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SCHEDULING OF SPORT LEAGUE SYSTEMS WITH INTER-LEAGUE CONSTRAINTS

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Scheduling of Sport League Systems with Inter-League Constraints

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Abstract

We investigate the simultaneous schedule determination of several leagues in a championship. Beside limited availability of venues, the substitution of players among teams of a club requires the consideration of mutual match slot exclusions associated with teams playing in different leagues during schedule construction. We propose a mathematical optimization model for this complicated decision task and report results from initial computational experiments.

1 Introduction

A set of sport leagues is called a championship. While in professional sports, the schedules of the leagues in a championship are determined consecutively starting with the most important league (e.g. the Premier League in soccer is scheduled first, followed by the Second League and so) non-commercial (leisure) sport typically cannot realize a sequential schedule determination due to additional constraints establishing interdependency between the schedules of different leagues. This paper addresses the simultaneous determination of schedules from several leagues called the *championship scheduling problem*. We report about the championship scheduling problem of a regional table tennis association in Germany that addresses the simultaneous determination of schedules for several leagues. Two types of inter-league constraints are to be considered: limited venue capacity as well as player substitution opportunities between several teams of a club. The first mentioned issue requires the coordination of available match slots usage among all teams of a club even if these teams are members of different leagues. The second mentioned issue requires that two teams of a club assigned to different leagues (the receiving as well as the providing team of a substitute player) do not have a match in the same slot.

A survey of the state-of-the-art in sport league scheduling is given by [4]. [1] proposes and compares several mathematical models for the sport league scheduling problem. Applications of sport league scheduling approaches in the context of table tennis are reported in [4, 6]. [2] as well as [5] consider a variation of the sport league scheduling setup in which one venue from a set of available venues has to be selected for each match from the competition program. To the best of the author's knowledge these are the only attempts to incorporate scarce venue issues into sport league schedule determination and there are no contributions that report research on the simultaneous scheduling of several leagues.

An informal problem description is provided in Section 2. Afterwards, Section 3 reports the development of a mathematical optimization model. The proposed model is verified in initial computational experiments whose results are given in Section 4.

2 The Championship Scheduling Problem

We consider a set CP of leagues formed by teams from the set $\mathcal{T}$ which are delegated by clubs collected in the set $\mathcal{C}$. The binary parameter $TC(m;c)$ is equal to 1 if and only if team $m \in \mathcal{T}$ is associated with club $c \in \mathcal{C}$. A *match* in the league $L \in CP$ is the ordered pair $(i,j) \in L \times L \setminus \{(i,i) \mid i \in L\}$. We call team i the home-team and team j the away team. It is assumed that the venue of the home team hosts the match $(i;j)$. If $(i;j)$ is a match then we call the set $\{i;j\}$ a *meeting* with involvement of i and j.

The competition program of league L contains all matches specified by competition rules. Without loss of generality, we assume that a match $(i;j)$ among two teams of league L is required exactly once. In the championship scheduling problem it is necessary to schedule all matches in all leagues of the championship. For each of these matches a time slot $s_{ij} \in S$ has to be selected as date of match $(i;j)$ from the set of available time slots S. The set S is partitioned into the set S^F of slots of the *fall round* and the set S^A of slots of the *autumn round*. We assume that all slots from S^F precede the slots of S^A. A feasible schedule of an individual league in the considered championship requires the fulfillment of the following 5 conditions. Exactly one slot $s_{ij} \in S$ must be selected for each match in the competition program (R_1). At most of match per team can be assigned to a slot from S (R_2). If match $(i;j)$ is scheduled in S^F then and only then match $(j;i)$ is scheduled in S^A. (R_3). For each team, home with away matches are alternately scheduled over the season (R_4). In order to achieve a regular distribution of all matches of a team over the season it is necessary to ensure that at least N^{DIST} slots can be found between two consecutive meetings with participation of this team (R_5). To achieve feasibility of all generated schedules in the championship it is necessary to respect the following inter-league conditions. Two teams for which a substitution opportunity is specified must not have a meeting (with any other team) in the same slot (R_6). The capacity of club c's venue $VC(c)$ must not be exceeded by the home matches of all teams associated with club c in any slot (R_7).

