Resource-constrained multi-project scheduling with activity and time flexibility

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Abstract

Project scheduling in manufacturing environments often requires flexibility in terms of the selection and the exact length of alternative production activities. Moreover, the simultaneous scheduling of multiple lots is mandatory in many production planning applications. To meet these requirements, a new resource-constrained project scheduling problem (RCPSP) is introduced where both decisions (activity flexibility and time flexibility) are integrated. Besides the minimization of makespan, two new alternative objectives are presented: maximization of balanced length of selected activities (time balance) and maximization of balanced resource utilization (resource balance). New mixed integer and constraint programming (CP) models are proposed for the developed integrated flexible project scheduling problem. Benchmark instances on an already existing flexible RCPSP and the newly developed problem are solved to optimality. The real-world applicability of the suggested CP models is shown by additionally solving a large industry case.

Keywords: Multi-project scheduling, activity and time flexibility, constraint programming, manufacturing

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1. Introduction and motivation

Project scheduling is an essential operational planning area in different business sectors where precedences between activities and the access to limited resources have to be taken into account. Besides a large number of applications such as research and development or software development, one important example is the scheduling of manufacturing activities (Artigues et al., 2013). The underlying optimization problem is the well-known NP-hard resource-constrained project scheduling problem (RCPSP), characterizing a project where all included activities have to be scheduled in such a way that resource constraints, processing times, and precedence relations are respected. The most common objective is the minimization of the makespan (Hartmann & Briskorn, 2010).

In a manufacturing context, decision-makers sometimes have the flexibility to choose between different manufacturing activities or decide on the exact length of them. Precisely these flexibility descriptions motivate the RCPSP presented in this work, faced by many different manufacturing industries. For the production of multiple lots (=jobs), there are several alternative production activities per lot. Due to existing technological requirements, alternative activities are aggregated to a number of alternative routes per lot. For every lot, one production route has to be selected, an individual delivery date has to be considered and early delivery is not permitted. Besides machines or manpower, also typical logistics renewable resources such as vehicles or intermediate storages (buffers) have to be considered since they are strongly limited in many factories. Every activity of every lot demands at least one scarce resource, e.g. a transporting, storaging or machining activity. Due to the consideration of all existing resources, all activities of one lot have to be sequenced directly one after another. This means that idle times between the activities within one lot are not allowed, since they would result in a temporary ficticious disappearance of the production lot. E.g., if the machining activity of lot 1 is finished, the next one in the precedence relationship, e.g. the storaging activity of lot 1 has to start immediately. However, routes (multiple activities) of different lots can be scheduled in parallel, competing for the available production resources. E.g., the storaging activity of lot 2 can start before the storaging activity of lot 1 is completed. Moreover, different lots use different production activities and the sequence of utilized resources is not identical for all lots. With special regard to logistics activities such as storaging, minimum and maximum allowed processing times are specified for activities. Thus, processing times are of variable length, i.e. the start and the end time per activity have to be decided during the optimization process (time flexibility). As a result, the treated problem integrates the two major decisions of activity selection and processing time determination. In addition, we introduce two new objective functions: maximization of balanced length of activity processing times (time balance), and maximization of balanced resource utilization (resource balance).

The described production process may be found in various production industries. Three different examples the authors know from several cooperations with production managers are the steel-, the food-, and the glass processing industry, to name just a few. The production of steel slabs is typically processed lot-wise and includes several logistics activities, e.g. a storaging activity between necessary cooling, reheating or transporting activities. Moreover, in many steel plants a minimum and maximum allowed processing time is given as it does not influence the quality of such a product whether the storaging activity of one lot is performed for one hour or two days in a slabyard. Furthermore, this time flexibility gives production managers an often demanded additional degree of freedom in their production planning possibilities. The same holds for the glass processing industry where e.g. transporting and storaging activities are necessary in the production process.

In the very different food processing industry, similar patterns can be found. Industrial bakeries for example typically prescribe a minimum purchase quantity for business customers to be able to carry out a lot-wise production. Furthermore, besides recipes for which precise time specifications have to be met, for other ones the production activities are allowed to vary up to one hour or even more, e.g. the cooling down of hot baked goods. For deep-frozen baked goods, there is an even higher time flexibility: the baked good has to be at least stored in a freezer for a certain amount of time but can be stored up to weeks or even longer if necessary. The same examples also apply to forbidden early deliveries. There are business customers who do not give their door keys to carriers for security reasons, and therefore only allow deliveries beginning at their opening hours. Some steel and glass industry customers (e.g. automobile industry) also do not accept early delivery, overall resulting in deliveries without earliness.

Furthermore, objective functions directly or indirectly influence financial burdens of companies, e.g. balancing the working time of all employees increases the acceptance of work schedules and balancing resource allocation avoids idle resources (Matl et al., 2017; Rieck et al., 2012). However, to the best of our knowledge, time balancing purposes concerning activities have not been considered yet in the scientific literature on RCPSP. For balancing resource utilization over time, resources are weighted by introducing costs (Li et al., 2018; Neumann & Zimmermann, 1999) although in many companies, there are often several equivalent resources (e.g. two deep freezing facilities of an industrial bakery or two slab yards of a steel manufacturer) with the only goal of avoiding uneven utilizations. Therefore, the two above presented new objectives are introduced.

The described choices between various alternative activities are known as flexible project scheduling (Beck & Fox, 2000; Tao & Dong, 2017). Related to this, Tao & Dong (2017) present the RCPSP with alternative activity chains (RCPSP-AC) and develop a simulated annealing algorithm for solving it. They describe that more efficient solution methods should be investigated for the RCPSP-AC in order to tackle related real-world problems. Moreover, they point out the necessity of an officially available benchmark set for the RCPSP-AC. Motivated by these suggestions, the new problem extensions described above, and the success of constraint programming (CP) for solving scheduling problems (Laborie et al., 2018; Schnell & Hartl, 2017), we develop and solve mixed integer programming (MIP) and CP models for the RCPSP-AC, its new multiproject version (RCMPSP-AC), and a new version featuring multiple projects as well as time flexibility. The latter we denote resource-constrained multiproject scheduling problem with alternative activity chains and time flexibility (RCMPSP-ACTF). To be more precise, the contribution of this work is fivefold:

- A new resource-constrained multi-project scheduling problem with alternative activity chains and time flexibility (RCMPSP-ACTF) is introduced and a related MIP model is proposed. It is based on the work of Tao & Dong (2017) who consider alternative activity chains in a single-project environment without time flexibility.
- Two new objective functions aiming at well-balanced solutions are presented.
- CP solution models are developed for the RCPSP-AC, its multi-project version, and the RCMPSP-ACTF.
- MIP and CP modeling approaches are compared on newly generated benchmark data sets, illustrating the advantage of using our new CP models: all benchmarks of the RCPSP-AC and many instances of the newly presented problems are solved to optimality.
- With the CP based models, a large industry case with more than 600 activities is solved to optimality and the impact of using the proposed alternative objective functions is evaluated.

The remainder of this paper is organized as follows. Section 2 gives an extensive review of related literature. The developed problem formulation is introduced in Section 3, while Section 4 provides a detailed description of the created constraint programming solution approach. In Section 5, the computational results for the generated benchmark data and the real-world case study are discussed. Finally, Section 6 gives concluding remarks and suggestions for further research.

2. Literature overview

The scheduling of manufacturing activities has been extensively investigated in the last decades since its efficient management is of high relevance in practice (Russell & Taghipour, 2019). One area of such scheduling problems are flexible manufacturing systems (FMS), considering flexibility within the production process (Błażewicz et al., 2019). Examples for FMS are flexible job shops (FJS), flexible or hybrid flow shops (FFS) or resource-constrained FMS. FJS and FFS typically consider machines as resources. In FJS, different jobs can consist of different activities (=operations) which can be performed on alternative machines (Rajabinasab & Mansour, 2011). In FFS, all jobs consist of the same activities but they can also be executed on alternative machines (Ruiz & Vázquez-Rodríguez, 2010). For the FJS and FFS, only one job can be handled at a time by each resource, there are no precedence constraints between the jobs and storage capacities (buffers) are assumed to be unlimited (unlimited idle times between activities are allowed) or zero (no idle times are allowed since there is no capacity) (Błażewicz et al., 2019). However, as described in Section 1, in the production environments considered in this work the production activities require additional resources with limited capacities such as storage areas. They all have capacities (i.e. no idle times between activities within one job are allowed since the capacities are modeled by activities that demand them; idle times between different jobs are allowed), and multiple activities and jobs can be handled at a time by each resource. Moreover, there are alternative activities for every job, all of them are in a precedence relationship and they have flexible processing times, overall resulting in a resource-constrained FMS which corresponds to a flexible RCPSP (Blazewicz et al., 2019) where several scheduling issues have to be newly mastered together.

The RCPSP is a well-researched topic, creating a schedule with starting times for all activities. Basically, there are fixed processing times, activity demands for limited resources, and precedence relations between all activities, typically represented by acyclic activity-on-node (AON) networks (Hans et al., 2007; Johnson & Garey, 1979). Besides the standard objective of makespan minimization, also a wide variety of alternative objectives has been studied. An example that is also tackled in this work is resource leveling, where varying resource utilization over time is minimized (Li et al., 2018). One of the many extensions which is examined in this work is related to time, considering an additional flexibility or a limitation of processing times (Artigues, 2017). Examples related to time extensions are idle times (Allahverdi, 2016), uncertain activity durations (Moradi et al., 2019), flexible resource usage durations (Naber & Kolisch, 2014), generalized precedence relations (GPR) (Schnell & Hartl, 2016), and setup times (Vanhoucke & Coelho, 2019).

A great variety of exact and heuristic solution methods has already been investigated. As the detailed presentation of algorithmic methods and the many existing extensions of the RCPSP is outside the scope of this work, the subsequent review is limited to flexible and multi-project scheduling and constraint programming. The interested reader is referred to the works of Artigues et al. (2013); Błażewicz et al. (2019); Hartmann & Briskorn (2010); Schwindt et al. (2015) and Weglarz (2012) for an additional comprehensive examination.

2.1. Flexible and multi-project resource-constrained project scheduling

Flexible project scheduling as a generalization of the RCPSP has proven to be also NP-hard (Blazewicz et al., 1983; Tao & Dong, 2017). It deals with the selection of the best out of multiple alternative activities (Beck & Fox, 2000; Burgelman & Vanhoucke, 2018). Already Pritsker (1966) has shown that besides so-called AND nodes which imply the selection of all successor nodes, also OR nodes can be introduced. OR nodes allow flexibility, as one out of multiple existing successor nodes is chosen. Johannes (2005) proofed that the minimization of weighted completion times under consideration of OR precedence constraints is already NP-hard with one single resource. Čapek et al. (2012) considered an RCPSP with alternative process plans for wire harnesses production. They proposed an integer linear programming (ILP) model and a heuristic algorithm for real-world applicability. Kellenbrink & Helber (2015) examined an aircraft turnaround process and proposed a genetic algorithm (GA) for the optimization of the developed flexible project structure. Vanhoucke & Coelho (2016) considered bidirectional relations besides AND/OR ones. They developed a satisfiability approach and showed its competitiveness on well-known benchmark datasets. Tao & Dong (2017) studied an AND/OR network under consideration of alternative activity chains (RCPSP-AC), which builds the base for the development of our problem formulations. They showed that their RCPSP-AC is a generalization of the multi-mode RCPSP (MRCPSP) and proposed a simulated annealing procedure. Tao & Dong (2018) extended the RCPSP-AC by integrating it into a bi-objective MRCPSP. They solved the new problem with a hybrid metaheuristic, consisting of a tabu search procedure and the NSGA II and compared it with the solutions generated with an exact solver. Tao et al. (2018) introduced an RCPSP with hierarchical alternatives and stochastic activity durations and proposed a metaheuristic framework consisting of sample average approximation and an evolutionary algorithm. Burgelman & Vanhoucke (2018) presented a new flexible MRCPSP under maximization of weighted alternative execution modes and proposed different ILP formulations. Servranckx & Vanhoucke (2019b) proposed an RCPSP with alternative subgraphs and solved it with a tabu search. Moreover, they extended the problem by introducing different strategies for the consideration of uncertainty for this new problem (Servranckx & Vanhoucke, 2019a). Birjandi et al. (2019) introduced a new nonlinear MIP model for an RCPSP with multiple routes (RCPSP-MR) and solved it with a hybrid metaheuristic based on particle swarm optimization (PSO) and a GA. Birjandi & Mousavi (2019) presented a fuzzy extension of the RCPSP-MR with flexible activities under uncertain conditions and proposed a hybrid approach consisting of distribution rules, PSO and a GA.

The resource-constrained multi-project scheduling problem (RCMPSP) as another generalization of the RCPSP considers a set of multiple projects $l \in$ $\{1, ..., L\}$ and activities $j \in N_l = \{1, ..., n+1\}$ per project (Hartmann & Briskorn, 2010; Lova et al., 2000). There are two possible ways for the representation of this multi-project variant. Through the single-project (SP) approach, all projects are cumulated into an AON network with one common dummy source and sink node (Lova & Tormos, 2001). Pritsker et al. (1969) were the first to suggest an additional sink node per project for the consideration of a due date per project within the SP approach. With the multi-project (MP) approach, source and sink nodes for every project are considered, and the connecting elements are commonly shared resources. A recent example is the one of Asta et al. (2016) who worked on a multi-mode RCMPSP under consideration of the SP and the MP approach and proposed a combination of monte-carlo and hyper-heuristic methods. Chakrabortty et al. (2017) suggested an evolutionary local search method based on priority rules for the MP approach. An already existing example for a manufacturing application of an SP approach for the RCMPSP is the work of Voß & Witt (2007). They modeled a hybrid flow shop scheduling problem as a multi-mode RCMPSP. Stages with variable capacities, waiting times between stages and renewable resources were considered. All existing stages must be traversed and different resources must be used. In their work, every machine only processed one job at a time, production routes were identical for every job and processing times were fixed. The objectives were the minimization of weighted tardiness and a maximized resource utilization. They applied dispatching rules for solving large real-world instances.

2.2. Scheduling and constraint programming

Constraint programming is a powerful optimization technique especially for combinatorial problems and thus, also for scheduling and real-world problems (Baptiste et al., 2012). Bockmayr & Hooker (2005) presented the general functionality of CP. They showed similarities of CP and MIP methods such as the generation of branching trees. One dissimilarity is constraint propagation, which is part of CP and removes all values from domains, which cannot take part in any feasible solution. CP has already been efficiently applied to different domains such as the deficiency problem (Altinakar et al., 2016), project driven manufacturing (Banaszak et al., 2009), ship scheduling and inventory management (Goel et al., 2015), operating theatres (Wang et al., 2015), resource-constrained FMS (Novas & Henning, 2014), and the RCPSP (Liess & Michelon, 2008). Recent works also showed the compatibility of the CP methodology with the RCPSP. Schnell & Hartl (2016, 2017) developed and analyzed exact algorithms, Boolean Satisfiability Solving and CP approaches for the MRCPSP with GPR and presented new best solutions. Kreter et al. (2017) developed new CP models and a special propagator for the RCPSP with general temporal constraints and calendar constraints and provided optimal solutions for all benchmarks sets. Kreter et al. (2018) developed new MIP and CP models for resource availability cost problems and solved all open benchmarks to optimality.

2.3. Identified research gap

Considering the described literature, the presented scheduling problem in Section 1 can be modeled as a resource-constrained multi-project scheduling problem since precedence relations, limited renewable resources and multiple lots (projects) have to be taken into account. Moreover, flexibility concerning activity selection like in Tao & Dong (2017) and activity processing times has to be incorporated. To the best of our knowledge, the integration of multiple projects and flexible processing times has not been considered yet in an RCPSP context. As the already described work of Tao & Dong (2017) on the RCPSP-AC builds the base for the development of our work, we call our new problem the resource-constrained *multi-project* scheduling problem with *alternative activity chains* and *time flexibility* (RCMPSP-ACTF). Two new objectives for the RCMPSP-ACTF, minimizing different processing time buffers and peak usages of resources are introduced and the necessary additional constraints are presented. CP models are developed for the RCPSP-AC, its new multi-project extension (RCMPSP-AC) and the new RCMPSP-ACTF and they are tested on newly generated benchmark data. The developed models also provide decision support for a steel industry company partner, illustrated by the presented real-world case study in this work.

3. Problem definition

In this section, the MIP formulations for the new RCMPSP-ACTF are presented. Section 3.1 provides basic assumptions and necessary notations, including an exemplarily AON network that is used to model the introduced problem. In Sections 3.2 - 3.4, we formally define the RCMPSP-ACTF and the two new objectives alongside the necessary constraints for time and resource balance.

3.1. Notations

For the RCMPSP-ACTF, all operations which have to be performed are called activities (or tasks or nodes) and are distinguished from the term job (or lot or project), which corresponds to a customer order. Precedence relations are defined using an AON project network. Every activity $i, j \in \{0, ..., n + 1\}$ has a specific task, except nodes 0 and n + 1, which are dummy production process source and sink nodes. "Activity 1" could for example be the heating and "activity 2" the transportation of a manufactured product. For the consideration of one sink node per lot and thus, per project, the subset $\mathcal{L} \subseteq \mathcal{J}$ is introduced. Every sink node corresponds to one customer delivery activity and therefore represents the completion of one lot. This kind of consideration complies with the well-known SP approach with one sink node per project (Lova & Tormos, 2001; Pritsker et al., 1969) as explained in Section 2. Related to this, we need a mandatory new activity type $p_j = 2$ which we call OUT activity in addition to the two activity types AND/OR ($p_j = 1/p_j = 0$) introduced by Tao & Dong (2017). It ensures that idle times between all activities within one lot

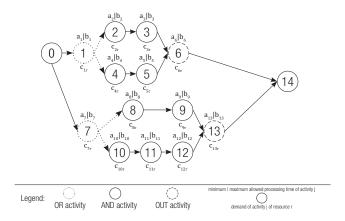


Figure 1: Example AND/OR/OUT network for the RCMPSP-ACTF.

are forbidden (since all intermediate storages have to be modeled as resources due to their scarcity in manufacturing environments) and it guarantees that no additional activities of one lot appear in the production schedule if they do not belong to the chosen alternative route of the optimization (see the following Section 3.2 for a detailed description). Related to this, all activities have minimum and maximum allowed processing times a_i and b_i now. The complete list of notations is given in Table 1. In order to illustrate the new RCMPSP-ACTF, we give an example AON network in Figure 1, demonstrating the alternative activity chains and time flexibility for multiple projects. Nodes 0 and 14 are the dummy source and sink nodes with zero processing times and no demands. With nodes 1 and 7, the production of the respective lots is started and with customer delivery activities 6 and 13, it is finished, i.e. every lot has its own start node and a customer delivery activity.

3.2. RCMPSP-ACTF MIP model: makespan minimization

In the following, we present the new multi-project scheduling problem with alternative activity chains and time flexibility. It extends the RCPSP-AC of Tao & Dong (2017). New variables and constraints are introduced for the consideration of multiple lots, alternative activity chains and time flexibility. Non-renewable resources (e.g. money) are not explicitly considered, since they typically do not exist in production applications (Błażewicz et al., 2019). However, they can be included into the model in a staightforward way if necessary.

Indices

- i, j Activities
- t, τ Time periods
- *r* Resource

\mathbf{Sets}

 \mathcal{J} Set of activities $i, j \in \{0, 1, .., n+1\}$

- \mathcal{L} Set of delivery activities $\mathcal{L} \subseteq \mathcal{J}$
- \mathcal{T} Set of time slots $t, \tau \in \{0, 1, .., T\}$
- \mathcal{R} Set of renewable resources $r \in \{0, 1, ..., R\}$
- \mathcal{R}^* Set of renewable resources $\mathcal{R}^* \subseteq \mathcal{R}$ considered for resource balance

Parameters

- A_{ij} Activity-adjacency matrix $A_{ij} = 1$ if j is the direct successor of i and 0 otherwise
- p_j Node type $p_j = 1$ if activity j is an AND activity, $p_j = 0$ if activity j is an OR activity, $p_j = 2$ if activity j is an OUT activity
- a_j Minimum allowed processing time (duration) of activity j
- b_j Maximum allowed processing time (duration) of activity j
- d_j Delivery time (due date) of activity $j \in \mathcal{L}$
- C_r Capacity of resource r
- c_{jr} Demand of activity j of resource r
- M Big M (large constant)

Decision variables

- $x_i = 1$ if activity j is selected and 0 otherwise
- $s_{jt} = 1$ if activity j is selected to start at time slot t and 0 otherwise
- $w_{jt} = 1$ if activity j is selected to be worked on (processed) at time slot t and 0 otherwise
- $y_{jt} = 1$ if activity j is selected to be completed at time slot t and 0 otherwise
- *B* Largest time buffer of the whole network
- S Smallest time buffer of the whole network
- u_r Maximum resource utilization (peak usage) of resource $r \in \mathcal{R}^*$

Minimize

$$\sum_{t \in \mathcal{T}} t \cdot y_{n+1t} \tag{1}$$

subject to

$$s_{00} = 1,$$
 (2)

$$\sum_{t \in \mathcal{T}} s_{it} = x_i \qquad \forall \ i \in \mathcal{J},\tag{3}$$

$$\sum_{t\in\mathcal{T}}^{i\in\mathcal{T}} y_{it} = x_i \qquad \forall \ i\in\mathcal{J},\tag{4}$$

$$\sum_{j \in \mathcal{J}} A_{ij} \cdot x_j = x_i \qquad \forall i \in \mathcal{J}, if \ p_i = 0,$$
(5)

$$A_{ij} \cdot x_i \le x_j \qquad \forall \ i, j \in \mathcal{J}, \ if \ p_i = 1, \tag{6}$$

$$\sum_{j \in \mathcal{I}} A_{ij} \cdot x_j = x_j \qquad \forall \ j \in \mathcal{J}, \ if \ p_j = 2,$$
(7)

$$\sum_{j \in \mathcal{J}} A_{ij} \cdot s_{jt} = y_{it} \qquad \forall i \in \mathcal{J}, \ t \in \mathcal{T}, \ if \ p_i = 0 \ and \ p_j \le 1,$$
(8)

$$y_{it} \cdot A_{ij} = s_{jt} \qquad \forall \ i, j \in \mathcal{J}, \ t \in \mathcal{T}, \ if \ p_i = 1 \ and \ p_j \le 1,$$
(9)

$$\sum_{i \in \mathcal{J}} A_{ij} \cdot y_{it} = s_{jt} \qquad \forall \ j \in \mathcal{J}, \ t \in \mathcal{T}, \ if \ p_j = 2, \tag{10}$$

$$\sum_{\substack{t \in \mathcal{T} \\ t}} t \cdot y_{it} \le \sum_{t \in \mathcal{T}} t \cdot s_{n+1t} \qquad \forall \ i \in \mathcal{L}, \tag{11}$$

$$\sum_{\tau=1}^{5} (s_{i\tau} - y_{i\tau}) = w_{it} \qquad \forall \ i \in \mathcal{J}, t \in \mathcal{T},$$
(12)

$$a_i \cdot x_i \le \sum_{\tau \in \mathcal{T}} w_{i\tau} \quad \forall i \in \mathcal{J},$$
(13)

$$b_i \cdot x_i \ge \sum_{\tau \in \mathcal{T}}^{\tau \in \mathcal{T}} w_{i\tau} \qquad \forall i \in \mathcal{J}, \tag{14}$$

$$\sum_{t \in \mathcal{T}} t \cdot y_{it} \ge d_i \qquad \forall \ i \in \mathcal{L}, \tag{15}$$

$$\sum_{i \in \mathcal{J}} (w_{it} \cdot c_{ir}) \le C_r \qquad r \in \mathcal{R}, t \in \mathcal{T}, \tag{16}$$

$$x_i \in \{0, 1\} \qquad \forall \ i \in \mathcal{J},\tag{17}$$

$$s_{it}, w_{it}, y_{it} \in \{0, 1\} \qquad \forall i \in \mathcal{J}, t \in \mathcal{T}.$$
(18)

Objective function (1) minimizes the makespan of the whole production process. The new condition (2) starts the production process with the first activity at the first time slot. Restrictions (3)-(4) define that every activity has to be started and finished exactly once. With constraints (5)-(10), flexibility in terms of alternative activity chains and processing times is determined. If an activity is an OR node $(p_i = 0)$, only one of its successors in the project network must be selected with conditions (5). If an activity is an AND node $(p_i = 1)$, all successors have to be selected via restrictions (6). New constraints (7) with the flexibility type $p_i = 2$ are necessary since they satisfy together with new constraints (10) the prohibition of selecting additional production nodes besides one activity chain per lot and the mandatory requirement of forbidden idle times between activity processing times within every lot. Conditions (8) and (9) are also new and guarantee the possibility of flexible processing times for AND/OR activities. It is assured that within one route, an activity j has to be started at the finishing time of predecessor activity i (no idle times are allowed) and that only activities can be selected which are in a precedence relationship. New constraints (11) ensure that all lots have to be finished before the whole project (production process) can be finished. With the new restrictions (12) it is guaranteed that every time slot t which is used for the processing of one activity i has to be between its decided start and end time. New conditions (13)-(14) ensure that the flexible processing time for every activity complies with its defined minimum and maximum allowed processing times. The new constraints (15) make sure that the production of one lot cannot be finished earlier than its delivery time and thus that tardiness is allowed but earliness is not. Conditions (16) represent the capacity restrictions for all renewable resources. Constraints (17)-(18) define all decision variables as Boolean ones.

