et al., 2007, pp. 530–531). Nevertheless, it is worthwhile to explore scheduling approaches because they often integrate staffing decisions and sometimes explicitly consider multi-skilled workers.

When multi-skilled workers are considered, it is possible but not advisable to represent a project scheduling problem as a multi-mode resource-constrained project scheduling problem (MRCPSP). In the MRCPSP, activities can be executed in alternative modes that differ in resource usage and activity duration (cf. De Reyck and Herroelen, 1999; Heilmann, 2003). To give an example, consider an activity that can be executed in two modes. In the first mode, the activity is executed by an expert and finished within two days. In the second mode, two beginners perform the activity and need three days. To demonstrate the disadvantage of a multi-mode model, consider a workforce of 20 workers and an activity that can be accomplished by any of the 20 workers alone but also by any team formed by the workers. Each distinct, non-empty subset of workers may represent a mode in which the task can be performed. Then, the activity can be executed in $2^{20} - 1 = 1\,048\,575$ different modes.[1] Here, the size of a model that explicitly describes all possible modes increases exponentially in the number of workers. Hence, if each worker is considered as an individual resource and workers have overlapping skill sets, the number of alternative modes per activity usually is so large that a multi-mode representation is not adequate (cf. Bellenguez-Morineau and Néron, 2007, pp. 156–158). That is why multi-mode models are not common for problems with multi-skilled workers. The work of Tiwari et al. (2009) is an exception as they use an MRCPSP formulation for scheduling activities given a multi-skilled workforce with heterogeneous skill levels.[2]

Table 2.2 lists a choice of papers that tackle either multi-project or single-project scheduling problems or problems that are no project scheduling problems but scheduling problems that involve multi-skilled workers. Papers that explicitly refer to multi-project scheduling are marked in the table. Furthermore, the table indicates when contributions consider multi-skilled resources, when skill levels are distinguished, and what kind of objective is pursued. Most of the listed papers that deal with multi-project scheduling determine project start times only and assume that activity start times are coupled to the start time of the corresponding project and cannot be shifted. Solely Kolisch and Heimerl (2012) determine project and also activity start times. In the models of Gutjahr et al. (2008, 2010) and Wu and Sun (2006), there is also freedom: The workload of an activity must be accomplished sometime between the release and the due date of the activity. In Kolisch et al. (2008), a start time and a mode must be chosen for each project; different modes are associated with different project durations and different resource requirement profiles.

Time related and cost related objectives are very common for scheduling approaches, as Table 2.2 reveals. In Alfares and Bailey (1997), costs depend on project duration and on the number of workers that are deployed in different days-off tours in each week of the planning horizon. Barreto et al. (2008) suggest different objectives for their scheduling and staffing problem, e.g., the minimization of project duration, staffing costs, and team size. Li and Womer (2009a) try to schedule tasks on a naval ship such that the size of the required crew is minimized. In Li and Womer (2009b), costs of a project schedule directly depend on the number of workers that are required to staff the project; in a numerical study, the costs of assigning a worker to the project are the same for each worker, hence they minimize project team size in the numerical study. Valls et al. (2009) consider three objectives, which are lexicographically ordered; their objective with lowest priority is leveling the workload of employees, which is also our lowest-priority objective. Dodin and Elimam (1997) take switching costs into account that are incurred every time when an employee is assigned to a task which belongs to another project than his previous

[1] The number of modes is even higher if a team can accomplish the task in different modes, as it will be the case in our models.

[2] The work of Tiwari et al. (2009) is noteworthy for a second reason as the authors explicitly consider quality in their approach. They require that an activity is completed by a suitable worker with a certain skill level in order to meet a desired quality requirement. However, a less skilled worker can start to process the activity and hand it to a worker with the required skill level for the final touch. As workers with high skill levels are a bottleneck, this splitting of an activity's accomplishment can shorten project duration.

Table 2.2: Classification of selected publications on (project) scheduling

		Skills		
	Multi-project model	Multi-skilled ressources	Different skill levels	Aim*
Alfares and Bailey (1997)				C
Drexl (1991)			•	C
Bellenguez-Morineau and Néron (2007)		•		T
Correia et al. (2012)		•		T
Drezet and Billaut (2008)		•		T
Ho and Leung (2010)		•		O
Li and Womer (2009a)		•		C
Li and Womer (2009b)		•		O
Vairaktarakis (2003)		•		T
Barreto et al. (2008)		•	•	C,T,O
Cordeau et al. (2010)		•	•	T
Fırat and Hurkens (2012)		•	•	T
Hegazy et al. (2000)		•	•	T
Valls et al. (2009)		•	•	O
Chen and Askin (2009)	•			B
Escudero and Salmeron (2005)	•			B
Ghasemzadeh et al. (1999)	•			B
Kolisch et al. (2008)	•			B
Grunow et al. (2004)	•	•		C
Bassett (2000)	•	•	•	C
Dodin and Elimam (1997)	•	•	•	C
Gutjahr et al. (2008)	•	•	•	O
Gutjahr et al. (2010)	•	•	•	O
Heimerl and Kolisch (2010a)	•	•	•	C
Kolisch and Heimerl (2012)	•	•	•	C
Wu and Sun (2006)	•	•	•	C

*Abbreviations for aims: B = portfolio benefit, C = cost,
T = time (makespan, completion times, lateness), O = other

task.[3] In Wu and Sun (2006), it is possible to outsource workload to external workers in order to meet due dates; the aim is to minimize costs for external staff.