The conditions R_1 to R_3 are *obligatory* since the table tables rules require the fulfillment of these conditions. Also the fulfillment of R_6 as well as R_7 is obligatory in order to get a feasible schedule. The conditions R_4 as well as R_5 are imposed in order to meet fairness aspects. They are not induced by any rule set. They are called *soft* conditions. We are going to minimize the number of violations of the soft conditions while all obligatory conditions are fulfilled without any exception.

3 A Mathematical Optimization Model

We first derive mathematical constraints whose consideration ensures the feasibility of an individual league schedule for a single league with respect to R_1 - R_5. Afterwards, we extend this model in order to meet the conditions R_6 as well as R_7.

Let L be a league. Team k meets each other team i twice. Let $\bar{L}$ be the set that contains two copies of each team $k \in L$, say k^+ and $k-$. Team k meets each other team from $\bar{L}(k) := \{i \in \bar{L} \mid i \neq k^+ \wedge i \neq k^-\}$ exactly once. All teams from $\bar{L}(k)$ labeled by $^+$ are collected in the set $\bar{L}^+(k)$ and a match against team $j \in \bar{L}^+(k)$ takes place in the venue of k (home-match of team k). All $^-$-labeled teams are put into the set $\bar{L}^-(k)$ accordingly. A match between k and and $i \in \bar{L}^-(k)$ is conducted at the venue of team i (away-match of team k). As an example, we consider the league $L = \{1,2,3,4\}$ and get $\bar{L} := \{1^+,1^-,2^+,2^-,3^+,3^-,4^+,4^-\}$. For team $k = 2$ we have the sets $\bar{L}(2) := \{1^+,1^-,3^+,3^-,4^+,4^-\}$ as well as $\bar{L}^+(2) := \{1^+,3^+,4^+\}$ and $\bar{L}^+(2) := \{1^-,3^-,4^-\}$. The meetings to be scheduled with participation of team 2 are

$\{\{1^+;2\},\{3^+;2\},\{4^+;2\},\{1^-;2\},\{3^-;2\},\{4^-;2\}\}$.

For team $k \in L$, a Hamiltonian path goes through all teams from $\bar{L}$. This path originates from k^+, terminates in k^- and visits each other member of $\bar{L}$ exactly once. It determines the sequence in which the meetings with participation of k are carried out. For the coding of such a sequence, we declare the binary decision variable x_{ijk} $(i,j \in \bar{L}, k \in L)$. If $x_{ijk} = 1$ then the meeting of k with i precedes the meeting of k with j and k has no other meeting between these two meetings. For example, the Hamiltonian path $(2^+, 3^-, 1^-, 2^+, 1^+, 3^+, 2^-)$ defines the match pattern for team 2: first, 2 has an away match (AM) against 3, followed by an AM against 1 and a home match (HM) against 2. The next matches are against 1 (HM), 3 (HM) and 2 (AM).

Beside the determination of the match pattern for each team $k \in L$ it is necessary to select the slot into which a match falls. We declare the integer-valued decision variable z_{ik} to carry the selected slot of the meeting with participation of k and i.

$$\sum_{j\in\bar{L}(k)} x_{k^+jk} = 1 \; \forall k \in L \wedge \sum_{j\in\bar{L}(k)} x_{jk^+k} = 0 \qquad \forall k \in L \tag{1}$$

$$\sum_{j\in\bar{L}(k)} x_{jk^-k} = 1 \; \forall k \in L \wedge \sum_{j\in\bar{L}(k)} x_{k^-jk} = 0 \qquad \forall k \in L \tag{2}$$

$$\sum_{j\in\bar{L}(k)} x_{ijk} = 1 \qquad \forall k \in L, i \in \bar{L}(k) \tag{3}$$

$$\sum_{j\in\bar{L}(k)} x_{ijk} = \sum_{j\in\bar{L}(k)} x_{jik} \qquad \forall k \in L, i \in \bar{L}(k) \tag{4}$$

As proposed for the well-known capacitated vehicle routing problem [3] (1)-(4) determines a set of Hamilton paths through the sets $\bar{L}(k)$ fulfilling condition R_2. (1) ensures that a first opponent is defined but prevents that the initial dummy opponent k^+ has a predecessor. Similarly, (2) ensures that team k's Hamilton path through $\bar{L}(k)$ terminates in k^-. Constraint (3) takes care that each meeting of team k has a predecessor as well as a successor and that a continuous path is achieved (4).