3.3. RCMPSP-ACTF MIP model: time balance maximization

We now present an alternative objective that concerns the imbalance between time buffers, i.e. the duration (length) of different activities. As a result, the time balance of activities is maximized. Decision variables B and S decide on the largest and smallest time buffers within the whole project. Similar approaches can for example be found for the Vehicle Routing Problem with route balancing where the difference between route lengths is minimized (Matl et al., 2017).

$$Minimize \qquad B-S \tag{19}$$

Objective function (19) minimizes the different lengths of activity durations. In addition to the already presented restrictions (2)-(18) in Section 3.2, three further conditions are necessary:

$$\sum_{t \in \mathcal{T}} w_{it} + (1 - x_i) \cdot M - x_i \cdot a_i \ge S \qquad \forall \ i \in \mathcal{J},$$
(20)

$$\sum_{t \in \mathcal{T}} w_{it} - x_i \cdot a_i \le B \qquad \forall \ i \in \mathcal{J},$$
(21)

$$B \ge 0, S \ge 0. \tag{22}$$

With the newly introduced constraints (20)-(21), minimum and maximum time buffers are connected to working times of activities. Conditions (22) restrict decision variables to be of non-negative values.

3.4. RCMPSP-ACTF MIP model: resource balance maximization

The third objective function aims at balanced resource utilization. In existing works on resource leveling problems which come closest to our problem formulation, total weighted sums of squared resource usages are considered for the minimization of varying resource utilization over time and weights are represented by unit costs of resources (Li et al., 2018; Neumann & Zimmermann, 1999). In our work, costs are not considered, since we do not discriminate between different resources but consider them equally important. However, motivated by the fact that resource balancing may not be meaningful for all of the considered resources (e.g. small vehicles versus large warehouses), we allow to select a subset of resources $\mathcal{R}^* \subseteq \mathcal{R}$ which are considered in the objective function. We use the decision variable u_r for the concerned balancing resources $r \in \mathcal{R}^*$ to denote the maximum concurrent usage of one resource r. The resource balance objective can now be formulated as follows:

$$Minimize \quad \max_{r \in \mathcal{R}^*} (u_r/C_r) \tag{23}$$

Objective function (23) minimizes the different peak usage of concerned renewable resources \mathcal{R}^* . In addition to constraints (2)-(15) and (17)-(18), the following conditions are necessary:

$$\sum_{\in \mathcal{J}} (w_{it} \cdot c_{ir}) \le u_r \qquad \forall r \in \mathcal{R}^*, t \in \mathcal{T},$$
(24)

$$u_r \le C_r \qquad \forall \ r \in \mathcal{R}^*,$$
 (25)

$$\sum_{i \in \mathcal{J}} (w_{it} \cdot c_{ir}) \le C_r \qquad \forall r \in \mathcal{R} \setminus \mathcal{R}^*, t \in \mathcal{T},$$
(26)

$$u_r \ge 0 \qquad \forall r \in \mathcal{R}^*. \tag{27}$$

With restrictions (24)-(26), conditions (16) are replaced. With the new constraints, capacity restrictions are satisfied for all renewable resources. Constraints (27) guarantee non-negative values for the new decision variable.

4. Constraint programming solution approach

Motivated by the recent success of CP based exact methods (Vilím et al., 2015), we now propose CP models for the RCPSP-AC, its multi-project version and the RCMPSP-ACTF which can be solved by the CP Optimizer of IBM ILOG CPLEX. We first describe the main building blocks of the CP Optimizer and our developments in order to fit this modeling framework in Section 4.1. Thereafter, in Sections 4.2 - 4.5, the developed CP models are presented.

4.1. Constraint Programming: Modeling developments and notations

Besides the possibility of implementing MIP models, IBM ILOG CPLEX also provides the constraint programming framework CP Optimizer. Laborie et al. (2018) described its main ingredients and illustrated its performance on scheduling and other real-world problems. In the following, we describe the CP Optimizer functions and expressions that are necessary to develop our CP models. For all standard functions and expressions, we refer to Appendix A.

Decision expressions: With the decision variable $interval(w_j)$, an interval of time w (a range or duration) is expressed for every activity j. Intervals are flexible in two ways: First, intervals can be of variable length (=time flexibility). Second, activities can be left unperformed, which is necessary as there are alternative routes and therefore some activities which have to be skipped (=alternative activity chains). The project horizon T is now used as a constant, which limits the maximum length of the interval decision variable in contrary to the MIP models in Section 3 where $t \in \{1, ..., T\}$ was a necessary index for decision variables. Alternative activity chains are considered by the statement optional. As a result, dvar $interval(w_j)$ optional in 0...T is introduced.

Alternative expressions: With the alternative $(w_i, \{w_i, w_k\})$ expression, the possibility of choosing between different alternative successor activities jand k is modeled. If node *i* is present, exactly *one* out of multiple alternative successor nodes $\{j,k\}$ can be selected and the selected alternative successor node *must* start and end together with node *i*. However, in typical scheduling applications, and also in the RCMPSP-ACTF, a node *i* cannot always start and end together with a successor node $\{j, k\}$ due to specified precedence relations and time restrictions. Thus, for every OR node i which implies a decision on a successor activity, one dummy alternative node $meta_a$ has to be introduced. In Figure 2, the introduction of the necessary $meta_a$ nodes inspired by the work of Tao & Dong (2017) is illustrated. On the left, an example AND/OR network with the necessary MIP adjacencies and flexibility types is depicted, including the OR relations $\{<1,2>,<1,3>\}$ and $\{<3,6>,<3,7>\}$ in the MIP adjacencies for nested OR nodes 1 and 3. For the CP transformation on the right, the alternative expression has to be introduced: The dummy meta node 9 is necessary since it can start and end together with the selected successor 2 or 3 in contrary to node 1, which has to be finished before the start of node 2 or 3. Exactly the same logic is applied for the nested OR node 3 with meta node 10. In contrary to the MIP adjacencies, the OR relations for the nested OR nodes 1 and 3 cannot be inserted in the CP adjacencies: Instead, the relations

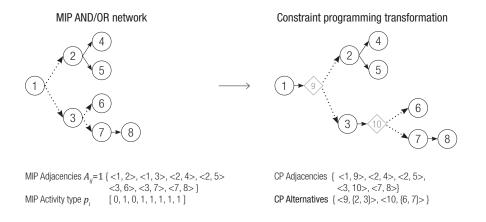


Figure 2: Introduction of meta nodes for the CP alternative() expression.

of OR nodes with the $meta_a$ nodes $\{<1, 9>, <3, 10>\}$ have to be inserted in the CP adjacencies and the relations of the $meta_a$ nodes with real nodes (9, $\{2, 3\}$) and (10, $\{6, 7\}$) have to be transferred to the CP alternatives.

Span expressions: With the span $(w_i, \{w_i, w_k\})$ expression, all activities j and k are included (spanned), if an activity i is selected. In an AON network with nested OR nodes and one common end node, which is only allowed to be started after all predecessors are scheduled, this expression is necessary. The before described alternative() expression is not applicable, since it allows only one predecessor and one successor node to start and end together but not all activities can be included. For every node that implies a decision on a successor activity chain, i.e. a relation which includes more than one node, one dummy span activity of the type $meta_s$ has to be introduced. In Figure 3, an example MIP network with one common end node 14 is shown on the left and the corresponding CP transformation is presented on the right. The OR nodes 1 and 3 are linked to $meta_a$ alternative nodes 9 and 10 as already described for Figure 2. However, the new common project end node 14 can only start if all predecessor nodes are finished. Hence, for every OR node, which includes more than one successor node, one additional $meta_s$ node is necessary: OR node 1 has two successor relations: The first relation has three nodes $\{2, 4, 5\}$ and thus, gets $meta_s$ node 11. The second with four nodes $\{3, 6, 7, 8\}$ is linked to $meta_s$ node 12. The nested OR node 3 also has two successor relations. The first relation includes only one successor node $\{6\}$ and therefore, it does not

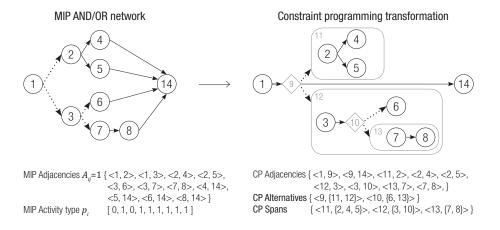


Figure 3: Introduction of meta nodes for the CP alternative() and span() expression.

require additional meta nodes. The second successor relation $\{7, 8\}$ contains more than one node and thus, the $meta_s$ node 13 is introduced. The span nodes are linked to the first node of a span successor relation in the CP adjacencies, e.g. span node 11 is linked to node 2. All further span and alternative relations have to be transferred to CP alternatives and spans instead of an inclusion into the adjacencies.

Resource function: The cumulFunction $q_r = \sum_{j \in \mathcal{J}: c_{jr} \ge 0} \operatorname{pulse}(w_j, c_{jr})$ expresses the cumulative usage q of a renewable resource $r \in \mathcal{R}$ over time for every activity j. It only counts the demand c_{jr} of one activity if the corresponding optional $interval(w_j)$ is used and only allows an accumulation if resource capacities C_r are exhausted. The temporal change of the resource usage in dependence of the demand c_{jr} is initiated by the integrated function pulse . As a result, the consideration of alternative activity chains and time flexibility is taken care of in this expression. The following Table 2 gives all notations, which are used for the development of our new CP models.

4.2. RCPSP-AC and RCMPSP-AC CP Model

We now propose a CP formulation for the RCPSP with alternative activity chains (RCPSP-AC) of Tao & Dong (2017) and its multi-project version, the RCMPSP-AC. To the best of our knowledge, this is the first time that this problem is modeled and solved with CP. It allows us to solve all RCPSP-AC benchmark instances to optimality. For the multi-project version, we use the well-known SP approach as already introduced for the MIP formulation of the Table 2: CP model notations.

Indices

- i, j Activities
- r Resource

Sets

- \mathcal{A} Set of adjacencies between activities (i, j)
- \mathcal{J} Set of activities $i, j \in \{0, 1, .., n+1\}$
- \mathcal{L} Set of delivery activities $\mathcal{L} \subseteq \mathcal{J}$
- \mathcal{M} Set of meta activities $\mathcal{M} \subseteq \mathcal{J}$
- \mathcal{R} Set of renewable resources $r \in \{0, 1, ..., R\}$
- \mathcal{R}^* Set of renewable resources $\mathcal{R}^* \subseteq \mathcal{R}$ considered for resource balance
- \mathcal{N} Set of non-renewable resources $r \in \{0, 1, ..., N\}$

Parameters

- a_j Minimum allowed processing time (duration) of activity j
- b_j Maximum allowed processing time (duration) of activity j
- D_j Fixed processing time (duration) of activity j
- d_j Delivery time (due date) of activity $j \in \mathcal{L}$
- \vec{T} Time horizon
- C_r Capacity of resource r
- c_{jr} Demand of activity j of resource r
- S_j Alternative start activities of alternative activity j
- E_j Alternative end activities of alternative activity j
- G_j Possible span activities (=selection relation) of alternative activity j

Decision variables

- q_r Cumulative resource usage of renewable resources $r \in \mathcal{R}$ over time
- u_r Maximum resource utilization (peak usage) of resource $r \in \mathcal{R}^*$
- w_j Optional interval decision variable: selection of activity j for the production process and assignment of start, duration, and end time (interval) for every selected activity j

RCMPSP-ACTF in Section 3. This means that we do not change the model of the RCPSP-AC but the precedence relations, i.e. the project structure itself, to obtain the computationally more expensive RCMPSP-AC (for a detailed explanation we refer to Section 5.1).

Minimize

$$endOf(w_{n+1}) \tag{28}$$

subject to

 $\mathsf{startOf}(w_0) = 1,\tag{29}$

- $presenceOf(w_0) = 1, \tag{30}$
- $\texttt{lengthOf}(w_i) = D_i \qquad \forall \ i \in \mathcal{J},\tag{31}$

alternative
$$(w_i, \{w_a \in S_i\})$$
 $\forall i \in \mathcal{M},$ (32)

$$\operatorname{span}(w_i, \{w_s \in G_i\}) \qquad \forall \ i \in \mathcal{M},\tag{33}$$

$$endBeforeStart(w_i, w_j) \qquad \forall \ i, j \in \mathcal{A}, \tag{34}$$

$$presenceOf(w_i) = presenceOf(w_j), \quad \forall i, j \in \mathcal{A}, \quad (35)$$

$$q_r \le C_r \qquad \forall \ r \in \mathcal{R},\tag{36}$$

$$\sum_{\substack{\in \mathcal{J} \setminus \mathcal{M}}} \texttt{presenceOf}(w_j) \cdot c_{jr} \leq C_r \qquad \forall \ r \in \mathcal{N}.$$
(37)

With objective function (28), the makespan of the project is minimized. Restrictions (29)-(30) determine the start of the project with the first activity at the first time slot of the project. Conditions (31) define that fixed processing times of all activities have to be satisfied. Constraints (32)-(33) guarantee activity selection flexibility for nested AND/OR relations. Restrictions (34)-(35) ensure that the precedence relations between different activities are met and that idle times between the scheduling of different activities are allowed. With constraints (36)-(37), capacity limits for renewable and non-renewable resources are satisfied.

4.3. RCMPSP-ACTF CP Model: makespan minimization

j

In this section, we present the CP model for the RCMPSP with alternative activity chains and time flexibility. As already stated for the MIP model of this new problem, flexible processing times are considered and idle times are not allowed within the production processes of single lots. However, the parallel production of multiple lots and thus, the concurrent scheduling of multiple activities of different lots is allowed. Non-renewable resources are not considered. Nevertheless, they can be included easily since they can be modeled in the same way as in the case of the RCPSP-AC (see constraints 37). *Minimize*

subject to

 $endOf(w_{n+1}) \tag{38}$

 $\mathsf{startOf}(w_0) = 1, \tag{39}$

$$\operatorname{presenceOf}(w_0) = 1, \qquad (40)$$

$$\operatorname{presenceUf}(w_{n+1}) = 1, \qquad (41)$$

$$\operatorname{soncoOf}(w_n) = 1 \quad \forall i \in \mathcal{L} \qquad (42)$$

$$presenceUf(w_i) = 1 \quad \forall i \in \mathcal{L},$$

$$lengthOf(w_i) > a_i \quad \forall i \in \mathcal{I}$$

$$(42)$$

$$\operatorname{endOf}(w_i) \ge d_i \qquad \forall \ i \in \mathcal{L}, \tag{45}$$

$$endOf(w_i) \le T \qquad \forall \ i \in \mathcal{L}, \tag{46}$$

- $alternative(w_i, \{w_a \in S_i\}) \quad \forall i \in \mathcal{M},$ (47)
- $endAtStart(w_i, w_a) \qquad \forall i \in \mathcal{M}, a \in E_i,$ (48)
- endBeforeStart (w_i, w_{n+1}) $\forall i, j \in \mathcal{L},$ (49)
 - $endAtStart(w_i, w_j) \qquad \forall \ i, j \in \mathcal{A}, \tag{50}$

$$presenceOf(w_i) = presenceOf(w_j) \quad \forall i, j \in \mathcal{A},$$
 (51)

$$q_r \le C_r \qquad \forall r \in \mathcal{R}.$$
 (52)

With objective (38), the makespan of the whole production process is minimized. Restrictions (39)-(42) define the start and end of the project and guarantee the production of all lots. Conditions (43)-(44) enable flexible processing times. The processing time of every selected activity has to comply with minimum and maximum allowed durations. Constraints (45) allow tardiness for every lot. The overall production planning time is set to the predefined horizon T in restrictions (46). Conditions (47)-(48) specify alternative production routes for every lot. One out of multiple existing meta alternative start and end activities has to be chosen and idle times between meta activities within one lot are forbidden. Restrictions (49)-(50) allow idle times between the production activities of different lots and forbid idle times between production activities within one lot. Constraints (51) guarantee that precedence relations are adhered to. With constraints (52), capacity restrictions for renewable resources are satisfied.

4.4. RCMPSP-ACTF CP Model: time balance maximization

We now show how to model the objective of time balance maximization: $Minimize (\max_{i \in \mathcal{J} \setminus \mathcal{M}} \texttt{lengthOf}(w_i) - a_i) - (\min_{i \in \mathcal{J} \setminus \mathcal{M}} \texttt{lengthOf}(w_i) - a_i)$ (53) With objective function (53), the difference between time buffer lengths of all activities is minimized and thus, time balance is maximized. There is no need for additional decision variables or changed restrictions in contrary to the MIP model in Section 3.3. Instead, the new objective function is employed together with the presented CP restrictions (39)-(52).

4.5. RCMPSP-ACTF CP Model: resource balance maximization

The objective of resource balance maximization is modeled as follows:

$$Minimize \quad \max_{r \in \mathcal{R}^*} \left(u_r / C_r \right) \tag{54}$$

Objective function (54) minimizes the difference between the resource usage of single resources and thus, maximizes load balancing between all resources. Besides the already introduced constraints (39)-(51), it requires the following additional ones:

$$q_r \le u_r \qquad \forall r \in \mathcal{R}^*, \tag{55}$$

$$u_r \le C_r \qquad \forall r \in \mathcal{R}^*, \tag{56}$$

$$q_r \le C_r \qquad \forall r \in \mathcal{R} \setminus \mathcal{R}^*.$$
 (57)

The new restrictions (55)-(57) replace constraints (52). They restrict the peak usage of all concerned resources to the defined capacity limits.

5. Computational experiments

The MIP and CP models are implemented in OPL and the CPLEX 12.9.0 MIP solver and CP Optimizer are used to solve them. All experiments are carried out on a virtual machine Intel(R) Xeon(R) CPU E5-2660 v4, 2.00GHz with 28 logical processors, Microsoft Windows 10 Education. Since Tao & Dong (2017) introduce a limit of 3.600 seconds for their runs and we derive results for benchmark instances generated as described in their work, we use the same limit for our optimization runs. We first describe the test design in Section 5.1 and then present and discuss the obtained results for the benchmark sets and the industry case study in Sections 5.2-5.4.

5.1. Instance generation

For the RCPSP-AC, we base our single-project instances on the information given in Tao & Dong (2017), since their employed instances are not available and they describe the necessity of an officially available benchmark set in their work. However, they fully present one instance in their work, consisting of a project structure with $\mathcal{J} = 30$ nodes in total and including five nested OR nodes. Following Tao & Dong (2017), to obtain five instance groups with 15 instances each, this project structure is multiplied by 2, 3, 4 and 5, resulting in instance groups with 30, 60, 90, 120, and 150 nodes besides two additional dummy nodes for each instance (start and end node). As described in their work, processing times and demands for all resources are randomly generated. In order to obtain multi-project instances, the single-project instances of Tao & Dong (2017) are extended by arranging several project structures in parallel instead of in sequence (see Figure 4 for an example). We note that the MIP and CP models for the RCPSP-AC do not have to be adapted for this multi-project case (=RCMPSP-AC), since the precedence relations, i.e. the project structure itself, is changed. This is in line with the way multi-project instances have for example been presented by Lova & Tormos (2001).

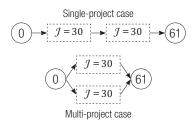


Figure 4: Benchmark instance generation for the RCPSP-AC and the RCMPSP-AC.

