A new solution procedure for multi-skilled resources in resource-constrained project scheduling

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1 Introduction

Creating a versatile and flexible workforce has become a paramount goal in the long term strategies of today's corporations. Investing in the development of a set of proficient human resources is a key concept in the success of companies that deal with projects (Riley, *et. al.* 2017). Moreover, the developing need for a team of complementary skillful resources is motivated by the current customer-specific wishes that have become regular for companies. This move from large production firms to job-shop companies with shorter product cycles creates a demand for workers who frequently learn to master new skills and adapt to new product requirements and specifications (Nembhard and Uzumeri 2000). Since a lot of projects are executed by workforces that consist of multi-skilled resources (Haas, *et. al.* 2001), this paper will study their impact on the project's characteristics and objectives.

This abstract addresses the *multi-skilled resource-constrained project scheduling problem*, further abbreviated as MSRCPSP. The MSRCPSP is an extension to resource-constrained project scheduling problem (RCPSP), which is NP-hard (Blazewicz, *et. al.* 1983). When dealing with multi-skilled resources in projects, two key decisions need to be taken. The first decision considers the workforce composition. Different from the RCPSP, the workers are not assumed to be uniform or to master the complete skillset, rather the multi-skilled resources are individually different and master a subset of the complete skillset. During the workforce composition stage, the goal is to create a workforce with the right size and available skills that match the skill requirements of the project at hand. The second decision to be taken involves simultaneously determining the activity schedule and the resource assignment. Using the assembled workforce, the aim is to construct resource-feasible solutions for the MSRCPSP that minimise two objectives. Additionally, we investigate the impact of skills on the final project schedule and resource assignment.

In our view of the problem, the multi-skilled resources are characterised by two key concepts known as breadth and depth. In this problem, the breadth of resources indicates the number of skills that a resource masters. Depth is linked to a skill that a resource masters, and signifies the efficiency at which the resource can perform the skill. The more proficient a resource is at a skill, the higher its depth is for that skill. In this study, the depth of a skill will impact the duration of the activities in the project. More specifically, the value of the depth can positively or negatively affect the variable duration of the activities dependent on the efficiency of the skills of the resources that are assigned to the activity.

In the literature, the MSRCPSP has been researched in several studies. Néron (2002) was the first to extend the RCPSP with resource skillsets, in this study two lower bounds were proposed. Furthermore, Bellenguez and Néron (2004) extended this research with hierarchical skill levels. This concept is similar to the depth of the resources, but is handled differently. In their research, the hierarchical skill levels are incorporated to specify a different required efficiency level for each skill requirement, which means that it only impacts the resource assignment and not the duration of the activities. Furthermore, various heuristics and other solutions were proposed for this problem (Bellenguez and Néron (2007), Li and Womer (2009), Correia, *et. al.* (2012)).

2 Problem Definition

In the MSRCPSP, a project can be represented by an acyclic activity-on-the-node network $G = (N, A)$, in which the minimum precedence relationships with a time-lag of zero are characterised by the arc set A and the activities by the node set N. The project consists of $|N|$ real activities and two additional dummy activities 0 and $|N| + 1$, which have no resource usage and a duration of zero. The activities are topologically ordered, that is, an activity always has a higher label than all of its predecessors. The project is said to be scheduled without pre-emption within the precedence relations and with a set of renewable multi-skilled resources R, with $R = 1, ..., |R|$, resulting in a baseline schedule with an activity starting time s_i and finishing time f_i for each activity i that minimises the makespan and resource idle time.

Each activity has a certain predefined duration and a demand for renewable resources, that are defined differently than for the RCPSP due to the presence of skills in the problem formulation. While the resource constraints for the RCPSP are defined as a set of renewable resource types (with index $k = 1, ..., |K|$), and each activity i is linked to a resource by its resource demand r_{ik} for each resource type k, the resource requirements are adjusted for skills in the MSRCPSP. Each activity $i \in N$ requires r_{ij} resources that master skill j of the set of available skills J for project G. More specifically, an activity i has a certain resource demand that is defined as a skill requirement for the skill j of a resource k. Note that a resource k can only be assigned to no more than one activity every time unit t. Every resource k from the set R masters at least one skill of the set of skills J, with $J = 1, ..., |J|$, defined by the breadth of the resource b_k. The depth d_{jk} of a skill j is the efficiency level of the resource k, and is defined as a rational number with a default standard value equal to 1. A resource k with a higher (lower) efficiency level is represented by a depth higher (lower) than 1.

An individual activity $i \in N$ has a predefined non-preemptive processing time of p_i, which is defined as the time required to execute the activity by workers $k \in R$ with skills of the default depth level, $d_{jk} = 1$. Higher depth values will reduce the processing time of an activity, while lower levels of depth will increase the processing time. To the best of the author's knowledge, there is no standardised equation in the literature that calculates the adjusted processing time of an activity i taking into account the depth d_{jk} of the skills ($j \in J$) of the assigned workers ($k \in R$). As proposed in Heimerl and Kolisch (2010) and Kolisch and Heimerl (2012), the reciprocal of the average depth will be used to calculate the impact of different efficiency levels on the activity duration. Moreover, we will investigate the impact of this variable activity duration on the activity scheduling and the resource assignment.