$$z_{k^+k} = 0 \; \forall k \in L \wedge z_{k^-k} = S^F + S^A + 1 \; \forall k \in L \tag{5}$$

$$z_{ik} + 1 \leq z_{jk} + (1 - x_{ijk}) * \mathcal{M} \; \forall k \in L, i, j \in \bar{L}(k) \tag{6}$$

$$z_{l^+k} = z_{k^-l} \; \forall k, l \in L, k \neq l \tag{7}$$

$$z_{ik} \neq z_{jk} \; \forall k \in L \; \forall i, j \in \bar{L}(k), i \neq j \tag{8}$$

$$z_{ik} + 1 + N^{DIST} \leq z_{jk} + (1 - x_{ijk}) * \mathcal{M} + e^{DIST}_{ijk} \; \forall k \in L, i, j \in \bar{L} \tag{9}$$

$$u^F_{ik} \cdot \mathcal{M} \geq S^F + 1 - z_{ik} \forall k \in L \; \forall i \in \bar{L}(k) \;\; \wedge \;\; u^A_{ik} \dot{\mathcal{M}} \geq z_{ik} - S^F \; \forall k \in L \; \forall i \in \bar{L}(k) \tag{10}$$

$$u^F_{i^+k} + u^F_{i^-k} \leq 1 \; \forall k, i \in L, k \neq i \;\; \wedge \;\; u^A_{i^+k} + u^A_{i^-k} \leq 1 \; \forall k, i \in L, k \neq i \tag{11}$$

$$x_{opk} + x_{pqk} \leq 1 + e^H_{opqk} \cdot \mathcal{M} \;\; \wedge \;\; x_{opk} + x_{pqk} \leq 1 + e^A_{opqk} \cdot \mathcal{M} \; \forall k \in L, o, p, q \in \bar{L}(k)^- \tag{12}$$

The constraint families (5)-(9) ensure the selection a feasible slot for each match. (5) determines the slot for the dummy meeting that initiates the Hamiltonian path and the slot for the dummy meeting that terminates the Hamiltonian path associated with team k. Let $\mathcal{M}$ be a sufficiently large number. In case that team k meets team j immediately after team i then the meeting of j with k is scheduled at least 1 slot later than the meeting of i with k (6). Constraint family (7) synchronizes the slots for the meetings scheduled for each pair of two different teams k and l. At most one meeting per slot is scheduled for team k (8). The binary indicator decision variable e_{ijk}^{DIST} is 1 if the required number N^{DIST} of free slots between the two consecutive meetings of k remains unconsidered (9).

In order to meet constraint R_3 it is necessary to decide for each meeting $\{i;k\}$ if it is scheduled in the fall season S^F or in the autumn season S^A. We introduce the binary decision variable families u_{ik}^F as well as u_{ik}^A as indicators for the selected half season of a meeting between two teams. (10) enforces u_{ik}^F to be 1 if i and k meet in the fall season and enforces u_{ik}^A to be 1 if i and k meet in the spring season. Either the meeting of both teams at the venue of k or the meeting of both teams in the venue of i can be assigned into the same half season (11).

In order to fulfill R_4 we state the constraint (12). It ensures that at most two consecutive meetings with the involvement of team k take place in the venue of k (in the venue of k's opponent). The binary indicator decision variables e_{opqk}^{H} (e_{opqk}^{AA}) is enforced into the value 1 if the three consecutive meetings $\{o;k\}$, $\{p;k\}$ and $\{q;k\}$ are all home (all away) matches for team k.

$$Z := \sum_{k\in L} \sum_{i,j\in \bar{L}(k)} e_{ijk}^{DIST} + \sum_{k\in L} \sum_{o,p,q\in \bar{L}(k)} e_{opqk}^{H} + e_{opqk}^{A} \tag{13}$$

$$\bar{Z} := \sum_{m\in CP} \sum_{k\in L_m} \sum_{i,j\in \bar{L}_m(k)} e_{ijk}^{DIST} + \sum_{m\in CP} \sum_{k\in L_m} \sum_{o,p,q\in \bar{L}_m(k)} e_{opqk}^{H} + e_{opqk}^{A} \tag{14}$$

The sport league schedule determination problem for a double round robin competition program is now represented by the mixed-integer-linear program (MILP) consisting of the constraints (1)-(12) and the objective function (13) to be minimized. This model follows a significantly different representation logic compared to the modeling approaches proposed in [1].