The instances for the RCMPSP-ACTF are inspired by the project network data obtained from cooperations with the manufacturing industries described in Section 1. This network consists of activities such as production (0), cooling (1), processing (2), relocation (3), storaging (4), vehicle relocation (5) and delivery (6). Activities (0) and (3) have a fixed duration, all other activities have variable processing times with minimum and maximum allowed durations. Each lot starts at (0) and ends at (6) via one alternative route. The customer orders are connected to related alternative routes, which may involve different activities at various locations. We use three different lot sizes $|\mathcal{L}| \in \{10, 50, 100\}$. All lots are sampled from existing customer orders. Processing times, resource capacities with related resource factors $\{0.25, 0.50, 0.75, 1.00\}$ and the resource strength are defined based on Kolisch et al. (1995). Resource demands are equal to one for the real-world situation and only one out of all existing resources is required by each activity. We use an additional, different demand pattern where the demands and the amount of required resources are defined randomly to be able to validate the real-world situation. As a result, we have two demand patterns real-world (rw) and random (rand). With the 3 lot sizes, the 2 demand patterns and the 4 resource strengths, we have 24 instance groups. For each group we generate 5 instances with varying random seed, which results in a total of 120 instances. The whole data generation procedure is presented in detail in Appendix B.

For all instances, we note that we limit the large constant M ("Big M") in the MIP models to the maximum allowed project duration T in order to support better relaxations and integer solvability and a less required computation time (Camm et al., 1990).

5.2. RCPSP-AC and RCMPSP-AC: Optimization results

In Table 3, we provide the results for the CP and the MIP models on the generated single-project instances for the RCPSP-AC of Tao & Dong (2017) and the multi-project instances for the RCMPSP-AC. Each entry is an average value across 15 instances per data set. The first column gives the instance size. In columns 2-6, CP solutions are presented: The second column provides the best bound and the best solution is found in the third column. In the fourth column, the runtime is shown in seconds, followed by the number of instances for which an optimal solution was found and the number of instances for which a feasible solution was found in columns 5 and 6. Bold letters indicate the optimal solution. Columns 7-11, where MIP solutions are shown, follow the same logic as columns 2-6. We note that in order to validate our optimization results for the RCPSP-AC, we implemented the MIP model presented by Tao & Dong (2017) and tested it with the benchmark instance $\mathcal{J} = 30$ which they presented in their paper. Since we had to add and change several constraints of their MIP model to obtain the same results as presented in their paper for this instance, we provide the modified MIP model in Appendix C. The detailed results for every examined benchmark instance are given in Appendix D.

СР							MIP				
	Best Bound	Best Sol	Run- time	# Opt	# Sol	-	Best Bound	Best Sol	Run- time	# Opt	# Sol
Single-Project Case (RCPSP-AC)											
30	25.47	25.47	0.08	15	15		25.47	25.47	1.26	15	15
60	51.13	51.13	0.30	15	15		50.67	51.67	298.88	14	15
90	78.27	78.27	1.02	15	15		75.68	82.27	1,046.42	11	15
120	105.73	105.73	62.23	15	15		89.70	115.85	3,020.17	4	13
150	131.07	131.07	173.73	15	15		91.43	256.25	Т	0	4
Multi-I	Project Ca	se (RCMF	PSP-AC)								
30	27.07	27.07	0.18	15	15		27.07	27.07	2.30	15	15
60	36.27	37.80	489.84	13	15		35.89	39.07	2,675.13	5	15
90	51.07	52.60	1,298.44	12	15		39.99	69.73	Т	0	15
120	67.47	81.00	Т	2	15		33.23	102.87	Т	0	15
150	72.33	86.60	Т	0	15		32.33	113.67	Т	0	15
	All values are average values per instance group. Best Sol best feasible solution found; Runtime in seconds; #Opt number of instances with an optimal solution; #Sol number of instances with a feasible solution; T time limit reached.										

Table 3: Results for the RCPSP-AC and the RCMPSP-AC.

For the single-project case presented in Table 3, all benchmarks are solved to

optimality by using the CP model but not when using the MIP model. The CP approach provides optimal solutions to dimensions of increasing difficulty with very little effort while in case of the MIP model the solver struggles to solve instances with more than 90 nodes within the allotted runtime. The results also show that the CP Optimizer solves instances of size 150 in less time on average than the MIP solver for dimension 60.

Given these results, we have generated additional new multi-project instances which are computationally more challenging. For this new RCMPSP-AC case, the CP and the MIP solver struggle to solve problems of increasing size to optimality. Although they both get feasible solutions for all problem instances, the CP Optimizer finds better bounds and better solutions on average than the MIP solver. Interestingly, for the MIP solver, finding feasible solutions for multi-project instances appears to be easier than for single-project instances. Nevertheless, proving their optimality is considerably more difficult.

As explained in Section 5.1, benchmarks are generated equal to the description of Tao & Dong (2017) with the only difference of a parallel project structure for the multi-project case. This means that the same resource capacities are used for the multi-project case where a lot more activities have to be scheduled in parallel than in the single-project case of Tao & Dong (2017). Thus, the resource strength, which is an indicator of instance hardness (Kolisch et al., 1995) is much higher.

5.3. RCMPSP-ACTF: Optimization results

In Table 4, we present the optimization results for the benchmark data generated for the RCMPSP-ACTF. They follow the same logic as the results for the RCPSP-AC and RCMPSP-AC shown in Table 3 with the only difference that in the second column now the respective demand patterns (real-world and random) are given in addition. The detailed results for every examined instance can be found in Appendix E. For illustration purposes, we provide the optimal solution for the exemplarily toy instance described in Figure 1, Section 3.1 in the form of a Gantt chart (see Figure 5).

For the objectives makespan and time balance presented in Table 4, the CP approach solves all instances to optimality while the MIP solver only solves all instances of lot size 10 and some of size 50 and 100. In all cases, it is much slower (more than two orders of magnitude) than the CP solver. Another difference between the two solution approaches is the runtime, as it could already be detected for the optimization results in Table 3. On average, the MIP solver

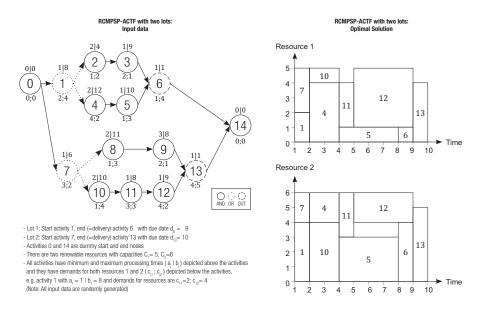


Figure 5: Illustrative optimization example for an RCMPSP-ACTF.

needs considerably more runtime or even reaches the time limit in contrary to the CP Optimizer.

Concerning the third objective of resource balance, the CP Optimizer overall, again finds better solutions than the MIP solver. However, it struggles a lot more to prove optimality within the allotted runtime than with the other objectives and does not find any optimal solution for instances of size 50 and 100. For the instances of size 50 and the demand pattern random, the MIP solver finds better bounds than the CP Optimizer does. Nevertheless, in contrary to the MIP solver, the CP Optimizer provides integer solutions for all instances.

Overall, two things particularly stand out in Table 4. First, the CP Optimizer solves larger instances to optimality than in the case of the RCPSP-AC in Table 3. We assume that the reason for this difference lies in the project structure of real-world manufacturing situations. For the generated benchmarks in Table 3, nested AND/OR relations and a parallel structure are considered as described in Tao & Dong (2017). For the industry situations which motivate the RCMPSP-ACTF, a production schedule has to be generated for a serial project structure with one OR relation per sub-project. Second, the CP Optimizer appears to be a lot more competitive than the MIP solver concerning flexible RCPSP. We assume that one major reason is the different modeling ap-

				СР			MIP				
		Ø Best Bound	Ø Best Sol	Ø Run- time	# Opt	# Sol	Ø Best Bound	Ø Best Sol	Ø Run- time	# Opt	# Sol
Obje	ctive: N	lakespan	l I								
10	rw	33.80	33.80	0.02	20	20	33.80	33.80	7.96	20	20
	rand	33.80	33.80	0.03	20	20	33.80	33.80	7.50	20	20
50	rw	74.20	74.20	0.08	20	20	74.25	74.25	3,420.52	8	8
50	rand	74.20	74.20	0.13	20	20	74.20	74.20	219.31	20	20
100	rw	125.00	125.00	0.15	20	20	-	-	Т	0	0
100	rand	125.00	125.00	0.29	20	20	124.00	124.00	3,097.82	13	13
Obje	ctive: 1	fime bala	nce								
10	rw	3.00	3.00	0.07	20	20	3.00	3.00	19.33	20	20
	rand	3.00	3.00	0.10	20	20	3.00	3.00	11.31	20	20
50	rw	4.00	4.00	0.57	20	20	2.97	25.56	Т	0	9
50	rand	4.00	4.00	0.56	20	20	4.00	4.00	422.54	20	20
100	rw	4.40	4.40	19.90	20	20	-	-	Т	0	0
100	rand	4.40	4.40	1.64	20	20	4.37	10.90	3,533.43	4	10
Obje	ctive: F	Resource	balance								
10	rw	0.3057	0.3057	0.92	20	20	0.3016	0.3205	1,061.71	16	20
10	rand	0.4180	0.4180	344.35	20	20	0.4177	0.4186	825.90	10	20
50	rw	0.1267	0.2323	Т	0	20	0.1746	0.4375	Т	0	1
50	rand	0.1631	0.4424	Т	0	20	0.3770	0.5795	Т	0	20
100	rw	0.1176	0.2613	Т	0	20	-	-	Т	0	0
100	rand	0.1983	0.4570	Т	0	20	-	-	Т	0	0
							ble solution four h a feasible solut				ımber

m 11 4	D 1.	c . 1	D GI (DGD	
Table 4:	Results	for the	RCMPSP-	ACTF.

proach concerning decision variables, resulting in a strongly divergent amount of constraints that have to be considered. For example taking a benchmark instance with 100 lots and 1,658 activities with the objective makespan minimization, the MIP solver has to take 490,765 constraints and 679,288 variables into account but the CP solver only considers 6,647 constraints and 1,658 variables. Moreover, CP and MIP do not apply the same optimization strategies as explained in the literature review in Section 2, which can also lead to very different results. However, its performance seems to depend on the considered objective function. A general observation is that instances following a random demand pattern are easier to solve than those mimicking real-world demand.

Since the CP Optimizer solves all instances for the makespan and time balance objectives to optimality, we decide to test two additional very large scale instances with l=1,000 and l=10,000 lots. With the makespan objective, optimal solutions are available for both instances in 21.76 and 315.61 seconds. However, with the time balance objective, optimality can only be proven for l=1,000 in 364.05 seconds; for l=10,000 a gap of 58,54% is left after the allowed runtime of one hour. Although the time balance objective cannot compete with the makespan for the largest instance, our results show that CP works far better for interval-related objectives (especially the makespan) than for the resource balance objective on the tested benchmarks.

5.4. Industry case study

In the following, we present our results of a case study for a globally operating steel producer. The considered products are steel slabs, which are large and bulky artefacts cast out of different sorts of metal. The manufacturer requires an optimized schedule starting with predefined continuous casting programs and ending with customer deliveries. The objective of this study is threefold: We evaluate our proposed models in terms of satisfying all constraints, providing optimal solutions and giving insights into the impact of the respective objectives on processing time lengths and resource utilizations. The manufacturer requests a maximum runtime of 1 hour. The reason is that the optimization results serve as a management decision support, which has to be available at short notice for a large-scale instance size. Since up to now, the operational production planning of the company is partially triggered manually or with spreadsheet software, unfortunately, we cannot compare our results with existing schedules. As it is not possible to publish the whole real-world data instance with the detailed project structure, we give the following company-released information.

The continuous casting plan for the following 2.5 hours has to be taken into account for the optimization, i.e. all customer orders (=lots), which are cast in the next 2.5 hours have to be included in the scheduling plan. However, the overall planning horizon, which has to be considered for the optimization is 3 days (and not 2.5 hours), since the delivery dates for the produced lots vary up to 3 days. This inclusion of the whole production cycle is also necessary since the company wants to generate new production schedules in this make-to-order environment as often as demanded for the already mentioned management decision support, as it is for example also explained in Voß & Witt (2007). The steel producer asks for a minute-by-minute planning, resulting in a total planning horizon of \mathcal{T} =4,088 minutes. Our partner produces \mathcal{L} =50 lots with related 556 activities. Whereas 21 lots have three route alternatives, 23 have two and six lots have to follow a fixed route. Some production activities have fixed processing times, such as automated handover activities. For other activities, strongly varying minimum (a_i) and maximum allowed processing times (b_i) are defined by the steel producer, e.g. having a storaging activity with $a_i=24$ and $b_i=506$ minutes. The manufacturer has eight renewable resources with very different capacities $C_r = [10; 10; 30; 10; 50; 240; 220; 80]$, since vehicles, a cooling bed and an automated handover resource with a much lower capacity than large warehouses, cooling and warming boxes are included. For some production resources such as the automated handover resource, concurrent use is not possible, i.e., it is always fully used by a maximum of one activity. Other resources such as warehouses have high and not fully utilized capacities. The company only considers their two conventional warehouses $r \in \{6, 8\}$ as appropriate for load balancing purposes $\mathcal{R}^* \subseteq \mathcal{R}$. All other resources have very different technical purposes, i.e. they are not considered since e.g. a load balancing between a handover and a vehicle resource would not make sense for the company.

With the presented MIP models, it is not possible to generate a feasible solution within the allowed runtime. We assume that the major reason is the time index t for the time-related decision variables together with the very long planning horizon of $\mathcal{T}=4,088$ minutes, since preliminary tests with a very low (unrealistic) time horizon provide at least a feastible solution. Thus, all presented results are obtained by means of the CP Optimizer.

For the CP optimization, 50 additional dummy meta nodes which are necessary for the route selection and 1 dummy start and 1 dummy end node are added, resulting in a total of $\mathcal{J}=608$ activities (for the MIP optimization only 1 dummy start and 1 dummy end node were added). Nevertheless, all three CP models are solved to optimality within seconds, as shown in Table 5, where the following information is provided for each run: the optimization runtime, the makespan of the obtained solution, the time buffer and the peak usage of resources 6 and 8 (R6 and R8). The optimal makespan is achieved with all three objectives. The reason for this equality is that the due date of the last lot is reached without any tardiness by all three objectives. However, the goal of balancing the peak usages of resources \mathcal{R}^* is much better reached with the resource balance objective than with the others. The same result applies to the time balance objective: the aim of the company to distribute processing times in such a way that buffer time variations are minimized is far better reached with this objective in contrary to the other ones. A related closer examination of the time buffer and peak usage variations is depicted in Figures 6-7.

Table 5: Constraint programming results for the real-world case study.

Objective	Runtime	Makespan	Time buffer	Peak usage
				R6 R8
Makespan	0.12	4,088	4,024	1.0000 1.0000
Time balance	2.09	4,088	1,422	1.0000 1.0000
Resource balance	27.20	4,088	4,024	0.6250 0.6250

Runtime in seconds; peak usage in percent; R6 | R8... resource 6 | 8; bold letters indicate the optimal solution.

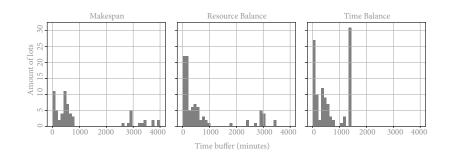


Figure 6: Time balance variations for all considered objectives.

In principle, our industry partner gives no tardiness restrictions except the overall planning horizon of three days due to special agreements with their customers. However, the company is interested in the amount of customer orders, which are provided too late, and the length of every delay. We decide to carry out an additional analysis to examine if it is even necessary to allow tardiness or if a full delivery date reliability or early delivery was possible with the existing alternative route and capacity restrictions. As a result, we study the following three scenarios: (a) tardiness is allowed, earliness is not allowed (current situation); (b) no earliness or tardiness is allowed; (c) earliness is allowed.

Scenario (a) exactly complies with constraints (45) presented in Section 4.3 and corresponds to the real-world case study examined so far (see Table 5). The makespan and time balance objectives do not bring any tardiness. For the resource balance objective, we have three delayed lots with a maximum delay of 6.16% with respect to the delivery time of the delayed lot. For scenario (b), we introduce constraints (45b) in order to prescribe on-time delivery:

$$\mathsf{endOf}(w_i) = d_i \qquad \forall \ i \in \mathcal{L} \tag{45b}$$

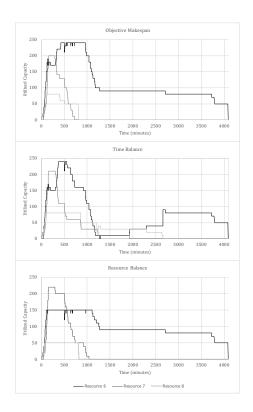


Figure 7: Resource utilization diagrams for all considered objectives.

The solutions for scenario (b) are presented in Table 6. All lots are delivered on time, all constraints are satisfied and the problems are solved to optimality. Due to the required on-time delivery of all lots, we now have a different optimal result for the resource balance objective (a higher peak usage), i.e. the capacity utilizations have been changed during the optimization process in order to guarantee the demanded on-time delivery. Moreover, the resource balance optimization needs nearly five times longer than for scenario (a) but is still finished in under three minutes.

In scenario (c), we want to find out if the produced lots could be delivered earlier. Therefore, we introduce the weighting factor v to allow a reduction of the delivery time d_i . It indicates the maximum allowed earliness $e_i = d_i \cdot (1 - v)$ compared to the original due date d_i . E.g. having the original delivery time $d_i = 50$ with the factor v = 0.10, a lot can be delivered 10% prior to the delivery time, resulting in the maximum allowed earliness of $e_i = 50 \cdot (1 - 0.1) = 45$.

$$e_i \le \texttt{endOf}(w_i) \le d_i \qquad \forall \ i \in \mathcal{L}$$
 (45c)

Objective	Run- time	Makespan	Time buffer		usage R8			
Makespan	0.15	4,088	4,020	1.0000	1.0000			
Time balance	1.52	4,088	1,422	1.0000	1.0000			
Resource balance	132.40	4,088	4,024	0.7083	0.7083			
Runtime in seconds; Peak usage R6 R8 peak usage for resources 6 and 8 in percent.								

Table 6: Optimization results for scenario (b).

With constraints (45c), all lots can be delivered earlier and must be at least delivered on time. In Table 7, the optimization results for the earliness restrictions (45c) are presented, including an allowed maximum early delivery of 10%, 50% and 90% (=maximum allowed early delivery of 408, 2044 and 3679 minutes) for a comprehensive evaluation of existing earliness possibilities. In columns 1-3, the considered earliness factor v, the employed objective and the optimization runtime in seconds is given. Column 4 shows the amount of lots that are delivered early. The makespan, time buffer and peak usage results for every employed objective are presented in columns 5-8; the peak usages are specified in percent for balancing resources 6 and 8. The utilized earliness in columns 9-10 represents the achieved minimum and maximum early delivery in absolute numbers (minutes), e.g. having v = 0.10 as the first case in Table 7, we observe that for the objective makespan, all lots are delivered between 13 and 408 minutes prior to their respective due date.

The results in Table 7 show that it is possible to introduce earliness for all lots. All restrictions are satisfied and all runs lead to optimal solutions for the respective employed objective. It is also shown that the optimal solution for the resource balance objective (0.6250) is the same for all runs in contrary to the results of the other two objectives. We assume that the reason is the possibility of a minimized equally proportioned peak usage at the cost of activity selection, starting time postponement and processing time variations in combination with very different determined early delivery dates.

Moreover, the maximum allowed earliness is exploited in all solutions. However, the results of the minimum utilized earliness are not the same for all test cases. It is much lower than the maximum one and the higher the earliness factor v is, the higher the minimum utilized earliness gets. We think that the reason lies in the very dissimilar capacity utilizations (and related peak usages) of the three employed objectives. Depending on the objective function, the selection of the activities, the starting times and the durations of single activities are very different. This results in very diverse earliness values for the due dates and resource utilizations for all objectives. We therefore assume that capacity efficiency suffers losses at the cost of time efficiency and vice versa, i.e. that the time objectives on the one hand and the resource objective on the other hand are contradictory goals. Overall, it can be concluded that the analysis of different tardiness scenarios also allows the satisfaction of all constraints and the generation of optimal production schedules and additionally gives insights into the possibility of postponing delivery times.

v	Objective	Run-	Early	Make-	Time	Time Peak usage			Earliness	
•	Objective	time	lots	span	buffer	R6	R8	min	max	
0.10	Makespan	0.23	50	3,680	3,616	0.6250	1.0000	13	408	
	Time balance	1.71	50	3,680	1,233	1.0000	1.0000	13	408	
	Resource balance	16.78	50	3,680	3,616	0.6250	0.6250	2	408	
0.50	Makespan	0.35	50	2,044	1,980	0.4583	1.0000	66	2044	
	Time balance	0.23	50	2,044	660	0.9167	1.0000	66	2044	
	Resource balance	20.90	50	2,044	1,980	0.6250	0.6250	4	2044	
	Makespan	0.15	50	1,207	345	0.6250	0.8750	83	3679	
0.90	Time balance	2.38	50	1,207	115	0.7500	1.0000	83	3679	
	Resource balance	0.37	50	1,207	345	0.6250	0.6250	83	3679	
v allo	v allowed delivery time reduction in percent; Runtime in seconds; Early lots number of early delivered lots; utilized earliness min/max minimum/maximum utilized earliness of the whole network; R6[R8 resources 6 and 8.									

Table 7: Optimization results for tardiness scenario (c): earliness is allowed, tardiness not.

6. Conclusion

In this work, a new resource-constrained multi-project scheduling problem with alternative activity chains and time flexibility (RCMPSP-ACTF) has been proposed. With this integrated problem, inspired by different manufacturing industries and based on the RCPSP-AC of Tao & Dong (2017), it is possible to integrate several decisions on flexibility. Besides the RCPSP typical choice on a start time for every activity, multiple projects are regarded, it is decided on the selection of alternative activities and on the length of the processing times of selected activities and early deliverys are not allowed. Moreover, two new objective functions considering time balance and resource balance maximization have been developed besides the consideration of the popular objective of makespan minimization. New MIP and CP models have been presented and in a comprehensive numerical study, the strong potential of our developed CP approach has been demonstrated in terms of solution quality and runtime: we solve all benchmarks for the RCPSP-AC to optimality and therefore provide an additional set where the computationally more expensive multi-project environment is considered. Moreover, many instances of the newly developed problem and the industry case are solved to optimality.