The listed works do not only differ in the characteristics stated in Table 2.2. Another difference is, for example, whether the number of workers necessary to accomplish a task is prescribed or not. A further difference in the respective models is whether a worker can contribute to one or more tasks per period. Moreover, the length of the planning horizons differs. A schedule searched for can span one day (cf. Ho and Leung, 2010; Valls et al., 2009; Grunow et al., 2004), a couple of days (cf. Drezet and Billaut, 2008; Cordeau et al., 2010; Fırat and Hurkens, 2012), several weeks (cf. Barreto et al., 2008; Li and Womer,

[3]The model presented by Dodin and Elimam (1997) is not utterly correct, as the constraints that are intended for counting the occurrences of switching can actually exclude some feasible solutions.

2009a; Hegazy et al., 2000), a number of month (Alfares and Bailey, 1997; Wu and Sun, 2006, cf.), one or two years (cf. Bassett, 2000; Gutjahr et al., 2008, 2010), or even a period between three and five years (cf. Escudero and Salmeron, 2005; Ghasemzadeh et al., 1999; Kolisch et al., 2008).

Teams are addressed by five works listed in Table 2.2. Ho and Leung (2010) solve a crew pairing and routing problem where teams of two persons must be formed and a job sequence must be assigned to each team such that at least one team member masters the skill that is required by a job in the sequence. For a scheduling and staffing problem, Barreto et al. (2008) formulate alternative objective functions that lead the search to either a fastest, a least expensive, a best qualified or a smallest team, for example. Cordeau et al. (2010) and Fırat and Hurkens (2012) consider a problem where for each day technicians must be grouped in teams that stay together for one day. A team can only accomplish tasks whose skill requirements can be satisfied by the team. In Grunow et al. (2004), workers that are assigned to tasks which belong to the same clinical study form a team. In the corresponding staffing subproblem that is embedded in their scheduling approach, Grunow et al. minimize average team size as we do in our approach. In our approach, though, the number of workers that are needed to accomplish a task of a project is not fixed a priory. Furthermore, we distinguish different skill levels for workers and do not assume homogeneous efficiencies.

Most of the listed papers on scheduling integrate staffing, i.e., tasks are assigned to individual workers or to single teams. In contrast, Alfares and Bailey (1997), Hegazy et al. (2000), Chen and Askin (2009), Escudero and Salmeron (2005), Ghasemzadeh et al. (1999), and Kolisch et al. (2008) only ensure resource feasibility of their schedules but do not specify which resource has to accomplish which tasks.

The third main task of multi-project management is to assign workers to projects and allocate project workload to them. For this task, many aspects such as availabilities, skills, and capacity for teamwork must be taken into account: Availabilities of workers must be observed, especially if workers have other duties apart from project work. Other duties are common in matrix organizations, where long-term organizational structures, which are embodied by functional departments, for example, and short-term project organizations coexist. Here, both department and project managers demand workers and hence coordination is necessary (cf. Schneider, 2008). Workers should master the skills that are needed to successfully accomplish those tasks they are assigned to. If collaboration of project team members is essential, an employee's ability to work in a team and his capability to cooperate with each co-worker in the team should be regarded. Our staffing model explicitly considers the situation in a matrix organization and takes workloads of functional departments and projects into account. Skills of workers and their efficiencies are also regarded.

In the literature, various aspects have been considered in staffing models and many approaches to workforce assignment problems have been presented. Table 2.3 contains a choice of papers that deal with staffing for the day-to-day business, staffing of single projects, or staffing of multiple projects. Those papers that consider multiple projects are marked in the second column of Table 2.3. The table further distinguishes whether mono- or multi-skilled workers are considered, whether workers differ in skill levels, and whether a single- or multi-period problem is tackled.

There are many other differences between the works compiled in Table 2.3. These

Table 2.3: Classification of selected publications on staff assignment

		Skills		
	Multi-project model	Multi-skilled ressources	Different skill levels	Multi-period model
Miller and Franz (1996)				•
Corominas et al. (2005)		•		
Gomar et al. (2002)		•		•
Krishnamoorthy et al. (2012)		•		•
Kumar et al. (2013)		•		
Slomp and Molleman (2002)		•		
Valls et al. (1996)		•		•
Brusco and Johns (1998)		•	•	•
Campbell and Diaby (2002)		•	•	
Eiselt and Marianov (2008)		•	•	
Fowler et al. (2008)		•	•	•
Otero et al. (2009)		•	•	
Fitzpatrick and Askin (2005)	•			
LeBlanc et al. (2000)	•			•
Lopes et al. (2008)	•		•	
Reeves and Hickman (1992)	•		•	
Certa et al. (2009)	•	•	•	
Patanakul et al. (2007)	•	•	•	
Santos et al. (2013)	•	•	•	•
Yoshimura et al. (2006)	•	•	•	

differences concern the level of detail with which workers are modeled, the interpretation of skill levels, and the objectives pursued, for example. First of all, the listed papers consider either individual workers or groups of workers where the workers of each group have identical skill sets and identical skill levels. Such groups of homogeneous workers are found in Corominas et al. (2005), Valls et al. (1996), Brusco and Johns (1998), and Fowler et al. (2008).