3 General Methodology

The MSRCPSP under study is an NP-hard problem (Bellenguez and Néron 2004), and is, therefore, solved using a genetic algorithm (GA). A schedule in the GA of this paper is represented by two lists which give a solution to the activity scheduling problem and the resource assignment problem (Figure 1). An activity list (AL) represents the activity schedule. In such an activity list of length $|N|$, activities with a higher priority to be scheduled in the schedule generation scheme are earlier in the list than activities with a lower priority. A new priority rule list (PL) is proposed that represents the resource assignment problem of the MSRCPSP. In this list of length $|N|$, every activity is assigned a priority list value PL_i that corresponds to a resource priority rule, which consists of |R| values. A priority rule can be appointed to multiple activities and the value PL_i determines the priority rule of activity i. A set of resource priority rules is carefully assembled to support the assignment of resources to the activities.

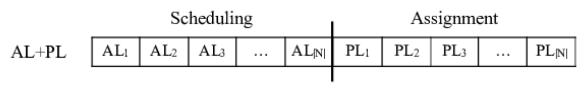

Fig. 1. Solution representation

To initialise the genetic algorithm several different initial solutions are created based on the skill requirements, the skill availabilities and a random approach. Afterwards, two parent solutions are selected from this initial population. These two parents will undergo a crossover to generate a new child solution. In this algorithm, two different crossovers are presented. The random two-point crossover randomly selects two points in the activity list or the priority rule list and creates a new child solution by copying the values outside the two points from the first parent, and inserting the values between the two points using the order of the second parent. The split low demand ranges crossover is specifically designed for the MSRCPSP and utilises ranges, or sections, of activities in the activity list that have a lower resource requirement than the average resource requirement. The middle points of the two longest ranges are then applied as in a two-point crossover to split the sections of activities with low resource requirements. Furthermore, two basic mutators are incorporated in this algorithm, which are the swap- and modify-mutator.

The generated solutions are further improved through several local searches. A local search is created that improves the schedule based on the forward-backward iterative scheduling technique of Li and Willis (1992). To improve the resource assignments of the generated schedules, two local searches are proposed that, respectively, focus on the availability of the skills in the workforce and the depth of the resources.

4 Computational experiments

The experimental results will consists of 3 different insightful analyses.

- A comparison of the solution quality of the algorithm against a benchmark to investigate the competitiveness of our algorithm.
- Investigating the quality of the set of resource priority rules used for the resource assignment problem.
- Managerial insights on the ideal workforce size and the availability of the skills. Preliminary results have shown that, in most cases, both the ideal workforce and the skill-pool size depend on the objective and the seriality of the project network (Table 1).

Table 1. Preliminary managerial insights

Objective	SP	Skill-pool size	Workforce size
Makespan	Low	Mid	Mid-High
Makespan	Mid	Low-Mid	No preference
Makespan	High	Low-Mid	No preference
Idle Time	Low	Mid	Low
Idle Time	Mid	Low	Low
Idle Time	High	Low	Low

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References

Bellenguez, O., Néron, E., 2004. "Lower bounds for the multi-skill project scheduling problem with hierarchical levels of skills", *International Conference on the Practice and Theory of Automated Timetabling*, Springer, pp. 229-243.

Bellenguez-Morineau, O., Néron, E., 2007. "A branch-and-bound method for solving multi-skill project scheduling problem", *RAIRO-Operations Research*, 41 (2), pp. 155-170.

Blazewicz, J., Lenstra, J. K. and Kan, A. R., 1983. "Scheduling subject to resource constraints: classification and complexity", *Discrete applied mathematics*, 5 (1), pp. 11-24.

Correia, I., Lampreia-Lourenc Ì§o, L., Saldanha-da Gama, F., 2012. "Project scheduling with flexible resources: formulation and inequalities", *OR spectrum*, 34 (3), pp. 635-663.

Gutjahr W.J., Katzensteiner, S., Reiter, P., Stummer, C., and Denk, M., 2010, "Multi-objective decision analysis for competence-oriented project portfolio selection", *European Journal of Operational Research*, 205 (3), pp. 670-679.

Haas, C. T., Rodriguez, A. M., Glover, R. and Goodrum, P. M., 2001. "Implementing a multiskilled workforce", *Construction Management & Economics*, 19 (6), pp. 633-641.

Heimerl, C., Kolisch, R., 2010. "Scheduling and staffing multiple projects with a multi-skilled workforce.", *OR spectrum*, 32 (2), pp. 343-368.

Kolisch, R., Heimerl, C., 2012. "An efficient metaheuristic for integrated scheduling and staffing it projects based on a generalized minimum cost flow network.", *Naval Research Logistics*, 59 (2), pp. 111-127.

Li, K. Y., Willis, R. J., 1992. "An iterative scheduling technique for resource-constrained project scheduling", *European journal of operational research*, 56 (3), pp. 370-379.

Li, H., Womer, K., 2009. "Scheduling projects with multi-skilled personnel by a hybrid MILP/CP benders decomposition algorithm", *Journal of Scheduling*, 12 (3), pp. 281.

Nembhard, D. A., and Uzumeri, M. V., 2000. "Experiential learning and forgetting for manual and cognitive tasks", *International journal of industrial ergonomics*, 25 (4), pp. 315-326.

Néron, E., 2002. "Lower bounds for the multi-skill project scheduling problem", *Proceeding of the Eighth International Workshop on Project Management and Scheduling*, pp. 274-277.

Riley, S. M., Michael, S. C. and Mahoney, J. T., 2017. "Human capital matters: Market valuation of firm investments in training and the role of complementary assets", *Strategic Management Journal*, 38 (9), pp. 1895-1914.