Future research will address several topics concerning the advancement of flexibility in a scheduling context. First, new methods, which provide better solutions for the multi-project RCPSP-AC and the RCMPSP-ACTF maximizing resource balance, should be addressed. Second, the mutual influence of the investigated three objectives should be examined in a multi-objective context. Third, an additional consideration of the MP approach for the new problem and a comparison to the established SP approach would be an interesting topic of investigation. Moreover, the robustness of the achieved optimization results with regard to disruptive incidents, such as the sudden breakdown of resources, can significantly influence the competitiveness of organizations. In order to meet this challenge, disturbance variables and related methods to obtain robust solutions should be investigated.

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A. Online appendix: Constraint programming model explanations

The CP modeling process works with different functions and expressions. At the beginning of the solution process of the CP Optimizer, constraint propagation is employed and several search heuristics are applied. For the presented CP models, one can distinguish between decision variables, expressions for decision variables and resource functions (Laborie et al., 2018; Laborie, 2009; Vilím et al., 2015). Moreover, a CP model can be solved with and without an objective function. If an objective function is given, it is considered as another constraint within the solution process and the solver tries to find the optimal solution for this objective function. Besides the *interval*, the **alternative** expression, the **span** expression and the resource function **cumulFunction**, which are introduced in the main paper, logical relation expressions and time expressions are used for the CP models in this work:

Logical relation expressions: With the expression $presenceOf(w_j)$, the mandatory presence of interval variables is defined.

Time expressions: With the expressions $\operatorname{endAtStart}(w_i, w_j)$ and $\operatorname{endBefore}$ $\operatorname{Start}(w_i, w_j)$, time positions of intervals are defined. Hence, two consecutive activities are processed without or with allowed idle times. With the expressions $\operatorname{startOf}(w_j)$, $\operatorname{endOf}(w_j)$, and $\operatorname{lengthOf}(w_j)$, the start and end time and the exact processing time (=duration or length) of an $\operatorname{interval}(w_j)$ are determined.

For a further detailed description of constraint programming and the CP Optimizer, we refer to Laborie et al. (2018); Laborie (2009); Vilím et al. (2015) and the online tutorial of the CP Optimizer Tutorial¹.

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¹https://www.ibm.com/analytics/cplex-cp-optimizer

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B. Online appendix: Test design procedure for the RCMPSP-ACTF benchmarks

For the evaluation of our models, three different test instance classes $|\mathcal{L} \in \{10, 50, 100\}|$ are used. Depending on the customer orders, different alternative activities and thus, alternative routes (=activity chains) are necessary. All lots and related alternative routes are sampled out of a steel company's customer orders. Since alternative routes can consist of different numbers of activities, the overall number of activities per lot (and thus, per instance class) varies. It can for example be the case that the first lot has three different alternative routes with involved activities 3, 4, and 5 and the second lot has two different routes, involving activities 3 and 5. Therefore, the number of non-dummy activities per instance class is depicted as an average number (rounded up to the nearest integer) in Table B.1.

Table B.1: Parameters for test classes of test instances for the RCMPSP-ACTF.

Instance	Lots	Non-dummy	OR
class		activities	activities
1	10	162	10
2	50	797	50
3	100	1,593	100

In the real-world situation, every activity only demands a single resource and the demand is normalized to 1. Thus, the demand pattern random (rand) is introduced additionally to the real-world (rw) situation. In the demand pattern rand, every activity demands random amounts of all resources. The demand, the related resource factor RF_R , the resource strength RS_R , the calculation for the shortest processing time per activity a_j and the slack \mathfrak{s} are presented in Table B.2. The resource factor $RF_R \in [0, 1]$ is defined as explained in Kolisch et al. (1995). It describes the number of resources r used by each activity j:

$$RF_R = \frac{1}{|\mathcal{J}|} \frac{1}{|\mathcal{R}|} \sum_{j \in \mathcal{J}} \sum_{r \in \mathcal{R}} \begin{cases} 1, & \text{if } c_{jr} > 0\\ 0, & \text{else} \end{cases} \quad \forall r \in \mathcal{R}$$
 (b.1)

The resource strength $RS_R \in [0, 1]$ determines the resource availability and is used as a scaling parameter to determine the resource availability C_r (Kolisch et al., 1995).

	rw	rand
c_{jr}	1	random[1;10)
RF_R	0.11	1
RS_R	$\{0.25,$	$0.50, 0.75, 1.00\}$
a_j	ra	ndom[1;5)
5	rar	ndom[10;20]

Table B.2: Parameters for test instance classes real-world (rw) and random (rand).

In addition to the parameters in Table B.2, we compute the necessary values for the due date of every lot d_l , the maximum duration b_j , and the resource availability C_r . The due date is calculated by the earliest possible release date per lot l plus a randomly generated value between the completion time in an earliest schedule \mathfrak{t}_l and the double value of \mathfrak{t}_l :

$$d_l = \mathfrak{t}_{\mathfrak{l}} + \operatorname{random}[\mathfrak{t}_{\mathfrak{l}}; 2\mathfrak{t}_{\mathfrak{l}}] \qquad \forall \ l \in \mathcal{L}$$
(b.2)

The maximum duration b_j for the activities with flexible processing time lengths is given by the difference between the lot's due date d_l and its completion time \mathfrak{t}_l in an earliest schedule with a slack \mathfrak{s} to allow tardiness:

$$b_j = d_l - \mathfrak{t}_{\mathfrak{l}} + \mathfrak{s} \qquad \forall \ j \in \mathcal{J}, \ l \in \mathcal{L}, \qquad if \ \mathbf{1}_{jl} = 1$$
 (b.3)

where $\mathbf{1}_{jl}$ denotes the indicator function, i.e. activity j and l belonging to the same lot (=project). For the computation of resource availability C_r , Kolisch et al. (1995) define the minimum and maximum demands C_r^{min} and C_r^{max} as input parameters besides the already explained resource strength RS_R :

$$C_r^{min} = \max\{c_{jr} \mid j = 2, ..., J\} \qquad \forall r \in \mathcal{R}$$
 (b.4)

$$C_r^{max} = \max\left\{\sum_{j\in\mathcal{J}} c_{jr} \mid j=2,...,J\right\} \quad \forall r \in \mathcal{R}$$
 (b.5)

The minimum capacity C_r^{min} in (b.4) is determined as the maximum demand of an activity j for resource r. The maximum capacity C_r^{max} in (b.5) is the peak demand calculated out of the earliest start time schedule under consideration of all precedence relations (Kolisch et al., 1995). In our project structure, multiple projects can run in parallel. Moreover, the selection of one alternative route per lot and the decision on the processing time lengths of single activities have to be regarded. Thus, resource availabilities would be too low when only considering (b.3)-(b.4). They have to be adapted in a way that they are high enough to get feasible solutions. Therefore, we determine the average amount of projects L^{par} that would be active concurrently. We compare the [release;due) intervals of all lots to satisfy the necessary consideration of parallel running projects. As a result, we extend C_r^{min} and C_r^{max} of Kolisch et al. (1995) for the RCMPSP-ACTF to the values C_r^{lower} and C_r^{upper} to generate feasible resource availabilities C_r in the following way:

$$C_r^{\ lower} = C_r^{\ min} \cdot L^{par} \tag{b.6}$$

$$C_r^{upper} = C_r^{lower} + C_r^{max} \tag{b.7}$$

$$C_r = C_r^{\ lower} + RS_R \cdot (C_r^{\ upper} - C_r^{\ lower})$$
(b.8)

By multiplying C_r^{min} with L^{par} in (b.6), resource capacities are set in such a way that the parallel execution of different projects is possible. Since the C_r^{upper} in (b.7) has to be higher than C_r^{lower} , this lower bound is added to C_r^{max} to guarantee this requirement. In (b.8) it can be seen that C_r^{lower} and C_r^{upper} are used instead of the originally introduced C_r^{min} and C_r^{max} of Kolisch et al. (1995) to calculate feasible resource availabilities.

For the real-world (rw) instances, the resource availabilities C_r for non-load balancing resources $\mathcal{R} \setminus \mathcal{R}^*$ are calculated in a different way. They are set to two times C_r^{min} instead of using (b.8) since this corresponds to the real-world case. However, for all *rand* instances, formulae (b.6)-(b.8) are applied.

References

Kolisch, R., Sprecher, A., & Drexl, A. (1995). Characterization and generation of a general class of resource-constrained project scheduling problems. *Management science*, 41, 1693–1703.

C. Online appendix: Adapted MIP model for the RCPSP-AC

With the following MIP model, alternative activity chains are considered for the optimization of one or multiple projects. In order to validate the optimization results for the RCPSP with alternative activity chains (RCPSP-AC), we implemented the MIP model presented by Tao & Dong (2017) and tested it with the presented benchmark instance $\mathcal{J} = 30$ in their paper. It is an extended version of the RCPSP-AC originally presented by Tao & Dong (2017), since we added constraint (c.2) and adapted constraints (c.4)-(c.6) to obtain the following model and hence, the same solutions as presented in their paper:

Minimize

$$\sum_{t \in \mathcal{T}} t \cdot y_{n+1t} \tag{c.1}$$

 $subject \ to$

$$x_0 = 1, \tag{c.2}$$

$$\sum_{t \in \mathcal{T}} y_{it} = x_i \qquad \forall \ i \in \mathcal{J}, \tag{c.3}$$

$$\sum_{j \in \mathcal{J}} A_{ij} \cdot x_j = x_i \qquad \forall i \in \mathcal{J}, if \ p_i = 0,$$
(c.4)

$$A_{ij} \cdot x_i \le x_j \qquad \forall \ i, j \in \mathcal{J}, \ if \ p_i = 1, \tag{c.5}$$

$$A_{ij}\left(\sum_{t\in\mathcal{T}}t\cdot y_{it}\right) + (x_j + x_i - 2)\cdot M \le \sum_{t\in\mathcal{T}}t\cdot y_{jt} - D_j \qquad \forall \ i, j\in\mathcal{J}, \quad (c.6)$$

$$\sum_{i \in \mathcal{J}} \sum_{\tau=t}^{t+D_i-1} y_{i\tau} \cdot c_{ir} \le C_r \qquad r \in \mathcal{R}, t \in \mathcal{T},$$
(c.7)

$$\sum_{i \in \mathcal{J}} x_i \cdot c_{ir} \le C_r \qquad r \in \mathcal{N}, t \in \mathcal{T}, \tag{c.8}$$

$$x_i \in \{0, 1\} \qquad \forall \ i \in \mathcal{J}, \tag{c.9}$$

$$y_{it} \in \{0, 1\} \qquad \forall i \in \mathcal{J}, t \in \mathcal{T}.$$
(c.10)

Objective function (c.1) minimizes the makespan of the project. With the newly added constraint (c.2), the project (production process) has to be started. Without the consideration of this condition, an optimization leads to a result of 0. Restrictions (c.3) define that every selected activity has to be finished exactly once. With altered constraints (c.4)-(c.5) activity selection flexibility relations are considered. If an activity is an OR node, only one of its successors in the project network must be selected. If an activity is an AND node, all successors have to be selected. Modified restrictions (c.6) guarantee that no activity within one production route can be started before the predecessor activities of this route are finished and that only activities can be selected which are related to each other. Idle times are allowed, also between successor activities and not only between those of different lots. Conditions (c.7)-(c.8) make sure that capacity restrictions for renewable and non-renewable resources are met. Constraints (c.9)-(c.10) define decision variables as binary ones.

We note that with the consideration of the two activity types AND/OR $(p_j = 1/p_j = 0)$, it can happen that additional nodes appear in the solution of an optimization although they do not belong to the chosen alternative route of the optimizer. This is possible since there is no restriction in the MIP model to select exactly one activity route after an OR activity and no additional activities out of other alternatives. These additional selected activities do not increase or influence a minimization objective since they are considered as a separate schedule by the MIP model optimization. They can be deleted in a manual post-processing step. Alternatively, a third activity type $p_j = 2$ for every customer delivery node j and a related new constraint, which forbids the explained additional node selection, can be introduced:

$$\sum_{i \in \mathcal{J}} A_{ij} \cdot x_j = x_j \qquad \forall \ j \in \mathcal{J}, \ if \ p_j = 2.$$
 (c.11)

With constraint (c.11) it is guaranteed that if one production route is selected, no additional activities of other routes within the project (lot) can be selected. Preliminary experiments showed that it is more efficient to use the post-processing step. Therefore, we use this approach in our experimental results. (We note that in contrary to the here presented model where this activity type $p_j = 2$ is a free choice, it is a mandatory activity type for the newly presented RCMPSP-ACTF in this work as explained in Section 3.1.)

References

Tao, S., & Dong, Z. S. (2017). Scheduling resource-constrained project problem with alternative activity chains. *Computers & Industrial Engineering*, 114, 288–296. doi:10.1016/j.cie.2017.10.027.

D. Online appendix: Optimization results for the RCPSP-AC and the RCMPSP-AC

On the following pages, we present the detailed examination of all designed benchmark instances for the resource-constrained project scheduling problem with alternative activity chains (RCPSP-AC) and its multi-project version, the RCMPSP-AC. The columns in Table D.1 give (1) the name of every instance, (2) the solver (MIP or CP) which has been applied, (3) the project-scheduling type, i.e. if it is a single- (RCPSP-AC) or a multi-project(RCMPSP-AC) instance, (4) the considered amount of nodes, (5) an identification number from 1-10 per project and node case, (6) the best objective value found, (7) the best bound found, and (8) the runtime in seconds. Bold letters represent the optimal solution.

-		tion results					RCMPSP- Runtime in
Instance name		Туре	Nodes	Id	Best objective	Best bound	seconds
CP-SingleProject_30_1	CP	Single-Project Case	30	1	26	26	0.04
CP-SingleProject_30_10 CP-SingleProject_30_11	CP CP	Single-Project Case Single-Project Case	30 30	10 11	26 24	26 24	0.04 0.03
CP-SingleProject_30_12	CP	Single-Project Case	30	12	24	24	0.03
CP-SingleProject_30_13	CP	Single-Project Case	30	13	30	30	0.05
CP-SingleProject_30_14	CP	Single-Project Case	30	14	23	23	0.04
CP-SingleProject_30_15	CP	Single-Project Case	30	15	23	23	0.08
CP-SingleProject_30_2	CP	Single-Project Case	30 30	2	22 34	22 34	0.04
CP-SingleProject_30_3 CP-SingleProject_30_4	CP	Single-Project Case Single-Project Case	30	3 4	34 27	34 27	0.03
CP-SingleProject_30_5	CP	Single-Project Case	30	5	24	24	0.03
CP-SingleProject_30_6	CP	Single-Project Case	30	6	27	27	0.03
CP-SingleProject_30_7	CP	Single-Project Case	30	7	22	22	0.03
CP-SingleProject_30_8	CP CP	Single-Project Case	30 30	8 9	26 21	26 21	0.04
CP-SingleProject_30_9 CP-SingleProject_60_1	CP	Single-Project Case Single-Project Case	50 60	9	50	50	0.57
CP-SingleProject_60_10	CP	Single-Project Case	60	10	48	48	0.06
CP-SingleProject_60_11	CP	Single-Project Case	60	11	56	56	0.33
CP-SingleProject_60_12	CP	Single-Project Case	60	12	47	47	0.07
CP-SingleProject_60_13	CP	Single-Project Case	60 60	13 14	55 56	55 56	0.05 0.04
CP-SingleProject_60_14 CP-SingleProject_60_15	CP	Single-Project Case Single-Project Case	60	14	50 46	50 46	0.04
CP-SingleProject_60_2	CP	Single-Project Case	60	2	52	52	0.09
CP-SingleProject_60_3	CP	Single-Project Case	60	3	46	46	0.04
CP-SingleProject_60_4	CP	Single-Project Case	60	4	49	49	0.03
CP-SingleProject_60_5	CP CP	Single-Project Case	60 60	5	46 72	46 72	0.03
CP-SingleProject_60_6 CP-SingleProject_60_7	CP	Single-Project Case Single-Project Case	60	6 7	47	47	2.73 0.3
CP-SingleProject_60_8	CP	Single-Project Case	60	8	44	44	0.04
CP-SingleProject_60_9	CP	Single-Project Case	60	9	53	53	0.03
CP-SingleProject_90_1	CP	Single-Project Case	90	1	67	67	0.12
CP-SingleProject_90_10	CP	Single-Project Case	90	10	90	90	0.52
CP-SingleProject_90_11 CP-SingleProject_90_12	CP	Single-Project Case Single-Project Case	90 90	11 12	79 80	79 80	0.04
CP-SingleProject_90_12	CP	Single-Project Case	90	13	70	70	0.1
CP-SingleProject_90_14	CP	Single-Project Case	90	14	77	77	0.04
CP-SingleProject_90_15	CP	Single-Project Case	90	15	73	73	0.04
CP-SingleProject_90_2	CP CP	Single-Project Case	90 90	2	71 82	71 82	0.04
CP-SingleProject_90_3 CP-SingleProject_90_4	CP	Single-Project Case Single-Project Case	90	3 4	82	82 70	0.04
CP-SingleProject_90_5	CP	Single-Project Case	90	5	70	70	1.56
CP-SingleProject_90_6	CP	Single-Project Case	90	6	82	82	0.53
CP-SingleProject_90_7	CP	Single-Project Case	90	7	95	95	3.52
CP-SingleProject_90_8	CP CP	Single-Project Case	90 90	8	75 91	75 91	0.04
CP-SingleProject_90_9 CP-SingleProject_120_1	CP	Single-Project Case Single-Project Case	90 120	9	91 93	91	8.02 0.05
CP-SingleProject_120_10	CP	Single-Project Case	120	10	103	103	0.57
CP-SingleProject_120_11	CP	Single-Project Case	120	11	105	105	0.49
CP-SingleProject_120_12	CP	Single-Project Case	120	12	105	105	0.05
CP-SingleProject_120_13 CP-SingleProject 120 14	CP CP	Single-Project Case Single-Project Case	120 120	13 14	105 94	105 94	1.85 0.15
CP-SingleProject_120_14 CP-SingleProject_120_15	CP	Single-Project Case Single-Project Case	120	14 15	94 103	94 103	0.15
CP-SingleProject_120_2	CP	Single-Project Case	120	2	144	144	471.46
CP-SingleProject_120_3	CP	Single-Project Case	120	3	89	89	0.76
CP-SingleProject_120_4	CP	Single-Project Case	120	4	102	102	0.05
CP-SingleProject_120_5	CP CP	Single-Project Case	120 120	5	148 94	148 94	456.21
CP-SingleProject_120_6 CP-SingleProject_120_7	CP	Single-Project Case Single-Project Case	120	6 7	94 109	94 109	0.74
CP-SingleProject_120_8	CP	Single-Project Case	120	8	94	94	0.98
CP-SingleProject_120_9	CP	Single-Project Case	120	9	98	98	0.05
CP-SingleProject_150_1	CP	Single-Project Case	150	1	126	126	0.15
CP-SingleProject_150_10 CP-SingleProject_150_11	CP CP	Single-Project Case Single-Project Case	150 150	10 11	167 112	167 112	1569.39 1.16
CP-SingleProject_150_12	CP	Single-Project Case	150	12	112	112	0.06
CP-SingleProject_150_13	CP	Single-Project Case	150	13	129	129	0.81
CP-SingleProject_150_14	CP	Single-Project Case	150	14	127	127	0.05
CP-SingleProject_150_15	CP	Single-Project Case	150	15	125	125	0.82
CP-SingleProject_150_2	CP	Single-Project Case	150	2	127	127	0.05
CP-SingleProject_150_3 CP-SingleProject_150_4	CP CP	Single-Project Case Single-Project Case	150 150	3	131 113	131 113	3.8 0.45
CP-SingleProject_150_5	CP	Single-Project Case	150	5	113	113	0.05
CP-SingleProject_150_6	CP	Single-Project Case	150	6	135	135	1.96
CP-SingleProject_150_7	CP	Single-Project Case	150	7	176	176	1026.76
CP-SingleProject_150_8 CP-SingleProject_150_9	CP	Single-Project Case Single-Project Case	150 150	8 9	129 116	129 116	0.11
CP-SingleProject_150_9 MIP-SingleProject_30_1	MIP	Single-Project Case Single-Project Case	30	9	26	26	1.23
sugar sjeet_so_r			50	-	20	20	1.20

Table D.1: Optimization results for the RCPSP-AC & the RCMPSP-AC for every instance.