Assume now, that the competition comprises several leagues collected in the set CP. Let $m \in CP$ and L_m denote the set of the teams forming league m. We can replace L by L_m in the previously presented constraints (1)-(12) and activate these constraints for all leagues $m \in CP$. Solving the resulting MILP consisting of the constraints (1)-(12) as well as the objective function (14) determines feasible schedules for each individual league in the championship but the inter-league constraints remain unconsidered. To incorporate the inter-league conditions we extend the previously described MILP.

$$z_{ji} <> z_{lk} \qquad \forall i,j,k,l \in \bigcup_{m\in CP} L_m \tag{15}$$

$$z_{ji} = \sum_{s\in S} y_{ijs}^{HOME} \cdot t \wedge \sum_{s\in S} y_{ijs}^{HOME} = 1 \qquad \forall m \in CP, i \in \bar{L}_m^+, j \in \bar{L}_m^+ \tag{16}$$

$$\sum_{t\in \mathcal{T}} TC(t,c) \cdot \sum_{i\in L_m} \sum_{j\in L_m} y_{ijt}^{HOME} \leq VC(c) \qquad \forall c \in \mathcal{C}, s \in S \tag{17}$$

Let $s(i,j,k,l)$ be a binary parameter that is fixed to 1 if and only if the two matches (i,j) and (k,l) have to be scheduled in different slots in order to allow player substitution by a player from team k to complete team i. Constraint (15) ensures that matches with the participation of two teams with a substitution relation are not assigned into the same time slot. This fulfills condition R_6.

To determine the number of home matches of the teams of club c in a slot t we use the binary indicator decision variables y_{ijs}^{HOME} which is 1 if and only if match $(i;j)$ is scheduled in slot s (16). Constraint (17) then limits the number of matches for each slot to the venue capacity $VC(c)$ fulfilling R_7.

schedules proposed without consideration of inter-league constraints (optimal, no errors)

team	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1(A)	—	-5	—	—	—	—	—	-6	—	3	2	-4	—	—	—	4	—	—	-2	—	6	-3	5	—
2(B)	—	—	—	—	—	—	—	-5	6	4	-1	3	—	—	—	—	—	-4	1	-3	—	-6	—	5
3(C)	6	—	—	—	—	—	—	—	5	-1	4	-2	—	—	—	—	—	—	—	2	-5	1	-6	-4
4(D)	—	6	—	—	—	—	5	—	—	-2	-3	1	—	—	—	-1	-5	2	-6	—	—	—	—	3
5(A)	—	1	—	—	—	—	-4	2	-3	6	—	—	—	—	-6	—	4	—	—	—	3	—	-1	-2
6(B)	-3	-4	—	—	—	—	—	1	-2	-5	—	—	—	—	5	—	—	—	4	—	-1	2	3	—
7(A)	—	—	—	-11	—	—	9	—	—	-8	12	10	-12	11	—	—	—	-9	—	—	—	8	-10	—
8(B)	-12	—	—	—	11	—	—	—	-10	7	9	—	-11	12	—	—	—	—	—	—	10	-7	-9	—
9(C)	—	—	—	—	—	10	-7	—	—	12	-8	-11	—	—	—	11	—	7	-10	—	—	—	8	-12
10(D)	—	—	11	—	—	-9	—	12	8	—	—	-7	—	—	—	—	—	—	9	—	-8	-12	7	-11
11(A)	—	—	-10	7	-8	—	—	—	-12	—	—	9	8	-7	12	-9	—	—	—	—	—	—	—	10
12(B)	8	—	—	—	—	—	—	-10	11	-9	-7	—	7	-8	-11	—	—	—	—	—	—	10	—	9

schedules proposed after activation of inter-league constraints (non-optimal)