A major difference lies in the interpretation of skill levels. Those papers that do not only distinguish whether a worker masters a certain skill or not but that also distinguish the level of excellence with which a skill is mastered, interpret skill levels in various ways. Some authors, namely, Brusco and Johns (1998), Fowler et al. (2008), and Otero et al. (2009), interpret skill levels as a measure of efficiency. We follow the same interpretation. According to this interpretation, a worker with a higher skill level accomplishes a corresponding task faster than a less skilled worker. Other authors, videlicet, Campbell and Diaby (2002), Lopes et al. (2008), Reeves and Hickman (1992), Certa et al. (2009), and Patanakul et al. (2007), interpret skill levels as a measure of quality. Here, utility of a task completion is the higher, the higher the skill level of the responsible worker is. Yoshimura et al. (2006) and also Barreto et al. (2008) (see Table 2.2) interpret skill levels in terms of both efficiency and quality, whereas Eiselt and Marianov (2008) use the positive difference between a worker's skill level and the skill level demanded by a task to express the degree of boredom resulting from the corresponding assignment for the worker. In Santos et al. (2013), the skill level impacts training costs that are incurred if a worker whose skill level is lower than the maximum level is assigned to a task requiring the skill. In the approach of Otero et al. (2009) a low skill level can be compensated by high levels in related skills.

As in the case of papers on scheduling, the staffing models differ with respect to the maximum number of projects or tasks a worker can contribute to in each period or during the complete planning horizon. The staffing models differ also with respect to the number of skills required by a task and whether the number of workers required to perform a task is predefined or not. Planning horizons range between one day (cf. Krishnamoorthy et al., 2012; Brusco and Johns, 1998; Campbell and Diaby, 2002), a couple of weeks (cf. Gomar et al., 2002), several months (cf. Eiselt and Marianov, 2008; Fowler et al., 2008; Patanakul et al., 2007), and one year (cf. LeBlanc et al., 2000). Most authors assume for their models that the workforce is fixed and that its size cannot be altered, i.e., that capacity is fixed. However, Gomar et al. (2002) and Fowler et al. (2008) include decisions about hiring and laying off workers; Santos et al. (2013) allow for hiring but not for firing. In Eiselt and Marianov (2008), the workforce is fixed but tasks can be outsourced.

Objectives of the listed contributions are different as well. Some models search for an assignment that maximizes the preferences of the workers, some minimize staffing costs. Staffing costs can comprise several types of cost, e.g., costs for hiring, firing, overtime, outsourcing, and training. The goal of a minimum number of required workers is pursued by Krishnamoorthy et al. (2012), Valls et al. (1996), and Brusco and Johns (1998); though, none of them considers a multi-project environment. Other objectives apart from the aforementioned are pursued as well. Multi-criteria models with more than one objective function are formulated by Reeves and Hickman (1992), Certa et al. (2009), and Yoshimura et al. (2006).

A special problem is the assignment of project managers to projects. The papers of LeBlanc et al. (2000) and Patanakul et al. (2007) address only this problem, while Yoshimura et al. (2006) tackle this problem as one of many. Patanakul et al. (2007) explicitly consider a manager's effort to head more than one project team simultaneously. Time needed for switching from one project to another is taken into account. This switching time represents the productivity loss that arises due to multi-tasking. Furthermore, the maximum number of projects a manager can lead is limited in the model of Patanakul et al.

Team issues are addressed by six contributions in Table 2.3. Certa et al. (2009) consider the relationship between pairs of workers and assume that a parameter describes for each pair of workers their preference to work together. One of the goals pursued by Certa et al. is to form project teams such that the preferences for cooperation of those team members who perform the same skill are maximized. Similarly, Kumar et al. (2013) seek for an assignment of workers to tasks such that those tasks whose execution requires cooperation between the responsible workers are assigned to workers who can collaborate as well as possible. Likewise, Yoshimura et al. (2006) integrate mutual compatibility of team members into one of their objective functions. Fitzpatrick and Askin (2005) try to determine a team such that personality traits and instinctive behaviors of team members are optimally balanced. Lopes et al. (2008) and Reeves and Hickman (1992) tackle problems where students must be assigned to projects that are part of the students' curricula. In both contributions, one aim is to form project teams of equal quality. Team

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