Instance name	Solver		Nodes	Id		Best bound	Runtime in seconds
MIP-SingleProject_30_10	MIP	Single-Project Case	30	10	26	26	1.74
MIP-SingleProject_30_11	MIP	Single-Project Case	30	11	24	24	0.5
MIP-SingleProject_30_12	MIP	Single-Project Case	30	12	27	27	1.08
MIP-SingleProject_30_13	MIP	Single-Project Case	30	13	30	30	1.92
MIP-SingleProject_30_14	MIP	Single-Project Case	30	14	23	23	1
MIP-SingleProject_30_15	MIP	Single-Project Case	30	15	23	23	1.66
MIP-SingleProject_30_2	MIP	Single-Project Case	30	2	22	22	0.61
MIP-SingleProject_30_3	MIP	Single-Project Case	30	3	34	34	4.78
MIP-SingleProject_30_4	MIP	Single-Project Case	30	4	27	27	0.41
MIP-SingleProject_30_5	MIP	Single-Project Case	30	5	24	24	0.63
MIP-SingleProject_30_6	MIP	Single-Project Case	30	6	27	27	0.78
MIP-SingleProject_30_7	MIP	Single-Project Case	30	7	22	22	0.69
MIP-SingleProject_30_8	MIP	Single-Project Case	30	8	26	26	1.39
MIP-SingleProject_30_9	MIP	Single-Project Case	30	9	21	21	0.55
MIP-SingleProject_60_1	MIP	Single-Project Case	60	1	50	50	14.01
MIP-SingleProject_60_10	MIP	Single-Project Case	60	10	48	48	13.16
MIP-SingleProject_60_11	MIP	Single-Project Case	60	11	56	56	339.67
MIP-SingleProject_60_12	MIP	Single-Project Case	60	12	47	47	40.47
MIP-SingleProject_60_13	MIP	Single-Project Case	60	13	55	55	364.67
MIP-SingleProject_60_14	MIP	Single-Project Case	60	14	56	56	9.66
MIP-SingleProject_60_15	MIP	Single-Project Case	60	15	46	46	6.72
MIP-SingleProject_60_2	MIP	Single-Project Case	60	2	52	52	11.77
MIP-SingleProject_60_3	MIP	Single-Project Case	60	3	46	46	11.09
MIP-SingleProject_60_4	MIP	Single-Project Case	60	4	49	49	6.47
MIP-SingleProject_60_5	MIP	Single-Project Case	60	5	46	46	5.78
MIP-SingleProject_60_6	MIP	Single-Project Case	60	6	80	65.09730234	1
MIP-SingleProject_60_7	MIP	Single-Project Case	60	7	47	47	33.41
MIP-SingleProject_60_8	MIP	Single-Project Case	60	8	44	44	7.36
MIP-SingleProject_60_9	MIP	Single-Project Case	60	9	53	53	14.2
MIP-SingleProject_90_1	MIP	Single-Project Case	90	1	67	67	213.34
MIP-SingleProject_90_10	MIP	Single-Project Case	90	10	99	83	1
MIP-SingleProject_90_11	MIP	Single-Project Case	90	11	79	79	64.75
MIP-SingleProject_90_12	MIP	Single-Project Case	90	12	80	80	160.44
MIP-SingleProject_90_13	MIP	Single-Project Case	90	13	70	70	159.97
MIP-SingleProject_90_14	MIP	Single-Project Case	90	14	77	77	41.19
MIP-SingleProject_90_15	MIP	Single-Project Case	90	15	73	73	39.75
MIP-SingleProject_90_2	MIP	Single-Project Case	90	2	71	71	31.98
MIP-SingleProject_90_3	MIP	Single-Project Case	90	3	82	82	49.47
MIP-SingleProject_90_4	MIP	Single-Project Case	90	4	70	70	76.72
MIP-SingleProject_90_5	MIP	Single-Project Case	90	5	73	72	1
MIP-SingleProject_90_6	MIP	Single-Project Case	90	6	82	82	381.5
MIP-SingleProject_90_7	MIP	Single-Project Case	90	7	114	81	1
MIP-SingleProject_90_8	MIP	Single-Project Case	90	8	75	75	73.81
MIP-SingleProject_90_9	MIP	Single-Project Case	90	9	122	73.13231487	1
MIP-SingleProject_120_1	MIP	Single-Project Case	120	1	93	92	1
MIP-SingleProject_120_10	MIP	Single-Project Case	120	10	112	99	1
MIP-SingleProject_120_11	MIP	Single-Project Case	120	11	113	90	1
MIP-SingleProject_120_12	MIP	Single-Project Case	120	12	106	104	3601.2
MIP-SingleProject_120_13	MIP	Single-Project Case	120	13	131	75	1
MIP-SingleProject_120_14	MIP	Single-Project Case	120	14	94	94	1123.39
MIP-SingleProject_120_15	MIP	Single-Project Case	120	15	103	103	768
MIP-SingleProject_120_2	MIP	Single-Project Case	120	2	156	56.22509767	1
MIP-SingleProject_120_3	MIP	Single-Project Case	120	3		86.002	1
MIP-SingleProject_120_4	MIP	Single-Project Case	120	4	102	102	772.05
MIP-SingleProject_120_5	MIP	Single-Project Case	120	5	183	69.3007463	1
MIP-SingleProject_120_6	MIP	Single-Project Case	120	6		82	1
MIP-SingleProject_120_7	MIP	Single-Project Case	120	7	109	109	1
MIP-SingleProject_120_8	MIP	Single-Project Case	120	8	106	87	1
MIP-SingleProject_120_9	MIP	Single-Project Case	120	9	98	97	1
MIP-SingleProject_150_1	MIP	Single-Project Case	150	1	,0	126	1
MIP-SingleProject_150_10	MIP	Single-Project Case	150	10		50	1
MIP-SingleProject_150_10 MIP-SingleProject_150_11	MIP	Single-Project Case	150	11		74	1
	MIP		150	12	326	104	1
MIP-SingleProject_150_12	MIP	Single-Project Case Single-Project Case	150	13	320	120	1
MIP-SingleProject_150_13	MIP			13	120		1
MIP-SingleProject_150_14		Single-Project Case	150		130	86.38461539	
MIP-SingleProject_150_15	MIP	Single-Project Case	150	15		104	1
MIP-SingleProject_150_2	MIP	Single-Project Case	150	2	214	94	1
MIP-SingleProject_150_3	MIP	Single-Project Case	150	3		102	1
MIP-SingleProject_150_4	MIP	Single-Project Case	150	4		104	1
MIP-SingleProject_150_5	MIP	Single-Project Case	150	5		102	1
MIP-SingleProject_150_6	MIP	Single-Project Case	150	6		82	1
MIP-SingleProject_150_7	MIP	Single-Project Case	150	7		44	1
MIP-SingleProject_150_8	MIP	Single-Project Case	150	8	355	89	1
MIP-SingleProject_150_9	MIP	Single-Project Case	150	9		90	1
CP-MultiProject_30_1	CP	Multi-Project Case	30	1	26	26	0.03
CP-MultiProject_30_10	CP	Multi-Project Case	30	10	23	23	0.03

Instance name	Solver	Туре	Nodes	Id	Best objective	Best bound	Runtime in seconds
CP-MultiProject_30_11	СР	Multi-Project Case	30	11	26	26	0.0
CP-MultiProject_30_12	CP	Multi-Project Case	30	12	23	23	0.03
CP-MultiProject_30_13	CP	Multi-Project Case	30	13	29	29	0.2
CP-MultiProject_30_14	CP	Multi-Project Case	30	14	32	32	0.2
CP-MultiProject_30_15	CP	Multi-Project Case	30	15	32	32	0.2
CP-MultiProject_30_2	CP	Multi-Project Case	30	2	22	22	0.03
CP-MultiProject_30_3	CP	Multi-Project Case	30	3	28	28	0.03
CP-MultiProject_30_4	CP	Multi-Project Case	30	4	24	24	0.3
CP-MultiProject_30_5	CP	Multi-Project Case	30	5	28	28	0.04
CP-MultiProject_30_6	CP	Multi-Project Case	30	6	31	31	0.6
CP-MultiProject_30_7	CP	Multi-Project Case	30	7	32	32	0.6
CP-MultiProject_30_8	CP	Multi-Project Case	30	8	25	25	0.03
CP-MultiProject_30_9	CP	Multi-Project Case	30	9	25	25	0.0
CP-MultiProject_60_1	CP	Multi-Project Case	60	1	35	35	26.1
CP-MultiProject_60_10	CP	Multi-Project Case	60	10	30	30	1.7
	CP	Multi-Project Case	60	11	30 62	49	1.7
CP-MultiProject_60_11	CP	,		11	28		
CP-MultiProject_60_12		Multi-Project Case	60			28	4.6
CP-MultiProject_60_13	CP	Multi-Project Case	60	13	40	40	23.0
CP-MultiProject_60_14	CP	Multi-Project Case	60	14	36	36	40.2
CP-MultiProject_60_15	CP	Multi-Project Case	60	15	44	44	11.1
CP-MultiProject_60_2	CP	Multi-Project Case	60	2	31	31	4.9
CP-MultiProject_60_3	CP	Multi-Project Case	60	3	33	33	3.43
CP-MultiProject_60_4	CP	Multi-Project Case	60	4	31	31	0.0
CP-MultiProject 60 5	CP	Multi-Project Case	60	5	43	43	22.
CP-MultiProject_60_6	CP	Multi-Project Case	60	6	32	32	2.4
CP-MultiProject_60_7	CP	Multi-Project Case	60	7	32	33	2.4
	CP						
CP-MultiProject_60_8		Multi-Project Case	60	8	33	33	4.7
CP-MultiProject_60_9	CP	Multi-Project Case	60	9	56	46	·
CP-MultiProject_90_1	CP	Multi-Project Case	90	1	57	47	
CP-MultiProject_90_10	CP	Multi-Project Case	90	10	48	48	879.8
CP-MultiProject_90_11	CP	Multi-Project Case	90	11	66	66	466.5
CP-MultiProject_90_12	CP	Multi-Project Case	90	12	45	45	154.1
CP-MultiProject_90_13	CP	Multi-Project Case	90	13	36	36	529.9
CP-MultiProject_90_14	CP	Multi-Project Case	90	14	54	54	591.8
CP-MultiProject_90_15	CP	Multi-Project Case	90	15	39	39	2938.2
CP-MultiProject_90_2	CP	Multi-Project Case	90	2	49	49	16.5
	CP		90	3		78	
CP-MultiProject_90_3	CP	Multi-Project Case	90	4	78 52	78 52	2054.2
CP-MultiProject_90_4		Multi-Project Case		-			530.0
CP-MultiProject_90_5	CP	Multi-Project Case	90	5	58	49	
CP-MultiProject_90_6	CP	Multi-Project Case	90	6	54	54	78.1
CP-MultiProject_90_7	CP	Multi-Project Case	90	7	46	46	24.
CP-MultiProject_90_8	CP	Multi-Project Case	90	8	49	49	412.8
CP-MultiProject_90_9	CP	Multi-Project Case	90	9	58	54	
CP-MultiProject_120_1	CP	Multi-Project Case	120	1	88	73	-
CP-MultiProject_120_10	CP	Multi-Project Case	120	10	124	94	
CP-MultiProject_120_11	CP	Multi-Project Case	120	11	53	46	
CP-MultiProject_120_12	CP	Multi-Project Case	120	12	94	81	
	CP					92	
CP-MultiProject_120_13		Multi-Project Case	120	13	111		
CP-MultiProject_120_14	CP	Multi-Project Case	120	14	117	94	
CP-MultiProject_120_15	CP	Multi-Project Case	120	15	68	56	
CP-MultiProject_120_2	CP	Multi-Project Case	120	2	82	69	
CP-MultiProject_120_3	CP	Multi-Project Case	120	3	114	89	
CP-MultiProject_120_4	CP	Multi-Project Case	120	4	49	49	78.
CP-MultiProject_120_5	CP	Multi-Project Case	120	5	62	51	-
CP-MultiProject_120_6	CP	Multi-Project Case	120	6	52	44	
CP-MultiProject_120_7	CP	Multi-Project Case	120	7	87	73	
CP-MultiProject_120_8	CP	Multi-Project Case	120	8	52	52	271.1
	CP	,	120	9	62	49	2/1.1.
CP-MultiProject_120_9		Multi-Project Case					
CP-MultiProject_150_1	CP	Multi-Project Case	150	1	108	90	
CP-MultiProject_150_10	CP	Multi-Project Case	150	10	65	55	
CP-MultiProject_150_11	CP	Multi-Project Case	150	11	64	52	
CP-MultiProject_150_12	CP	Multi-Project Case	150	12	109	85	
CP-MultiProject_150_13	CP	Multi-Project Case	150	13	87	75	
CP-MultiProject_150_14	CP	Multi-Project Case	150	14	108	91	-
CP-MultiProject_150_15	CP	Multi-Project Case	150	15	58	49	
CP-MultiProject_150_2	CP	Multi-Project Case	150	2	77	62	-
CP-MultiProject_150_2 CP-MultiProject_150_3	CP	Multi-Project Case	150	3	140	117	-
CP-MultiProject_150_4	CP	Multi-Project Case	150	4	96	82	
CP-MultiProject_150_5	CP	Multi-Project Case	150	5	91	77	
CP-MultiProject_150_6	CP	Multi-Project Case	150	6	89	74	
CP-MultiProject_150_7	CP	Multi-Project Case	150	7	69	58	
CP-MultiProject_150_8	CP	Multi-Project Case	150	8	63	53	-
CP-MultiProject_150_9	CP	Multi-Project Case	150	9	75	65	
MIP-MultiProject_30_1	MIP	Multi-Project Case	30	1	26	26	0.5
MIP-MultiProject_30_10		Multi-Project Case	30	10	20	20	0.5
	MIP						

Ins	tance name	Solver	Туре	Nodes	Id	Best objective	Best bound	Runtime in seconds
	P-MultiProject_30_12	MIP	Multi-Project Case	30	12	23	23	0.5
	P-MultiProject_30_13	MIP	Multi-Project Case	30	13	29	29	2.1
	P-MultiProject_30_14	MIP MIP	Multi-Project Case	30 30	14 15	32 32	32 32	9.8 5.4
	P-MultiProject_30_15	MIP	Multi-Project Case	30	15 2	32	32	5.4
	P-MultiProject_30_2 P-MultiProject 30 3	MIP	Multi-Project Case Multi-Project Case	30	3	22	22	1.1
	-MultiProject_30_3	MIP	Multi-Project Case	30	4	28	28	1.1
	P-MultiProject_30_5	MIP	Multi-Project Case	30	4	24	24	2.0
								2.0
	P-MultiProject_30_6	MIP MIP	Multi-Project Case	30	6 7	31	31	
	P-MultiProject_30_7	MIP	Multi-Project Case	30 30	8	32 25	32	3.5
	P-MultiProject_30_8	MIP	Multi-Project Case Multi-Project Case	30	9	25	25	1.3
	P-MultiProject_30_9 P-MultiProject_60_1	MIP	Multi-Project Case	50 60	9	25	25 34	1.3
		MIP		60	10	30	34	121 /
	P-MultiProject_60_10	MIP	Multi-Project Case Multi-Project Case	60	10	68	52.05493117	131.6
	P-MultiProject_60_11	MIP	,		11	28	52.05493117 28	(50)
	P-MultiProject_60_12	MIP	Multi-Project Case	60 60	12	43	28	650.9
	P-MultiProject_60_13	MIP	Multi-Project Case	60	13	43	35	
	P-MultiProject_60_14 P-MultiProject 60 15	MIP	Multi-Project Case Multi-Project Case	60	14	36 46	43	
	,		,					022.5
	P-MultiProject_60_2	MIP	Multi-Project Case	60	2	31	31	832.2
	P-MultiProject_60_3	MIP	Multi-Project Case	60	3	33	32	
	P-MultiProject_60_4	MIP	Multi-Project Case	60	4	31	31	6.5
	P-MultiProject_60_5	MIP	Multi-Project Case	60	5	46	42	
	P-MultiProject_60_6	MIP	Multi-Project Case	60	6	32	32	2484.
	P-MultiProject_60_7	MIP	Multi-Project Case	60	7	34	33	
	P-MultiProject_60_8	MIP	Multi-Project Case	60	8	33	32	
	P-MultiProject_60_9	MIP	Multi-Project Case	60	9	60	45.29245876	
	P-MultiProject_90_1	MIP	Multi-Project Case	90	1	64	42.28875354	
	P-MultiProject_90_10	MIP	Multi-Project Case	90	10	53	42	
	P-MultiProject_90_11	MIP	Multi-Project Case	90	11	77	42	
	P-MultiProject_90_12	MIP	Multi-Project Case	90	12	49	36.37645594	
	P-MultiProject_90_13	MIP	Multi-Project Case	90	13	38	36	
	P-MultiProject_90_14	MIP	Multi-Project Case	90	14	68	41.00336215	
	P-MultiProject_90_15	MIP	Multi-Project Case	90	15	42	36	
	P-MultiProject_90_2	MIP	Multi-Project Case	90	2	60	37.0675747	
	P-MultiProject_90_3	MIP	Multi-Project Case	90	3	233	49.55991856	
	P-MultiProject_90_4	MIP	Multi-Project Case	90	4	57	38.65460085	
	P-MultiProject_90_5	MIP	Multi-Project Case	90	5	69	43.95874473	
	P-MultiProject_90_6	MIP	Multi-Project Case	90	6	63	39.83051839	
	P-MultiProject_90_7	MIP	Multi-Project Case	90	7	52	36.05089349	
	P-MultiProject_90_8	MIP	Multi-Project Case	90	8	54	37.64176625	
	P-MultiProject_90_9	MIP	Multi-Project Case	90	9	67	41.46633183	
MI	P-MultiProject_120_1	MIP	Multi-Project Case	120	1	118	35	
	P-MultiProject_120_10	MIP	Multi-Project Case	120	10	175	33.59646636	
	P-MultiProject_120_11	MIP	Multi-Project Case	120	11	58	30	
	P-MultiProject_120_12	MIP	Multi-Project Case	120	12	132	33	
MI	P-MultiProject_120_13	MIP	Multi-Project Case	120	13	149	46.02206268	
MI	P-MultiProject_120_14	MIP	Multi-Project Case	120	14	165	35.5618358	
MI	P-MultiProject_120_15	MIP	Multi-Project Case	120	15	76	30	
MI	P-MultiProject_120_2	MIP	Multi-Project Case	120	2	99	30	
	P-MultiProject_120_3	MIP	Multi-Project Case	120	3	150	39	
MI	P-MultiProject_120_4	MIP	Multi-Project Case	120	4	53	30	
MI	P-MultiProject_120_5	MIP	Multi-Project Case	120	5	69	35	
MI	P-MultiProject_120_6	MIP	Multi-Project Case	120	6	56	27	
MI	P-MultiProject_120_7	MIP	Multi-Project Case	120	7	110	39.22162996	
MI	P-MultiProject_120_8	MIP	Multi-Project Case	120	8	58	26	
MI	P-MultiProject_120_9	MIP	Multi-Project Case	120	9	75	29	
MI	P-MultiProject_150_1	MIP	Multi-Project Case	150	1	161	31	
MI	P-MultiProject_150_10	MIP	Multi-Project Case	150	10	73	33.11055313	
MI	P-MultiProject_150_11	MIP	Multi-Project Case	150	11	71	29	
MI	P-MultiProject_150_12	MIP	Multi-Project Case	150	12	135	37.56741542	
MI	P-MultiProject_150_13	MIP	Multi-Project Case	150	13	128	30	
	P-MultiProject_150_14	MIP	Multi-Project Case	150	14	134	35	
MI	P-MultiProject_150_15	MIP	Multi-Project Case	150	15	66	32	
MI	P-MultiProject_150_2	MIP	Multi-Project Case	150	2	98	37	
	P-MultiProject_150_3	MIP	Multi-Project Case	150	3	248	29	
	P-MultiProject_150_4	MIP	Multi-Project Case	150	4	126	32	
	P-MultiProject_150_5	MIP	Multi-Project Case	150	5	112	31.32498581	
	P-MultiProject_150_6	MIP	Multi-Project Case	150	6	112	33	
	P-MultiProject_150_7	MIP	Multi-Project Case	150	7	81	28	
	-MultiProject_150_7 P-MultiProject 150 8	MIP	Multi-Project Case	150	8	73	32	
MI								

CP ... Constraint Programming MIP ... Mixed Integer Programming Id ... Identification number of instance

T ... Maximum allowed computation time exploited (3.600 seconds) bold characters ... optimal solution found

E. Online appendix: Optimization results for the RCMPSP-ACTF

On the following pages, we present the detailed examination of all designed benchmark instances for the newly developed resource-constrained multi-project scheduling problem with alternative activity chains and time flexibility (RCMPSP-ACTF). The columns in Table E.1 give (1) the name of every instance, (2) the solver (MIP or CP) which has been applied, (3) the considered amount of nodes, (4) the demand patterns real-world (rw) or random (rand), (5) an identification number from 1-5 per project and node case, (6) the considered objective function, (7) the best objective value found, (8) the best bound found, and (9) the runtime in seconds. Bold letters represent the optimal solution.