team	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1(A)	—	—	-6	—	3	2	-4	—	—	—	—	-5	—	6	—	—	-3	—	5	-2	4	—	—	—
2(B)	—	6	—	—	—	-1	—	-3	—	5	4	—	-4	—	—	—	—	—	—	1	—	-6	-5	3
3(C)	—	—	4	5	-1	—	—	2	—	—	—	6	-5	—	-6	—	1	—	-4	—	—	—	—	-2
4(D)	6	5	-3	—	—	—	1	—	—	—	-2	—	2	—	-5	—	-6	—	3	—	-1	—	—	—
5(A)	—	-4	—	-3	—	—	—	—	6	-2	—	1	3	—	4	-6	—	—	-1	—	—	—	2	—
6(B)	-4	-2	1	—	—	—	—	—	-5	—	—	-3	—	-1	3	5	4	—	—	—	—	2	—	—
7(A)	-9	—	12	—	—	—	-11	-10	—	—	8	—	—	-12	—	—	—	10	—	—	-8	9	—	11
8(B)	—	—	—	-11	10	—	9	-12	—	—	-7	—	12	—	—	—	—	—	11	-9	7	—	—	-10
9(C)	7	12	—	—	—	—	-8	—	11	-10	—	—	—	10	—	-11	—	-12	—	8	—	-7	—	—
10(D)	—	—	—	—	-8	11	—	7	—	9	—	-12	—	-9	—	—	—	-7	—	-11	—	12	—	8
11(A)	—	—	—	8	—	-10	7	—	-9	12	—	—	—	—	—	9	—	—	-8	10	—	—	-12	-7
12(B)	—	-9	-7	—	—	—	—	8	—	-11	—	10	-8	7	—	—	—	9	—	—	—	-10	11	—

Figure 1: Generated schedules: The table entry gives the opponent. If the opponent number is ≤ 0 then the meeting will take place at the opponent's venue. The number in brackets right of the team number indicates the team's club.

4 First Computational Experiments

In order to verify the proposed model we have setup an artificial championship with two leagues ($CP = \{1;2\}$). League 1 is composed by six teams $\{1;2;3;4;5;6\}$ and league 2 is composed by the other six teams $\{7;8;9;10;11;12\}$. The teams are delegated by four clubs. Teams 1, 5, 7 and 11 are associated with club 1 while teams 2, 6, 8 and 12 are formed by players from club 2. Team 3 and 9 are associated with club 3 and team 4 and 10 belong to club 4. We have the venue capacity vector $VC = (1;1;1;1)$, i.e. each club allows one home match in a slot. Substitution opportunities must be considered between the following pairs of teams: (1;5), (5;7), (7;11), (2;6), (6;8), (8;12), (3;9) as well as (4;10). The complete season comprises 24 slots and the fall round is formed by the first twelve slots. The minimal number of slots between two consecutively scheduled matches of a team is $N^{DIST} = 0$, so that two adjacent slots can be used for matches in which the same team is involved.

We use CPLEX to solve the resulting model instance. In a first experiment, we do not consider any inter-league constraints. The solver is granted 15 minutes processing time. After approx. 3 minutes an optimal solution is found. In a second experiment we activate the two inter-league constraints. The solver returns an solution after 15 minutes. This solution was not proven to be optimal. Fig. 1 shows the generated schedules for the championship. In the upper table, the gray shaded entries contribute to conflicts due to venue capacity excess or disregarded substitution opportunities. There are neither home-away alternation errors nor regularity errors. The lower table contains the schedules with activated cross-league constraints. Nearly all matches a re-scheduled and shifted into another slot in order to meet the requirements of the inter-league constraints. However, seven home-away-alternation errors cannot be eliminated within 15 minutes computational time (the gray shaded entries contribute to these failures).

5 conclusions

We have proposed and validated a mathematical optimization model of a complex decision problem from non-commercial sports management. For the first time, the simultaneous determination of schedules for several round-robin competitions sharing scarce venues is addressed. Furthermore, it is the first time that substitution options are considered in the schedule determination. The next research steps comprise the conduction of further computational experiments even with larger championships in order to identify the most critical factors for the simultaneous schedule determination. Due to the quite high complexity of the proposed model we are going to develop a heuristic approach that is able to handle championships of realistic size. In this context, we can use comprehensive historized real planning data. Furthermore, additional regularity measures will be evaluated.

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