	Opti	mization	rea	uns ioi	the nom	51-AU11	Runtime
Instance	Solver	Nodes Demand	l Id	Objective	Best objective	Best bound	(seconds)
l10-rand-0,25-1_160_CP	CP	10 rand	1	makespan	39	39	0.03
l10-rand-0,25-2_163_CP	CP	10 rand	2	makespan	29	29	0.03
l10-rand-0,25-3_158_CP	CP	10 rand		makespan	31	31	0.03
110-rand-0,25-4_163_CP	CP CP	10 rand 10 rand		makespan	33 37	33 37	0.03
l10-rand-0,25-5_167_CP l10-rand-0,5-1_160_CP	CP	10 rand		makespan makespan	37	37	0.03
110-rand-0,5-2_163_CP	CP	10 rand		makespan makespan	29	29	0.03
l10-rand-0,5-3_158_CP	CP	10 rand		makespan	31	31	0.03
l10-rand-0,5-4_163_CP	CP	10 rand		makespan	33	33	0.03
l10-rand-0,5-5_167_CP	CP	10 rand		makespan	37	37	0.03
110-rand-0,75-1_160_CP	CP	10 rand		makespan	39	39	0.03
l10-rand-0,75-2_163_CP l10-rand-0,75-3_158_CP	CP CP	10 rand 10 rand		makespan makespan	29 31	29 31	0.03
110-rand-0.75-4 163 CP	CP	10 rand		makespan	31	33	0.03
l10-rand-0,75-5_167_CP	CP	10 rand		makespan	37	37	0.03
l10-rand-1-1_160_CP	CP	10 rand	1	makespan	39	39	0.03
l10-rand-1-2_163_CP	CP	10 rand	2	makespan	29	29	0.03
l10-rand-1-3_158_CP	CP	10 rand		makespan	31	31	0.03
110-rand-1-4_163_CP	CP	10 rand		makespan	33	33	0.03
l10-rand-1-5_167_CP l10-rw-0,25-1_160_CP	CP CP	10 rand 10 rw		makespan makespan	37 39	37 39	0.03
110-rw-0,25-2_163_CP	CP	10 rw 10 rw		makespan makespan	29	29	0.02
110-rw-0.25-3 158 CP	CP	10 rw		makespan makespan	31	31	0.02
l10-rw-0,25-4_163_CP	CP	10 rw	4	makespan	33	33	0.02
l10-rw-0,25-5_167_CP	CP	10 rw	5	makespan	37	37	0.02
l10-rw-0,5-1_160_CP	CP	10 rw		makespan	39	39	0.02
l10-rw-0,5-2_163_CP	CP	10 rw		makespan	29	29	0.02
110-rw-0,5-3_158_CP	CP	10 rw		makespan	31	31	0.02
110-rw-0,5-4_163_CP	CP CP	10 rw 10 rw		makespan	33 37	33 37	0.02
l10-rw-0,5-5_167_CP l10-rw-0,75-1_160_CP	CP	10 rw		makespan makespan	37	37	0.02
l10-rw-0,75-2_163_CP	CP	10 rw		makespan	29	29	0.02
l10-rw-0,75-3_158_CP	CP	10 rw	3	makespan	31	31	0.02
l10-rw-0,75-4_163_CP	CP	10 rw	4	makespan	33	33	0.02
l10-rw-0,75-5_167_CP	CP	10 rw		makespan	37	37	0.02
l10-rw-1-1_160_CP	CP	10 rw		makespan	39	39	0.02
110-rw-1-2_163_CP	CP	10 rw		makespan	29	29	0.02
l10-rw-1-3_158_CP l10-rw-1-4_163_CP	CP CP	10 rw 10 rw		makespan makespan	31 33	31 33	0.02
110-rw-1-5_167_CP	CP	10 rw		makespan	33	33	0.02
l50-rand-0,25-1_768_CP	CP	50 rand		makespan	72	72	0.13
l50-rand-0,25-2_803_CP	CP	50 rand	2	makespan	75	75	0.14
l50-rand-0,25-3_803_CP	CP	50 rand		makespan	70	70	0.13
150-rand-0,25-4_823_CP	CP	50 rand		makespan	80	80	0.13
150-rand-0,25-5_787_CP	CP	50 rand		makespan	74	74	0.13
l50-rand-0,5-1_768_CP l50-rand-0,5-2_803_CP	CP CP	50 rand 50 rand		makespan makespan	72 75	72 75	0.13 0.13
150-rand-0,5-3_803_CP	CP	50 rand		makespan	73	73	0.13
150-rand-0,5-4_823_CP	CP	50 rand		makespan	80	80	0.13
l50-rand-0,5-5_787_CP	CP	50 rand	5	makespan	74	74	0.13
l50-rand-0,75-1_768_CP	CP	50 rand	1	makespan	72	72	0.13
l50-rand-0,75-2_803_CP	CP	50 rand		makespan	75	75	0.13
150-rand-0,75-3_803_CP	CP CP	50 rand 50 rand		makespan	70 80	70 80	0.13 0.13
l50-rand-0,75-4_823_CP l50-rand-0,75-5_787_CP	CP	50 rand 50 rand		makespan makespan	80 74	80 74	0.13
150-rand-1-1_768_CP	CP	50 rand		makespan makespan	74	74	0.13
150-rand-1-2_803_CP	CP	50 rand		makespan	75	75	0.14
l50-rand-1-3_803_CP	CP	50 rand	3	makespan	70	70	0.13
l50-rand-1-4_823_CP	CP	50 rand		makespan	80	80	0.14
l50-rand-1-5_787_CP	CP	50 rand		makespan	74	74	0.13
l50-rw-0,25-1_768_CP	CP	50 rw		makespan	72	72	0.07
l50-rw-0,25-2_803_CP l50-rw-0,25-3_803_CP	CP CP	50 rw 50 rw		makespan makespan	75 70	75 70	0.07 0.08
150-rw-0,25-4_823_CP	CP	50 rw		makespan	80	80	0.07
150-rw-0,25-5_787_CP	CP	50 rw		makespan	74	74	0.08
l50-rw-0,5-1_768_CP	CP	50 rw		makespan	72	72	0.07
150-rw-0,5-2_803_CP	CP	50 rw		makespan	75	75	0.07
150-rw-0,5-3_803_CP	CP	50 rw		makespan	70	70	0.08
150-rw-0,5-4_823_CP	CP	50 rw		makespan	80 74	80 74	0.07
l50-rw-0,5-5_787_CP l50-rw-0,75-1_768_CP	CP CP	50 rw 50 rw		makespan makespan	74 72	74 72	0.08
150-rw-0,75-1_768_CP 150-rw-0,75-2_803_CP	CP	50 rw 50 rw		makespan makespan	72	72	0.08
150-rw-0,75-3_803_CP	CP	50 rw		makespan	73	70	0.09
150-rw-0,75-4_823_CP	CP	50 rw		makespan	80	80	0.07
150-rw-0,75-5_787_CP	CP	50 rw		makespan	74	74	0.07
l50-rw-1-1_768_CP	CP	50 rw	1	makespan	72	72	0.07

Table E.1: Optimization results for the RCMPSP-ACTF for every instance.

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Instance	Solver	Nodes	Demand	Id	Objective	Best objective	Best bound	Runtime (seconds)
l50-rw-1-2_803_CP	CP	50	rw	2	makespan	75	75	0.0
l50-rw-1-3_803_CP	CP	50	rw	3	makespan	70	70	0.0
l50-rw-1-4_823_CP	CP	50	rw	4	makespan	80	80	0.0
l50-rw-1-5_787_CP	CP	50	rw		makespan	74	74	0.0
1100-rand-0.25-1 1557 CP	CP	100	rand		makespan	125	125	0.2
1100-rand-0,25-2_1605_CP	CP		rand		makespan	123	123	0.2
l100-rand-0,25-3_1580_CP	CP		rand		makespan	128	128	0.2
l100-rand-0,25-4_1649_CP	CP		rand		makespan	129	129	0.2
l100-rand-0,25-5_1573_CP	CP	100	rand	5	makespan	122	122	0.3
l100-rand-0,5-1_1557_CP	CP	100	rand	1	makespan	125	125	0.2
1100-rand-0,5-2_1605_CP	CP	100	rand		makespan	121	121	0.2
1100-rand-0,5-3_1580_CP	CP		rand		makespan	128	128	0.2
l100-rand-0,5-4_1649_CP	CP		rand		makespan	129	129	0.2
l100-rand-0,5-5_1573_CP	CP		rand		makespan	122	122	0.2
l100-rand-0,75-1_1557_CP	CP	100	rand	1	makespan	125	125	0.2
1100-rand-0,75-2_1605_CP	CP	100	rand	2	makespan	121	121	0.2
1100-rand-0,75-3_1580_CP	CP	100	rand	3	makespan	128	128	0.2
1100-rand-0,75-4_1649_CP	CP		rand		makespan	129	129	0.2
l100-rand-0,75-5_1573_CP	CP		rand		makespan	122	122	0.2
l100-rand-1-1_1557_CP	CP		rand		makespan	125	125	0.2
1100-rand-1-2_1605_CP	CP	100	rand	2	makespan	121	121	0.2
1100-rand-1-3_1580_CP	CP	100	rand	3	makespan	128	128	0.2
1100-rand-1-4_1649_CP	CP		rand		makespan	129	129	0.3
1100-rand-1-5_1573_CP	CP		rand		makespan	123	122	0.2
	CP	100					122	0.1
l100-rw-0,25-1_1557_CP					makespan	125		
l100-rw-0,25-2_1605_CP	CP	100	rw	2	makespan	121	121	0.1
l100-rw-0,25-3_1580_CP	CP	100	rw	3	makespan	128	128	0.1
l100-rw-0,25-4_1649_CP	CP	100	rw	4	makespan	129	129	0.1
l100-rw-0,25-5_1573_CP	CP	100		5	makespan	122	122	0.1
1100-rw-0,5-1_1557_CP	CP	100			makespan	125	125	0.1
l100-rw-0,5-2_1605_CP	CP	100			makespan	121	121	0.1
l100-rw-0,5-3_1580_CP	CP	100		3	makespan	128	128	0.1
l100-rw-0,5-4_1649_CP	CP	100	rw	4	makespan	129	129	0.1
l100-rw-0,5-5_1573_CP	CP	100	rw	5	makespan	122	122	0.1
1100-rw-0.75-1 1557 CP	CP	100	rw		makespan	125	125	0.1
1100-rw-0,75-2_1605_CP	CP	100			makespan	123	123	0.1
l100-rw-0,75-3_1580_CP	CP	100			makespan	128	128	0.1
l100-rw-0,75-4_1649_CP	CP	100			makespan	129	129	0.1
l100-rw-0,75-5_1573_CP	CP	100	rw	5	makespan	122	122	0.1
l100-rw-1-1_1557_CP	CP	100	rw	1	makespan	125	125	0.1
1100-rw-1-2_1605_CP	CP	100	rw	2	makespan	121	121	0.1
1100-rw-1-3_1580_CP	CP	100			makespan	121	121	0.1
l100-rw-1-4_1649_CP	CP	100			makespan	129	129	0.1
l100-rw-1-5_1573_CP	CP	100	rw	5	makespan	122	122	0.1
l10-rand-0,25-1_160_CP	CP	10	rand	1	timebalance	4	4	0.1
110-rand-0,25-2_163_CP	CP	10	rand	2	timebalance	2	2	0.1
110-rand-0,25-3_158_CP	CP		rand	_	timebalance	3	3	0.1
110-rand-0,25-4_163_CP	CP		rand		timebalance	3	3	0.1
110-rand-0,25-5_167_CP	CP		rand		timebalance	3	3	0.1
110-rand-0,5-1_160_CP	CP	10	rand	1	timebalance	4	4	0.1
110-rand-0,5-2_163_CP	CP		rand		timebalance	2	2	0.0
110-rand-0,5-3_158_CP	CP		rand		timebalance	3	3	0.1
	CP		rand		timebalance	3	3	0.0
l10-rand-0,5-4_163_CP						-	-	
l10-rand-0,5-5_167_CP	CP		rand		timebalance	3	3	0.1
l10-rand-0,75-1_160_CP	CP	10	rand	1	timebalance	4	4	0.1
110-rand-0,75-2_163_CP	CP	10	rand	2	timebalance	2	2	0.1
110-rand-0.75-3 158 CP	CP	10	rand	3	timebalance	3	3	0.1
110-rand-0,75-4_163_CP	CP		rand		timebalance	3	3	0.0
	-							
l10-rand-0,75-5_167_CP	CP		rand		timebalance	3	3	0.1
l10-rand-1-1_160_CP	CP		rand	-	timebalance	4	4	0.1
110-rand-1-2_163_CP	CP	10	rand	2	timebalance	2	2	0.1
110-rand-1-3_158_CP	CP	10	rand	3	timebalance	3	3	0.1
110-rand-1-4_163_CP	CP		rand		timebalance	3	3	0.0
				-				
110-rand-1-5_167_CP	CP		rand		timebalance	3	3	0.1
l10-rw-0,25-1_160_CP	CP		rw		timebalance	4	4	0.0
110-rw-0,25-2_163_CP	CP	10	rw	2	timebalance	2	2	0.0
l10-rw-0,25-3_158_CP	CP	10	rw	3	timebalance	3	3	0.0
110-rw-0,25-4_163_CP	CP	10	rw	4	timebalance	3	3	0.0
110-rw-0,25-5_167_CP	CP	10			timebalance	3	3	0.0
l10-rw-0,5-1_160_CP	CP	10			timebalance	4	4	0.0
110-rw-0,5-2_163_CP	CP	10	rw	2	timebalance	2	2	0.0
110-rw-0,5-3_158_CP	CP	10	rw	3	timebalance	3	3	0.0
110-rw-0,5-4_163_CP	CP	10			timebalance	3	3	0.0
110-rw-0,5-5_167_CP								
	CP	10	гW	5	timebalance	3	3	0.0
110-rw-0,75-1_160_CP 110-rw-0,75-2_163_CP	CP CP	10 10		-	timebalance timebalance	4 2	4 2	0.0

Instance	Solver	Nodes Demand		Best objective	Best bound	Runtime (seconds)
10-rw-0,75-3_158_CP	CP	10 rw	3 timebalance	3	3	0.0
10-rw-0,75-4_163_CP	CP	10 rw	4 timebalance	3	3	0.0
10-rw-0,75-5_167_CP	CP	10 rw	5 timebalance	3	3	0.0
10-rw-1-1_160_CP	CP	10 rw	1 timebalance	4	4	0.0
10-rw-1-2_163_CP	CP	10 rw	2 timebalance	2	2	0.0
10-rw-1-3_158_CP	CP	10 rw	3 timebalance	3	3	0.0
10-rw-1-4_163_CP	CP	10 rw	4 timebalance	3	3	0.0
10-rw-1-5_167_CP	CP	10 rw	5 timebalance	3	3	0.0
50-rand-0,25-1_768_CP	CP	50 rand	1 timebalance	4	4	0.5
50-rand-0,25-2_803_CP	CP	50 rand	2 timebalance	4	4	0.5
50-rand-0.25-3 803 CP	CP	50 rand	3 timebalance	4	4	0.6
50-rand-0,25-4_823_CP	CP	50 rand	4 timebalance	4	4	0.5
50-rand-0,25-5_787_CP	CP	50 rand	5 timebalance	4	4	0.5
50-rand-0.5-1 768 CP	CP	50 rand	1 timebalance	4	4	0.5
150-rand-0,5-2_803_CP	CP	50 rand	2 timebalance	4	4	0.5
50-rand-0,5-3_803_CP	CP	50 rand	3 timebalance	4	4	
	CP	50 rand				0.5
50-rand-0,5-4_823_CP			4 timebalance	4	4	0.6
50-rand-0,5-5_787_CP	CP	50 rand	5 timebalance	4	4	0.5
50-rand-0,75-1_768_CP	CP	50 rand	1 timebalance	4	4	0.5
50-rand-0,75-2_803_CP	CP	50 rand	2 timebalance	4	4	0.5
50-rand-0,75-3_803_CP	CP	50 rand	3 timebalance	4	4	0.5
50-rand-0,75-4_823_CP	CP	50 rand	4 timebalance	4	4	0.6
50-rand-0,75-5_787_CP	CP	50 rand	5 timebalance	4	4	0.5
50-rand-1-1_768_CP	CP	50 rand	1 timebalance	4	4	0.5
50-rand-1-2 803 CP	CP	50 rand	2 timebalance	4	4	0.5
50-rand-1-3_803_CP	CP	50 rand	3 timebalance	4	4	0.5
50-rand-1-4_823_CP	CP	50 rand	4 timebalance	4	4	0.5
50-rand-1-5 787 CP	CP	50 rand	5 timebalance	4	4	0.5
	CP	50 ranu 50 rw				
50-rw-0,25-1_768_CP			1 timebalance	4	4	0.5
50-rw-0,25-2_803_CP	CP	50 rw	2 timebalance	4	4	0.4
50-rw-0,25-3_803_CP	CP	50 rw	3 timebalance	4	4	0.6
50-rw-0,25-4_823_CP	CP	50 rw	4 timebalance	4	4	0.5
50-rw-0,25-5_787_CP	CP	50 rw	5 timebalance	4	4	0.5
50-rw-0,5-1_768_CP	CP	50 rw	1 timebalance	4	4	0.5
50-rw-0,5-2_803_CP	CP	50 rw	2 timebalance	4	4	0.5
50-rw-0,5-3_803_CP	CP	50 rw	3 timebalance	4	4	0.0
50-rw-0,5-4_823_CP	CP	50 rw	4 timebalance	4	4	0.5
50-rw-0,5-5_787_CP	CP	50 rw	5 timebalance	4	4	0.5
50-rw-0,75-1_768_CP	CP	50 rw	1 timebalance	4	4	0.4
50-rw-0,75-2_803_CP	CP	50 rw	2 timebalance	4	4	0.5
50-rw-0,75-3_803_CP	CP	50 rw	3 timebalance	4	4	0.0
50-rw-0.75-4 823 CP	CP	50 rw	4 timebalance	4	4	0.6
	CP	50 rw		-		
50-rw-0,75-5_787_CP			5 timebalance	4	4	0.5
50-rw-1-1_768_CP	CP	50 rw	1 timebalance	4	4	0.5
50-rw-1-2_803_CP	CP	50 rw	2 timebalance	4	4	0.4
50-rw-1-3_803_CP	CP	50 rw	3 timebalance	4	4	0.6
50-rw-1-4_823_CP	CP	50 rw	4 timebalance	4	4	0.6
50-rw-1-5_787_CP	CP	50 rw	5 timebalance	4	4	0.5
100-rand-0,25-1_1557_CP	CP	100 rand	1 timebalance	4	4	1.5
100-rand-0,25-2_1605_CP	CP	100 rand	2 timebalance	4	4	1.5
100-rand-0,25-3_1580_CP	CP	100 rand	3 timebalance	4	4	1.9
100-rand-0,25-4_1649_CP	CP	100 rand	4 timebalance	5	5	1.8
100-rand-0,25-5_1573_CP	CP	100 rand	5 timebalance	5	5	1.5
100-rand-0,2-3-3_1575_CP	CP	100 rand	1 timebalance	4	4	1.
100-rand-0,5-2_1605_CP	CP	100 rand	2 timebalance	4	4	2.0
100-rand-0,5-2_1605_CP 100-rand-0.5-3 1580 CP	CP	100 rand	2 timebalance 3 timebalance	4	4	2.1
100-rand-0,5-3_1580_CP 100-rand-0,5-4_1649_CP	CP	100 rand 100 rand	3 timebalance 4 timebalance	4 5	4 5	1.
100-rand-0,5-5_1573_CP	CP	100 rand	5 timebalance	5	5	1.
100-rand-0,75-1_1557_CP	CP	100 rand	1 timebalance	4	4	1.1
100-rand-0,75-2_1605_CP	CP	100 rand	2 timebalance	4	4	1.4
100-rand-0,75-3_1580_CP	CP	100 rand	3 timebalance	4	4	1.0
100-rand-0,75-4_1649_CP	CP	100 rand	4 timebalance	5	5	1.4
100-rand-0,75-5_1573_CP	CP	100 rand	5 timebalance	5	5	1.3
100-rand-1-1_1557_CP	CP	100 rand	1 timebalance	4	4	1.1
100-rand-1-2_1605_CP	CP	100 rand	2 timebalance	4	4	1.4
100-rand-1-3_1580_CP	CP	100 rand	3 timebalance	4	4	1.
100-rand-1-4_1649_CP	CP	100 rand	4 timebalance	5	5	1.
100-rand-1-5_1573_CP	CP	100 rand	5 timebalance	5	5	1.1
	CP	100 rand 100 rw				
100-rw-0,25-1_1557_CP			1 timebalance	4	4	10.
100-rw-0,25-2_1605_CP	CP	100 rw	2 timebalance	4	4	1.9
100-rw-0,25-3_1580_CP	CP	100 rw	3 timebalance	4	4	28.3
100-rw-0,25-4_1649_CP	CP	100 rw	4 timebalance	5	5	5.
100-rw-0,25-5_1573_CP	CP	100 rw	5 timebalance	5	5	10.1
100-rw-0,5-1_1557_CP	CP	100 rw	1 timebalance	4	4	47.8
100-rw-0,5-2_1605_CP	CP	100 rw	2 timebalance	4	4	15.

Instance	Solver		Demand	Id	Objective	Best objective	Best bound	Runtime (seconds)	
100-rw-0,5-4_1649_CP	CP	100			timebalance	5	5	2.03	
100-rw-0,5-5_1573_CP	CP	100		5	timebalance	5	5	6.83	
l100-rw-0,75-1_1557_CP l100-rw-0,75-2_1605_CP	CP CP	100 100		-	timebalance timebalance	4 4	4	186.91 2.09	
1100-rw-0,75-3_1580_CP	CP	100			timebalance	4	4	2.09	
1100-rw-0,75-4_1649_CP	CP	100			timebalance	5	5	1.67	
100-rw-0,75-5_1573_CP	CP	100			timebalance	5	5	18.54	
100-rw-1-1_1557_CP	CP	100			timebalance	4	4	21.33	
1100-rw-1-2_1605_CP	CP	100			timebalance	4	4	16.60	
100-rw-1-3_1580_CP	CP	100	rw	3	timebalance	4	4	1.52	
100-rw-1-4_1649_CP	CP	100	rw	4	timebalance	5	5	2.01	
1100-rw-1-5_1573_CP	CP	100	rw	5	timebalance	5	5	3.34	
110-rand-0,25-1_160_CP	CP		rand	1	loadbalance	0.571429	0.571429	339.89	
110-rand-0,25-2_163_CP	CP	10	rand	2	loadbalance	0.614286	0.614286	146.76	
110-rand-0,25-3_158_CP	CP	10	rand	3	loadbalance	0.633803	0.633803	238.99	
110-rand-0,25-4_163_CP	CP	10	rand		loadbalance	0.60274	0.60274	524.80	
110-rand-0,25-5_167_CP	CP		rand		loadbalance	0.597403	0.597403	426.21	
110-rand-0,5-1_160_CP	CP	10	rand	1	loadbalance	0.415094	0.415094	144.90	
110-rand-0,5-2_163_CP	CP	10	rand	2	loadbalance	0.452632	0.452632	172.13	
10-rand-0,5-3_158_CP	CP		rand		loadbalance	0.463918	0.463918	244.66	
10-rand-0,5-4_163_CP	CP		rand		loadbalance	0.438776	0.438776	291.07	
10-rand-0,5-5_167_CP	CP		rand		loadbalance	0.425926	0.425926	888.89	
10-rand-0,75-1_160_CP	CP		rand		loadbalance	0.323529	0.323529	201.64	
110-rand-0,75-2_163_CP	CP		rand		loadbalance	0.358333	0.358333	288.08	
110-rand-0,75-3_158_CP	CP		rand		loadbalance	0.366667	0.366667	372.53	
110-rand-0,75-4_163_CP	CP		rand		loadbalance	0.34375	0.34375	259.90	
10-rand-0,75-5_167_CP	CP		rand		loadbalance	0.330935	0.330935	289.32	
110-rand-1-1_160_CP	CP		rand	-	loadbalance	0.26506	0.26506	402.17	
110-rand-1-2_163_CP	CP		rand		loadbalance	0.296552	0.296552	151.17	
110-rand-1-3_158_CP	CP		rand		loadbalance	0.303448	0.303448	255.18	
110-rand-1-4_163_CP	CP		rand		loadbalance	0.283871	0.283871	721.19	
110-rand-1-5_167_CP	CP		rand		loadbalance	0.272109	0.272109	527.45	
110-rw-0,25-1_160_CP	CP	10		1	loadbalance	0.333333	0.333333	0.52	
10-rw-0,25-2_163_CP	CP	10			loadbalance	0.3333333	0.333333	0.53	
10-rw-0,25-3_158_CP	CP CP	10 10			loadbalance loadbalance	0.3333333	0.333333	0.37	
10-rw-0,25-4_163_CP 10-rw-0,25-5_167_CP	CP	10			loadbalance	0.5 0.333333	0.5 0.333333	0.12	
10-rw-0,25-5_167_CP 10-rw-0.5-1 160 CP	CP	10				0.285714	0.285714	0.53	
	CP	10			loadbalance loadbalance	0.285714	0.285714 0.285714	0.40	
10-rw-0,5-2_163_CP 10-rw-0,5-3_158_CP	CP	10		_	loadbalance	0.285714	0.285714	0.76	
110-rw-0,5-3_158_CP 110-rw-0,5-4_163_CP	CP	10			loadbalance	0.285714	0.4285714	0.73	
110-rw-0,5-5_167_CP	CP	10			loadbalance	0.285714	0.285714	0.56	
10-rw-0,75-1 160 CP	CP	10			loadbalance	0.283714	0.283714	0.30	
110-rw-0,75-2_163_CP	CP	10		-	loadbalance	0.25	0.25	0.55	
110-rw-0,75-3_158_CP	CP	10			loadbalance	0.25	0.25	1.00	
10-rw-0,75-4_163_CP	CP	10			loadbalance	0.375	0.375	0.52	
10-rw-0,75-5_167_CP	CP	10			loadbalance	0.25	0.25	0.44	
10-rw-1-1_160_CP	CP	10			loadbalance	0.25	0.25	0.86	
10-rw-1-2_163_CP	CP	10		-	loadbalance	0.25	0.25	1.10	
10-rw-1-3_158_CP	CP	10			loadbalance	0.25	0.25	2.67	
10-rw-1-4 163 CP	CP	10			loadbalance	0.333333	0.3333333	0.90	
110-rw-1-5_167_CP	CP	10			loadbalance	0.333333	0.25	3.70	
50-rand-0,25-1_768_CP	CP		rand		loadbalance	0.548387	0.210327	1	
150-rand-0,25-2_803_CP	CP		rand		loadbalance	0.554217	0.200357	т	
50-rand-0,25-3_803_CP	CP		rand		loadbalance	0.586826	0.213456	Т	
50-rand-0,25-4_823_CP	CP		rand		loadbalance	0.532544	0.193621	Т	
50-rand-0,25-5_787_CP	CP	50	rand	5	loadbalance	0.541667	0.197566	т	
50-rand-0,5-1_768_CP	CP		rand		loadbalance	0.472826	0.176667	Т	
50-rand-0,5-2_803_CP	CP	50	rand	2	loadbalance	0.462687	0.168552	т	
50-rand-0,5-3_803_CP	CP	50	rand	3	loadbalance	0.482927	0.179592	Т	
50-rand-0,5-4_823_CP	CP	50	rand	4	loadbalance	0.450495	0.162887	Т	
50-rand-0,5-5_787_CP	CP	50	rand	5	loadbalance	0.458537	0.168001	Т	
50-rand-0,75-1_768_CP	CP	50	rand	1	loadbalance	0.403756	0.152312	т	
50-rand-0,75-2_803_CP	CP	50	rand	2	loadbalance	0.394737	0.145418	Т	
50-rand-0,75-3_803_CP	CP	50	rand	3	loadbalance	0.416667	0.154862	Т	
50-rand-0,75-4_823_CP	CP		rand		loadbalance	0.391489	0.140582	Т	
50-rand-0,75-5_787_CP	CP	50	rand	5	loadbalance	0.402715	0.145789	Т	
50-rand-1-1_768_CP	CP	50	rand	1	loadbalance	0.352941	0.133864	Т	
I50-rand-1-2_803_CP	CP		rand	_	loadbalance	0.338521	0.128168	Т	
50-rand-1-3_803_CP	CP		rand		loadbalance	0.360153	0.136294	Т	
50-rand-1-4_823_CP	CP	50	rand	4	loadbalance	0.339552	0.123717	Т	
50-rand-1-5_787_CP	CP	50	rand	5	loadbalance	0.357143	0.129285	Т	
50-rw-0,25-1_768_CP	CP	50		-	loadbalance	0.266667	0.133333	Т	
50-rw-0,25-2_803_CP	CP	50			loadbalance	0.25	0.125	Т	
							0.405		
150-rw-0,25-3_803_CP	CP	50	rw	- 3	loadbalance	0.25	0.125	Т	

Instance	Solver	Nodes	Demand	Id	Objective	Best objective	Best bound	Runtime (seconds)
50-rw-0,25-5_787_CP	CP	50			loadbalance	0.25	0.125	
50-rw-0,5-1_768_CP	CP	50			loadbalance	0.25	0.133333	
50-rw-0,5-2_803_CP	CP	50	rw	2	loadbalance	0.235294	0.125	
50-rw-0,5-3_803_CP	CP	50	rw	3	loadbalance	0.235294	0.125	
50-rw-0,5-4_823_CP	CP	50	rw	4	loadbalance	0.235294	0.125	
50-rw-0,5-5_787_CP	CP	50	rw	5	loadbalance	0.235294	0.125	
50-rw-0,75-1_768_CP	CP	50	rw	1	loadbalance	0.235294	0.133333	
50-rw-0.75-2 803 CP	CP	50	rw		loadbalance	0.222222	0.125	
50-rw-0,75-3_803_CP	CP	50	rw	3	loadbalance	0.222222	0.125	
50-rw-0,75-4_823_CP	CP	50	rw		loadbalance	0.222222	0.125	
50-rw-0,75-5_787_CP	CP	50			loadbalance	0.222222	0.125	
50-rw-1-1 768 CP	CP	50			loadbalance	0.2222222	0.1333333	
	CP	50		-				
50-rw-1-2_803_CP					loadbalance	0.210526	0.125	
50-rw-1-3_803_CP	CP	50			loadbalance	0.210526	0.125	
50-rw-1-4_823_CP	CP	50		-	loadbalance	0.210526	0.125	
50-rw-1-5_787_CP	CP	50			loadbalance	0.210526	0.125	
100-rand-0,25-1_1557_CP	CP	100	rand	1	loadbalance	0.554286	0.244761	
100-rand-0,25-2_1605_CP	CP	100	rand	2	loadbalance	0.565714	0.254743	
100-rand-0,25-3_1580_CP	CP	100	rand	3	loadbalance	0.586592	0.238098	
100-rand-0,25-4_1649_CP	CP	100	rand	4	loadbalance	0.550562	0.233447	
100-rand-0,25-5_1573_CP	CP		rand		loadbalance	0.560694	0.251437	
100-rand-0,5-1_1557_CP	CP		rand		loadbalance	0.487805	0.208326	
100-rand-0,5-2_1605_CP	CP		rand		loadbalance	0.487803	0.216216	
	CP		rand rand		loadbalance	0.5	0.216216	
100-rand-0,5-3_1580_CP								
100-rand-0,5-4_1649_CP	CP		rand		loadbalance	0.473934	0.197304	
100-rand-0,5-5_1573_CP	CP		rand		loadbalance	0.477612	0.215531	
100-rand-0,75-1_1557_CP	CP		rand		loadbalance	0.414938	0.181234	
100-rand-0,75-2_1605_CP	CP	100	rand	2	loadbalance	0.418803	0.18762	
100-rand-0,75-3_1580_CP	CP	100	rand	3	loadbalance	0.422594	0.175258	
100-rand-0,75-4_1649_CP	CP	100	rand	4	loadbalance	0.404255	0.170982	
100-rand-0,75-5_1573_CP	CP	100	rand	5	loadbalance	0.411523	0.188082	
100-rand-1-1_1557_CP	CP	100	rand	1	loadbalance	0.364662	0.160552	
100-rand-1-2_1605_CP	CP		rand		loadbalance	0.369403	0.166089	
100-rand-1-3_1580_CP	CP		rand		loadbalance	0.362963	0.154981	
	CP		rand		loadbalance	0.355072	0.150907	
100-rand-1-4_1649_CP	CP		rand					
100-rand-1-5_1573_CP					loadbalance	0.372093	0.167529	
100-rw-0,25-1_1557_CP	CP	100			loadbalance	0.294118	0.117647	
100-rw-0,25-2_1605_CP	CP	100		2	loadbalance	0.235294	0.117647	
100-rw-0,25-3_1580_CP	CP	100	rw	3	loadbalance	0.294118	0.117647	
100-rw-0,25-4_1649_CP	CP	100	rw	4	loadbalance	0.294118	0.117647	
100-rw-0,25-5_1573_CP	CP	100	rw	5	loadbalance	0.294118	0.117647	
100-rw-0,5-1_1557_CP	CP	100	rw	1	loadbalance	0.277778	0.117647	
100-rw-0,5-2_1605_CP	CP	100	rw	2	loadbalance	0.277778	0.117647	
100-rw-0,5-3_1580_CP	CP	100	rw	3	loadbalance	0.235294	0.117647	
100-rw-0,5-4_1649_CP	CP	100			loadbalance	0.235294	0.117647	
	CP	100			loadbalance	0.233234	0.117647	
100-rw-0,5-5_1573_CP								
100-rw-0,75-1_1557_CP	CP	100			loadbalance	0.263158	0.117647	
100-rw-0,75-2_1605_CP	CP	100			loadbalance	0.235294	0.117647	
100-rw-0,75-3_1580_CP	CP	100			loadbalance	0.235294	0.117647	
100-rw-0,75-4_1649_CP	CP	100		4	loadbalance	0.263158	0.117647	
100-rw-0,75-5_1573_CP	CP	100		5	loadbalance	0.263158	0.117647	
100-rw-1-1_1557_CP	CP	100	rw	1	loadbalance	0.25	0.117647	
100-rw-1-2_1605_CP	CP	100			loadbalance	0.25	0.117647	
100-rw-1-3_1580_CP	CP	100			loadbalance	0.25	0.117647	
100-rw-1-4_1649_CP	CP	100			loadbalance	0.25	0.117647	
100-rw-1-5_1573_CP	CP	100		-	loadbalance	0.25	0.117647	
100-rw-1-5_1575_CP 10-rand-0.25-1_160_MIP	MIP		rw rand		makespan	0.25 39	0.11/64/	8.
10-rand-0.25-2_163_MIP	MIP		rand		makespan	29	29	6.
10-rand-0.25-3_158_MIP	MIP		rand		makespan	31	31	6.
10-rand-0.25-4_163_MIP	MIP		rand		makespan	33	33	7.
10-rand-0.25-5_167_MIP	MIP	10	rand	5	makespan	37	37	8.
10-rand-0.5-1_160_MIP	MIP	10	rand	1	makespan	39	39	9.
10-rand-0.5-2_163_MIP	MIP	10	rand	2	makespan	29	29	6.
10-rand-0.5-3_158_MIP	MIP	10	rand	3	makespan	31	31	5.
10-rand-0.5-4_163_MIP	MIP	10	rand		makespan	33	33	5.
10-rand-0.5-5_167_MIP	MIP		rand		makespan	33	33	7.
	MIP		rand rand				37	
10-rand-0.75-1_160_MIP					makespan	39		7.
10-rand-0.75-2_163_MIP	MIP	10	rand		makespan	29	29	6.
10-rand-0.75-3_158_MIP	MIP		rand		makespan	31	31	5.
10-rand-0.75-4_163_MIP	MIP	10	rand	4	makespan	33	33	7.
10-rand-0.75-5_167_MIP	MIP	10	rand	5	makespan	37	37	8.
10-rand-1-1_160_MIP	MIP	10	rand		makespan	39	39	8.0
10-rand-1-2 163 MIP	MIP		rand		makespan	29	29	5.1
10.1000.1.7 ⁻¹ 102 ⁻¹⁰⁰				-		31	31	5.
10 rand 1 2 150 MID								
10-rand-1-3_158_MIP 10-rand-1-4_163_MIP	MIP MIP	10 10	rand rand		makespan makespan	31	31	7.

Instance	Solver	Nodes	Demand	Id	Objective	Best objective	Best bound	Runtime (seconds)
l10-rw-0.25-1_160_MIP	MIP	10	rw	1	makespan	39	39	7.9
l10-rw-0.25-2_163_MIP	MIP	10	rw		makespan	29	29	5.6
l10-rw-0.25-3_158_MIP	MIP	10	rw	3	makespan	31	31	6.2
l10-rw-0.25-4_163_MIP	MIP	10	rw	4	makespan	33	33	9.1
l10-rw-0.25-5_167_MIP	MIP	10	rw	5	makespan	37	37	8.4
l10-rw-0.5-1_160_MIP	MIP	10	rw	1	makespan	39	39	10.6
l10-rw-0.5-2_163_MIP	MIP	10	rw	2	makespan	29	29	7.1
110-rw-0.5-3_158_MIP	MIP	10	rw	3	makespan	31	31	7.5
l10-rw-0.5-4_163_MIP	MIP	10	rw	4	makespan	33	33	7.6
l10-rw-0.5-5_167_MIP	MIP	10	rw	5	makespan	37	37	7.9
l10-rw-0.75-1_160_MIP	MIP	10	rw	1	makespan	39	39	8.4
l10-rw-0.75-2_163_MIP	MIP	10	rw	2	makespan	29	29	5.8
l10-rw-0.75-3_158_MIP	MIP	10	rw	3	makespan	31	31	7.1
l10-rw-0.75-4_163_MIP	MIP	10	rw	4	makespan	33	33	8.7
l10-rw-0.75-5_167_MIP	MIP	10	rw	5	makespan	37	37	8.1
l10-rw-1-1_160_MIP	MIP	10	rw	1	makespan	39	39	7.7
l10-rw-1-2_163_MIP	MIP	10	rw	2	makespan	29	29	6.0
110-rw-1-3_158_MIP	MIP	10	rw	3	makespan	31	31	5.8
l10-rw-1-4_163_MIP	MIP	10	rw	4	makespan	33	33	8.3
l10-rw-1-5_167_MIP	MIP	10	rw	5	makespan	37	37	14.3
l50-rand-0.25-1_768_MIP	MIP	50	rand	1	makespan	72	72	211.9
l50-rand-0.25-2_803_MIP	MIP	50	rand	2	makespan	75	75	188.3
l50-rand-0.25-3_803_MIP	MIP	50	rand	3	makespan	70	70	188.5
l50-rand-0.25-4_823_MIP	MIP	50	rand	4	makespan	80	80	258.2
150-rand-0.25-5_787_MIP	MIP	50	rand	5	makespan	74	74	195.3
l50-rand-0.5-1_768_MIP	MIP	50	rand	1	makespan	72	72	221.7
150-rand-0.5-2_803_MIP	MIP	50	rand	2	makespan	75	75	241.7
150-rand-0.5-3_803_MIP	MIP	50	rand	3	makespan	70	70	199.2
150-rand-0.5-4_823_MIP	MIP	50	rand	4	makespan	80	80	238.1
150-rand-0.5-5_787_MIP	MIP	50	rand	5	makespan	74	74	200.5
150-rand-0.75-1_768_MIP	MIP	50	rand	1	makespan	72	72	265.7
150-rand-0.75-2_803_MIP	MIP	50	rand	2	makespan	75	75	216.8
150-rand-0.75-3_803_MIP	MIP	50	rand	3	makespan	70	70	185.9
150-rand-0.75-4_823_MIP	MIP	50	rand	4	makespan	80	80	277.1
150-rand-0.75-5_787_MIP	MIP	50	rand	5	makespan	74	74	196.8
150-rand-1-1_768_MIP	MIP	50	rand	1	makespan	72	72	174.0
150-rand-1-2_803_MIP	MIP	50	rand	2	makespan	75	75	210.3
150-rand-1-3_803_MIP	MIP	50	rand	3	makespan	70	70	185.2
150-rand-1-4_823_MIP	MIP	50	rand	4	makespan	80	80	263.9
150-rand-1-5_787_MIP	MIP	50	rand	5	makespan	74	74	266.5
	MIP	50	rw	1		/4	/4	200.3
150-rw-0.25-1_768_MIP					makespan			
150-rw-0.25-2_803_MIP	MIP	50	rw	2	makespan			
150-rw-0.25-3_803_MIP	MIP	50	rw	3	makespan	00	00	2,609.8
150-rw-0.25-4_823_MIP	MIP	50	rw	4	makespan	80	80	
150-rw-0.25-5_787_MIP	MIP	50	rw	5	makespan			2.400.2
150-rw-0.5-1_768_MIP	MIP	50	rw	1	makespan	72	72	2,199.2
150-rw-0.5-2_803_MIP	MIP	50	rw	2	makespan			
150-rw-0.5-3_803_MIP	MIP	50	rw	3	makespan	70	70	2 200 0
150-rw-0.5-4_823_MIP	MIP	50	rw	4	makespan	80	80	3,388.9
150-rw-0.5-5_787_MIP	MIP	50	rw	5	makespan	74	74	3,280.9
l50-rw-0.75-1_768_MIP	MIP	50	rw	1	makespan	72	72	3,538.8
150-rw-0.75-2_803_MIP	MIP	50	rw	2	makespan			
150-rw-0.75-3_803_MIP	MIP	50	rw	3	makespan			
150-rw-0.75-4_823_MIP	MIP	50	rw	4	makespan			
l50-rw-0.75-5_787_MIP	MIP	50	rw	5	makespan	74	74	3,011.9
l50-rw-1-1_768_MIP	MIP	50	rw	1	makespan	72	72	3,394.2
l50-rw-1-2_803_MIP	MIP	50	rw	2	makespan			
l50-rw-1-3_803_MIP	MIP	50	rw	3	makespan			-
l50-rw-1-4_823_MIP	MIP	50	rw	4	makespan			-
l50-rw-1-5_787_MIP	MIP	50	rw	5	makespan			
l100-rand-0.25-1_1557_MIP	MIP	100	rand	1	makespan	125	125	
l100-rand-0.25-2_1605_MIP	MIP	100	rand	2	makespan	121	121	
l100-rand-0.25-3_1580_MIP	MIP	100	rand	3	makespan	128	128	2,600.8
l100-rand-0.25-4_1649_MIP	MIP	100	rand	4	makespan			3,621.7
l100-rand-0.25-5_1573_MIP	MIP	100	rand		makespan	122	122	
1100-rand-0.5-1_1557_MIP	MIP	100	rand		makespan	125	125	2,228.0
1100-rand-0.5-2_1605_MIP	MIP	100	rand		makespan	123	120	2,472.5
1100-rand-0.5-3_1580_MIP	MIP	100	rand	3	makespan			2,172.0
1100-rand-0.5-4_1649_MIP	MIP	100	rand	4	makespan	129	129	2,667.3
1100-rand-0.5-5_1573_MIP	MIP	100	rand	5	makespan	123	129	2,007.3
1100-rand-0.75-1_1557_MIP	MIP	100	rand	1		122	122	
1100-rand-0.75-1_1557_MIP 1100-rand-0.75-2_1605_MIP			rand rand			121	121	2,357.3
	MIP	100		2		121	141	
1100-rand-0.75-3_1580_MIP	MIP	100	rand	3	makespan			
l100-rand-0.75-4_1649_MIP	MIP	100	rand	4	makespan			
l100-rand-0.75-5_1573_MIP l100-rand-1-1_1557_MIP	MIP MIP	100 100	rand rand	5	makespan makespan	122 125	122 125	1,978.9

	Instance	Solver	Nodes	Demand	Id	Objective	Best objective	Best bound	Runtime (seconds)
	00-rand-1-2_1605_MIP	MIP	100	rand		makespan			
	00-rand-1-3_1580_MIP	MIP	100	rand	3	makespan	100	400	
	00-rand-1-4_1649_MIP	MIP MIP	100 100	rand rand	4	makespan	129	129	2,474
	00-rand-1-5_1573_MIP	MIP	100	rand	5 1	makespan makespan	122	122	1,799
	00-rw-0.25-1_1557_MIP 00-rw-0.25-2_1605_MIP	MIP	100	rw	2	makespan			
	00-rw-0.25-3_1580_MIP	MIP	100	rw	3	makespan			
	00-rw-0.25-4_1649_MIP	MIP	100	rw	4	makespan			
	00-rw-0.25-5_1573_MIP	MIP	100	rw	5	makespan			
	00-rw-0.5-1_1557_MIP	MIP	100	rw	1	makespan			
	00-rw-0.5-2_1605_MIP	MIP	100	rw	2	makespan			
	00-rw-0.5-3_1580_MIP	MIP	100	rw	3	makespan			
	00-rw-0.5-4_1649_MIP	MIP	100	rw	4	makespan			
110	00-rw-0.5-5_1573_MIP	MIP	100	rw	5	makespan			
110	00-rw-0.75-1_1557_MIP	MIP	100	rw	1	makespan			
110	00-rw-0.75-2_1605_MIP	MIP	100	rw	2	makespan			
110	00-rw-0.75-3_1580_MIP	MIP	100	rw	3	makespan			
110	00-rw-0.75-4_1649_MIP	MIP	100	rw	4	makespan			
110	00-rw-0.75-5_1573_MIP	MIP	100	rw	5	makespan			
110	00-rw-1-1_1557_MIP	MIP	100	rw	1	makespan			
110	00-rw-1-2_1605_MIP	MIP	100	rw	2	makespan			
l1(00-rw-1-3_1580_MIP	MIP	100	rw	3	makespan			
l1(00-rw-1-4_1649_MIP	MIP	100	rw	4	makespan			
l1(00-rw-1-5_1573_MIP	MIP	100	rw	5	makespan			
110	0-rand-0.25-1_160_MIP	MIP	10	rand	1	timebalance	4	4	14
110	0-rand-0.25-2_163_MIP	MIP	10	rand	2	timebalance	2	2	6
l1(0-rand-0.25-3_158_MIP	MIP	10	rand	3	timebalance	3	3	10
l1(0-rand-0.25-4_163_MIP	MIP	10	rand	4	timebalance	3	3	9
l1(0-rand-0.25-5_167_MIP	MIP	10	rand	5	timebalance	3	3	11
l1(0-rand-0.5-1_160_MIP	MIP	10	rand	1	timebalance	4	4	14
l1(0-rand-0.5-2_163_MIP	MIP	10	rand	2	timebalance	2	2	7
l1(0-rand-0.5-3_158_MIP	MIP	10	rand	3	timebalance	3	3	10
110	0-rand-0.5-4_163_MIP	MIP	10	rand	4	timebalance	3	3	ç
l1(0-rand-0.5-5_167_MIP	MIP	10	rand	5	timebalance	3	3	16
	0-rand-0.75-1_160_MIP	MIP	10	rand	1	timebalance	4	4	14
110	0-rand-0.75-2_163_MIP	MIP	10	rand	2	timebalance	2	2	8
110	0-rand-0.75-3_158_MIP	MIP	10	rand	3	timebalance	3	3	ç
	0-rand-0.75-4_163_MIP	MIP	10	rand	4	timebalance	3	3	10
	0-rand-0.75-5_167_MIP	MIP	10	rand	5	timebalance	3	3	13
	0-rand-1-1_160_MIP	MIP	10	rand	1	timebalance	4	4	18
	0-rand-1-2_163_MIP	MIP	10	rand	2	timebalance	2	2	2
	0-rand-1-3_158_MIP	MIP	10	rand	3	timebalance	3	3	10
	0-rand-1-4_163_MIP	MIP	10	rand	4	timebalance	3	3	ç
	0-rand-1-5_167_MIP	MIP	10	rand	5	timebalance	3	3	12
	0-rw-0.25-1_160_MIP	MIP	10	rw	1	timebalance	4	4	16
	0-rw-0.25-2_163_MIP	MIP	10	rw	2	timebalance	2	2	13
	0-rw-0.25-3_158_MIP	MIP	10	rw	3	timebalance	3	3	12
	0-rw-0.25-4_163_MIP	MIP	10	rw	4	timebalance	3	3	13
	0-rw-0.25-5_167_MIP	MIP	10	rw	5	timebalance	3	3	35
	0-rw-0.5-1_160_MIP	MIP	10	rw	1	timebalance	4	4	18
	0-rw-0.5-2_163_MIP	MIP	10	rw	2	timebalance	2	2	7
	0-rw-0.5-3_158_MIP	MIP	10	rw	3	timebalance	3	3	25
	0-rw-0.5-4_163_MIP	MIP	10	rw	4	timebalance	3	3	15
	0-rw-0.5-5_167_MIP	MIP	10	rw	5	timebalance	3	3	23
	0-rw-0.75-1_160_MIP	MIP	10	rw	1	timebalance	4	4	28
	0-rw-0.75-2_163_MIP	MIP MIP	10 10	rw	2	timebalance timebalance	23	2	10
	0-rw-0.75-3_158_MIP			rw					
	0-rw-0.75-4_163_MIP	MIP	10	rw	4	timebalance	3	3	15
	0-rw-0.75-5_167_MIP	MIP MIP	10 10	rw	5	timebalance timebalance	3	3 4	38
	0-rw-1-1_160_MIP			rw	2				25
	0-rw-1-2_163_MIP	MIP	10	rw	3	timebalance	2	2	1
	D-rw-1-3_158_MIP D-rw-1-4_163_MIP	MIP MIP	10	rw	3 4	timebalance	3	3	15
			10	rw	4	timebalance		3	12
	0-rw-1-5_167_MIP	MIP	10	rw		timebalance	3	3	30
	0-rand-0.25-1_768_MIP	MIP	50	rand	1	timebalance	4	4	310
	0-rand-0.25-2_803_MIP	MIP	50	rand	2	timebalance	4	4	447
	0-rand-0.25-3_803_MIP	MIP	50	rand		timebalance	4	4	441
	0-rand-0.25-4_823_MIP	MIP	50	rand	4	timebalance	4	4	520
	0-rand-0.25-5_787_MIP	MIP	50	rand		timebalance	4	4	664
	0-rand-0.5-1_768_MIP	MIP	50	rand		timebalance	4	4	328
	0-rand-0.5-2_803_MIP	MIP	50	rand	2	timebalance	4	4	380
	0-rand-0.5-3_803_MIP	MIP	50	rand	3	timebalance	4	4	369
	0-rand-0.5-4_823_MIP	MIP	50	rand	4	timebalance	4	4	489
	0-rand-0.5-5_787_MIP	MIP	50	rand	5	timebalance	4	4	453
	0-rand-0.75-1_768_MIP	MIP	50	rand	1	timebalance	4	4	277

Instance	Solver	Nodes	Demand	Id	Objective	Best objective	Best bound	Runtime (seconds)
l50-rand-0.75-3_803_MIP	MIP	50	rand	3	timebalance	4	4	379.6
50-rand-0.75-4_823_MIP	MIP	50	rand	4	timebalance	4	4	452.8
50-rand-0.75-5_787_MIP	MIP	50	rand	5	timebalance	4	4	373.2
50-rand-1-1_768_MIP	MIP	50	rand	1	timebalance	4	4	313.1
50-rand-1-2_803_MIP	MIP	50	rand	2	timebalance	4	4	344.6
50-rand-1-3_803_MIP	MIP	50	rand	3	timebalance	4	4	377.7
50-rand-1-4_823_MIP	MIP	50	rand	4	timebalance	4	4	434.0
50-rand-1-5_787_MIP	MIP	50	rand	5	timebalance	4	4	591.3
50-rw-0.25-1_768_MIP	MIP	50	rw	1	timebalance			
50-rw-0.25-2_803_MIP	MIP	50	rw	2	timebalance			
50-rw-0.25-3_803_MIP	MIP	50	rw	3	timebalance	27	2.176212308	
50-rw-0.25-4_823_MIP	MIP	50	rw	4	timebalance	2,	2.17 0212000	
50-rw-0.25-5_787_MIP	MIP	50	rw	5	timebalance	20	3	
	MIP	50	rw	1	timebalance	20	3	
50-rw-0.5-1_768_MIP 50-rw-0.5-2 803 MIP				1				
	MIP	50	rw	_				
50-rw-0.5-3_803_MIP	MIP	50	rw	3		27	2.202663552	
50-rw-0.5-4_823_MIP	MIP	50	rw	4		26	3.239925626	
50-rw-0.5-5_787_MIP	MIP	50	rw	5	timebalance	22	3	
50-rw-0.75-1_768_MIP	MIP	50	rw	1	timebalance			
50-rw-0.75-2_803_MIP	MIP	50	rw	2	timebalance			
50-rw-0.75-3_803_MIP	MIP	50	rw	3	timebalance			
50-rw-0.75-4_823_MIP	MIP	50	rw	4	timebalance	28	3.157533472	
50-rw-0.75-5_787_MIP	MIP	50	rw	•	timebalance	20		
50-rw-1-1_768_MIP	MIP	50	rw	1		26	3.415547878	
	MIP	50			timebalance	26	3.41334/8/8	
50-rw-1-2_803_MIP			rw					
50-rw-1-3_803_MIP	MIP	50	rw	3	timebalance	27	2.531647880	
50-rw-1-4_823_MIP	MIP	50	rw	4	timebalance			
50-rw-1-5_787_MIP	MIP	50	rw	5	timebalance	27	4	
100-rand-0.25-1_1557_MIP	MIP	100	rand	1	timebalance			
100-rand-0.25-2_1605_MIP	MIP	100	rand	2	timebalance	11	4	
100-rand-0.25-3_1580_MIP	MIP	100	rand	3	timebalance			
100-rand-0.25-4_1649_MIP	MIP	100	rand	4				
100-rand-0.25-5 1573 MIP	MIP	100	rand	5	timebalance			
100-rand-0.5-1_1557_MIP	MIP	100	rand	1	timebalance			
100-rand-0.5-2_1605_MIP	MIP	100	rand	2	timebalance			
	MIP	100	rand	3	timebalance	10	B	
100-rand-0.5-3_1580_MIP						18	3.666666667	
100-rand-0.5-4_1649_MIP	MIP	100	rand	4				
100-rand-0.5-5_1573_MIP	MIP	100	rand		timebalance	15	5	
100-rand-0.75-1_1557_MIP	MIP	100	rand	1	timebalance	4	4	3,318.
100-rand-0.75-2_1605_MIP	MIP	100	rand	2	timebalance	4	4	3,483.
100-rand-0.75-3_1580_MIP	MIP	100	rand	3	timebalance	4	4	3,548.8
100-rand-0.75-4_1649_MIP	MIP	100	rand	4	timebalance	12	5	
100-rand-0.75-5_1573_MIP	MIP	100	rand	5	timebalance	20	5	
100-rand-1-1 1557 MIP	MIP	100	rand	1	timebalance			
100-rand-1-2_1605_MIP	MIP	100	rand	2	timebalance	16	4	
100-rand-1-3_1580_MIP	MIP	100	rand	3	timebalance	10	4	
			rand	4	timebalance			
100-rand-1-4_1649_MIP	MIP	100		•	unicountrice			
100-rand-1-5_1573_MIP	MIP	100	rand	5	timebalance	5	5	2,490.
100-rw-0.25-1_1557_MIP	MIP	100	rw	1	timebalance			
100-rw-0.25-2_1605_MIP	MIP	100	rw	2	timebalance			
100-rw-0.25-3_1580_MIP	MIP	100	rw	3	timebalance			
100-rw-0.25-4_1649_MIP	MIP	100	rw	4	timebalance			
100-rw-0.25-5 1573 MIP	MIP	100	rw	5	timebalance			
100-rw-0.5-1_1557_MIP	MIP	100	rw	1				
100-rw-0.5-2_1605_MIP	MIP	100	rw	2	timebalance			
100-rw-0.5-3_1580_MIP	MIP	100	rw	3	timebalance			
	MIP	100		4	timebalance			
100-rw-0.5-4_1649_MIP			rw	-				
100-rw-0.5-5_1573_MIP	MIP	100	rw	5	timebalance			
100-rw-0.75-1_1557_MIP	MIP	100	rw	1	timebalance			
100-rw-0.75-2_1605_MIP	MIP	100	rw	2	timebalance			
100-rw-0.75-3_1580_MIP	MIP	100	rw	3	timebalance			
100-rw-0.75-4_1649_MIP	MIP	100	rw	4	timebalance			
100-rw-0.75-5_1573_MIP	MIP	100	rw	5	timebalance			
100-rw-1-1_1557_MIP	MIP	100	rw	1	timebalance			
100-rw-1-2_1605_MIP	MIP	100	rw	2	timebalance			
100-rw-1-3 1580 MIP	MIP	100	rw	3				
	MIP	100	rw rw	3 4				
100-rw-1-4_1649_MIP								
100-rw-1-5_1573_MIP	MIP	100	rw		timebalance			
10-rand-0.25-1_160_MIP	MIP	10	rand	1		0.571428571	0.571428571	348.
10-rand-0.25-2_163_MIP	MIP	10	rand	2	loadbalance	0.614285714	0.614224548	1,783.
10-rand-0.25-3_158_MIP	MIP	10	rand	3	loadbalance	0.633802816	0.633766234	345.
10-rand-0.25-4_163_MIP	MIP	10	rand	4	loadbalance	0.602739726	0.602739726	465.0
10-rand-0.25-5_167_MIP	MIP	10	rand	5	loadbalance	0.597402597	0.597343533	1,627.
10-rand-0.5-1_160_MIP	MIP	10	rand	1	loadbalance	0.415094340	0.415094340	216.9
		10		-				
10-rand-0.5-2_163_MIP	MIP	10	rand	2	loadbalance	0.452631579	0.452631579	451.

Instance		Nodes	Demand		Objective	Best objective	Best bound	Runtime (seconds)
10-rand-0.5-4_163_MIP	MIP	10	rand	4	loadbalance	0.438775509	0.438731857	710.13
10-rand-0.5-5_167_MIP	MIP	10	rand	5	loadbalance	0.425925926	0.425883568	1,307.42
10-rand-0.75-1_160_MIP	MIP	10	rand	1	loadbalance	0.323529412	0.323529412	206.56
10-rand-0.75-2_163_MIP	MIP	10	rand	2	loadbalance	0.358333333	0.358333333	470.44
10-rand-0.75-3_158_MIP	MIP	10	rand	3	loadbalance	0.3666666667	0.366643321	196.05
10-rand-0.75-4_163_MIP	MIP	10	rand	4	loadbalance	0.343750000	0.343750000	703.00
10-rand-0.75-5_167_MIP	MIP	10	rand	5	loadbalance	0.330935252	0.330919296	1,499.09
10-rand-1-1_160_MIP	MIP	10	rand	1	loadbalance	0.265060241	0.265060241	471.81
10-rand-1-2_163_MIP	MIP	10	rand	2	loadbalance	0.296551724	0.296549919	793.09
10-rand-1-3_158_MIP	MIP	10	rand	3	loadbalance	0.303448276	0.303448276	287.36
10-rand-1-4_163_MIP	MIP	10	rand	4	loadbalance	0.283870968	0.283870968	420.34
10-rand-1-5_167_MIP	MIP	10	rand	5	loadbalance	0.283950617	0.265930870	Т
10-rw-0.25-1_160_MIP	MIP	10	rw	1	loadbalance	0.3333333333	0.3333333333	66.06
10-rw-0.25-2 163 MIP	MIP	10	rw	2	loadbalance	0.3333333333	0.33333333333	909.58
10-rw-0.25-3_158_MIP	MIP	10	rw	3	loadbalance	0.3333333333	0.3333333333	236.63
10-rw-0.25-4_163_MIP	MIP	10	rw	4	loadbalance	0.500000000	0.500000000	10.73
10-rw-0.25-5_167_MIP	MIP	10	rw	5	loadbalance	0.33333333333	0.33333333333	36.23
10-rw-0.5-1_160_MIP	MIP	10	rw	1	loadbalance	0.285714286	0.285714286	574.05
10-rw-0.5-2_163_MIP	MIP	10	rw	2	loadbalance	0.285714286	0.285714286	414.41
10-rw-0.5-3_158_MIP	MIP	10	rw	3	loadbalance	0.3333333332	0.253145849	414.41 T
10-rw-0.5-4 163 MIP	MIP	10	rw	4	loadbalance	0.428571429	0.428571429	12.23
10-rw-0.5-5_167_MIP	MIP	10	rw	5	loadbalance	0.285714286	0.285714286	118.80
10-rw-0.75-1_160_MIP	MIP	10	rw	1	loadbalance	0.250000000	0.250000000	171.38
10-rw-0.75-2_163_MIP	MIP	10	rw	2	loadbalance	0.250000000	0.250000000	440.59
10-rw-0.75-3_158_MIP	MIP	10	rw	3	loadbalance	0.3333333332	0.250000000	T
10-rw-0.75-4_163_MIP	MIP	10	rw	4	loadbalance	0.375000000	0.375000000	15.63
10-rw-0.75-5_167_MIP	MIP	10	rw	5	loadbalance	0.250000000	0.250000000	142.28
10-rw-1-1_160_MIP	MIP	10	rw	1	loadbalance	0.250000000	0.250000000	1,713.78
10-rw-1-2_163_MIP	MIP	10	rw	2	loadbalance	0.3333333332	0.229477187	Т
10-rw-1-3_158_MIP	MIP	10	rw	3	loadbalance	0.3333333332	0.222222222	Т
10-rw-1-4_163_MIP	MIP	10	rw	4	loadbalance	0.3333333333	0.3333333333	12.39
0-rw-1-5_167_MIP	MIP	10	rw	5	loadbalance	0.250000000	0.250000000	1,937.67
0-rand-0.25-1_768_MIP	MIP	50	rand	1	loadbalance	0.834394904	0.471791014	Т
0-rand-0.25-2_803_MIP	MIP	50	rand	2	loadbalance	0.728915663	0.470106371	Т
0-rand-0.25-3_803_MIP	MIP	50	rand	3	loadbalance	0.760479042	0.490834855	Т
50-rand-0.25-4_823_MIP	MIP	50	rand	4	loadbalance	0.668639053	0.435022617	Т
50-rand-0.25-5_787_MIP	MIP	50	rand	5	loadbalance	0.676829268	0.480128353	Т
0-rand-0.5-1_768_MIP	MIP	50	rand	1	loadbalance	0.494565216	0.397511769	т
0-rand-0.5-2_803_MIP	MIP	50	rand	2	loadbalance	0.566326531	0.394969311	Т
50-rand-0.5-3_803_MIP	MIP	50	rand	3	loadbalance	0.678571429	0.412551739	т
50-rand-0.5-4 823 MIP	MIP	50	rand	4	loadbalance	0.534653465	0.369292271	Т
50-rand-0.5-5_787_MIP	MIP	50	rand	5	loadbalance	0.557213930	0.403976181	Т
0-rand-0.75-1_768_MIP	MIP	50	rand	1	loadbalance	0.544600939	0.342940348	Т
50-rand-0.75-2_803_MIP	MIP	50	rand	2	loadbalance	0.551111111	0.343028677	т Т
0-rand-0.75-3 803 MIP		50		_	loadbalance	0.536796537		T
	MIP		rand	3			0.354972202	
50-rand-0.75-4_823_MIP	MIP	50	rand	4	loadbalance	0.463302752	0.318438736	Т
0-rand-0.75-5_787_MIP	MIP	50	rand	5	loadbalance	0.529147982	0.348461875	Т
50-rand-1-1_768_MIP	MIP	50	rand	1	loadbalance	0.578512397	0.300623027	Т
0-rand-1-2_803_MIP	MIP	50	rand	2	loadbalance	0.477443609	0.302171606	Т
50-rand-1-3_803_MIP	MIP	50	rand	3	loadbalance	0.498084291	0.313358764	Т
0-rand-1-4_823_MIP	MIP	50	rand	4	loadbalance	0.426294821	0.281793250	Т
50-rand-1-5_787_MIP	MIP	50	rand	5	loadbalance	0.484962406	0.308868437	Т
0-rw-0.25-1_768_MIP	MIP	50	rw	1	loadbalance			Т
50-rw-0.25-2_803_MIP	MIP	50	rw	2	loadbalance			Т
0-rw-0.25-3_803_MIP	MIP	50	rw	3	loadbalance			Т
50-rw-0.25-4_823_MIP	MIP	50	rw	4	loadbalance			Т
50-rw-0.25-5_787_MIP	MIP	50	rw	5	loadbalance			Т
50-rw-0.5-1_768_MIP	MIP	50	rw	1	loadbalance	0.437500000	0.174603175	Т
50-rw-0.5-2_803_MIP	MIP	50	rw	2	loadbalance			Т
50-rw-0.5-3_803_MIP	MIP	50	rw	3	loadbalance			T
0-rw-0.5-4_823_MIP	MIP	50	rw	4	loadbalance			T
50-rw-0.5-5_787_MIP 50-rw-0.5-5_787_MIP	MIP	50	rw	4 5	loadbalance			T
50-rw-0.5-5_787_MIP 50-rw-0.75-1_768_MIP	MIP	50	rw	5 1	loadbalance			T
50-rw-0.75-2_803_MIP	MIP	50	rw	2	loadbalance			Т
50-rw-0.75-3_803_MIP	MIP	50	rw	3	loadbalance			Т
50-rw-0.75-4_823_MIP	MIP	50	rw	4	loadbalance			Т
50-rw-0.75-5_787_MIP	MIP	50	rw	5	loadbalance			Т
50-rw-1-1_768_MIP	MIP	50	rw	1	loadbalance			Т
50-rw-1-2_803_MIP	MIP	50	rw	2	loadbalance			Т
50-rw-1-3_803_MIP	MIP	50	rw	3	loadbalance			Т
50-rw-1-4_823_MIP	MIP	50	rw	4	loadbalance			Т
50-rw-1-5_787_MIP	MIP	50	rw	5	loadbalance			Т
100-rand-0.25-1_1557_MIP	MIP	100	rand	1	loadbalance			Т
100-rand-0.25-2_1605_MIP	MIP	100	rand	2	loadbalance			Т
			rand	-				T
00-rand-0.25-3_1580_MIP	MIP	100		3	loadbalance			

Instance	Solver	Nodes	Demand	Id	Objective	Best objective	Best bound	Runtime (seconds)
l100-rand-0.25-5_1573_MIP	MIP	100	rand	5	loadbalance			
1100-rand-0.5-1_1557_MIP	MIP	100	rand	1	loadbalance			
1100-rand-0.5-2_1605_MIP	MIP	100	rand	2	loadbalance			
1100-rand-0.5-3_1580_MIP	MIP	100	rand	3	loadbalance			
1100-rand-0.5-4_1649_MIP	MIP	100	rand	4	loadbalance			
1100-rand-0.5-5_1573_MIP	MIP	100	rand	5	loadbalance			
l100-rand-0.75-1_1557_MIP	MIP	100	rand	1	loadbalance			
l100-rand-0.75-2_1605_MIP	MIP	100	rand	2	loadbalance			
l100-rand-0.75-3_1580_MIP	MIP	100	rand	3	loadbalance			
l100-rand-0.75-4_1649_MIP	MIP	100	rand	4	loadbalance			
1100-rand-0.75-5_1573_MIP	MIP	100	rand	5	loadbalance			
1100-rand-1-1_1557_MIP	MIP	100	rand	1	loadbalance			
1100-rand-1-2_1605_MIP	MIP	100	rand	2	loadbalance			
1100-rand-1-3_1580_MIP	MIP	100	rand	3	loadbalance			
1100-rand-1-4_1649_MIP	MIP	100	rand	4	loadbalance			
1100-rand-1-5_1573_MIP	MIP	100	rand	5	loadbalance			
1100-rw-0.25-1_1557_MIP	MIP	100	rw	1	loadbalance			
1100-rw-0.25-2_1605_MIP	MIP	100	rw	2	loadbalance			
1100-rw-0.25-3_1580_MIP	MIP	100	rw	3	loadbalance			
l100-rw-0.25-4_1649_MIP	MIP	100	rw	4	loadbalance			
1100-rw-0.25-5_1573_MIP	MIP	100	rw	5	loadbalance			
1100-rw-0.5-1_1557_MIP	MIP	100	rw	1	loadbalance			
1100-rw-0.5-2_1605_MIP	MIP	100	rw	2	loadbalance			
1100-rw-0.5-3_1580_MIP	MIP	100	rw	3	loadbalance			
l100-rw-0.5-4_1649_MIP	MIP	100	rw	4	loadbalance			
l100-rw-0.5-5_1573_MIP	MIP	100	rw	5	loadbalance			
l100-rw-0.75-1_1557_MIP	MIP	100	rw	1	loadbalance			
l100-rw-0.75-2_1605_MIP	MIP	100	rw	2	loadbalance			
l100-rw-0.75-3_1580_MIP	MIP	100	rw	3	loadbalance			
l100-rw-0.75-4_1649_MIP	MIP	100	rw	4	loadbalance			
l100-rw-0.75-5_1573_MIP	MIP	100	rw	5	loadbalance			
l100-rw-1-1_1557_MIP	MIP	100	rw	1	loadbalance			
1100-rw-1-2_1605_MIP	MIP	100	rw	2	loadbalance			
l100-rw-1-3_1580_MIP	MIP	100	rw	3	loadbalance			
l100-rw-1-4_1649_MIP	MIP	100	rw	4	loadbalance			
1100-rw-1-5_1573_MIP	MIP	100	rw	5	loadbalance			

CP ... Constraint Programming MIP ... Mixed Integer Programming Id ... Identification number of instance T ... Maximum allowed computation time exploited (3.600 seconds) rw. .. real world rand ... random bold characters ... optimal solution found