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A Framework for a Highly Constrained Sports Scheduling Problem

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***Abstract*— This paper introduces a framework for a highly constrained sports scheduling problem which is modeled from the requirements of various professional sports leagues. We define a sports scheduling problem, introduce the necessary terminology and detail the constraints of the problem. A set of artificial and real-world instances derived from the actual problems solved for the professional sports league owners are proposed. We publish the best solutions we have found, and invite the sports scheduling community to find solutions to the unsolved instances. We believe that the instances will help researchers to test the value of their solution methods. The instances are available online.**

***Index Terms*—Real-World Scheduling, Sports Scheduling.**

I. Introduction

Professional sports leagues are big businesses. An increase in revenue comes from many factors: an increased number of spectators both in stadiums and via TV networks, reduced traveling costs for teams, a more interesting tournament for the media and sports fans, and a fairer tournament for the teams. Furthermore, TV networks buy the rights to broadcast the games and in return want the most attractive games to be scheduled at certain times.

One major reason for the increased academic interest in sports scheduling was the introduction of the traveling tournament problem [1], where the total distance traveled by the teams is minimized. Since the 1990s the evolution of sports scheduling has closely tracked the development of computers. In recent years microcomputers have reached a level of being powerful enough for demanding computational tasks in practical areas of sports scheduling. This is the second of the four reasons for the current interest in sports scheduling. The third reason is that new efficient algorithmic techniques have been developed to tackle previously intractable problems, and the fourth is that sports leagues are now organized more professionally than before and it has been realized that a good schedule is vital for a league's success.

Excellent overviews of sports scheduling can be found in [2]-[5]. An extensive bibliography can be found in [6] and an annotated bibliography in [7]. Successful methods of solving sports scheduling problems include ant algorithms [8],[9], constraint programming [2],[10]-[11], evolutionary algorithms [12]-[14], integer programming [15]-[20], metaheuristics [21]-[23], simulated annealing [24]-[26] and tabu search [27]-[29].

To the best of our knowledge, there are not many cases where academic researchers have been able to close a contract with a sports league owner. We are aware of the following: the major soccer league in The Netherlands [30], the major baseball league in the USA [31], the major soccer league in Austria [32], the 1st division soccer in Chile [33], the major basketball league in New Zealand [26], the major soccer league in Belgium [34], the major soccer league in Denmark [35], the major volleyball league in Argentina [36], the major and 1st division ice hockey leagues in Finland [37],[38] and the major soccer league in Brazil [19].

The focus of this paper is to introduce a framework for a highly constrained sports scheduling problem, which is modeled from the various requirements of professional sports leagues. In Section 2 we introduce the necessary sports scheduling terminology. Section 3 details the constraints of the sports scheduling problem. In Section 4 we propose a set of artificial test instances and in Section 5 we present real-world instances derived from the actual problems solved for the professional sports league owners. The idea of these sections is to lay out the foundation for comparable results. Finally, in Section 6 we publish the best solutions we have found for the real-world instances, and invite the sports scheduling community to find solutions to the unsolved instances. We also briefly discuss our solution methods.

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II. Sports Scheduling Terminology

In a sports competition, *n teams* play against each other over a period of time according to a given timetable. The teams belong to a *league*. In general, *n* is assumed to be an even number. A dummy team is added if a league has an odd number of teams. The league organizes *games* between the teams. Each game consists of an ordered pair of teams *(i, j)*. The first team, *i,* plays *at home* - that is, uses its own *venue* (stadium) for a game - and the second team, *j,* plays *away*. Games are scheduled in *rounds*. Each round is played on a given *day*. A *schedule* consists of games assigned to rounds. A schedule is *compact* if each team plays exactly one game in each round; otherwise it is *relaxed*. If a team has no game in a round, it is said to have a *bye*.

If a team plays two home or two away games in two consecutive rounds, it is said to have a *break*. In general, for reasons of fairness, breaks are to be avoided. The problem of finding a schedule with the minimum number of breaks is the *minimum break problem*. However, a team can prefer to have two or more consecutive away games if it is located far from the opponent's venues, and the venues of these opponents are close to each other. A series of consecutive away games is called an *away tour*. We call a schedule *k-balanced* if the numbers of home and away games for each team differ by at most *k* in any stage of the tournament. Teams can be partitioned into *strength groups*. Strength groups can be formed on the basis of the expected strengths of the teams. Teams can also be grouped by their location.

In a *round robin tournament* every team plays against every other team a fixed number of times. Most sports leagues play a double round robin tournament (*2RR*), where the teams meet twice (once at home, once away), but quadruple round robin tournaments (*4RR*) are also quite common. The number of rounds in a compact single round robin tournament (*1RR*) is $n-1$ and the number of games is $n(n-1)/2$. If *n* is even, it is always possible to construct a schedule with $n-2$ breaks, and this number is the minimum [30]. A *mirrored* double round robin tournament (*M2RR*) is a tournament where every team plays against every other team once in the first $n-1$ rounds, followed by the same games with reversed venues in the last $n-1$ rounds. For an M2RR, it is always possible to construct a schedule with exactly $3n-6$ breaks [39].

Table I shows an example of a compact mirrored 2RR with n = 6. The schedule has no breaks for teams 1 and 5, three breaks for teams 2 and 3, three-in-a-row home games for team 6 and five-in-a-row away games for team 4.

Table I
A compact mirrored double round robin tournament with six teams

R1	R2	R3	R4	R5
1 – 6	3 – 1	1 – 5	2 – 1	1 – 4
2 – 5	6 – 2	2 – 4	5 – 3	3 – 2
4 – 3	5 – 4	3 – 6	6 – 4	6 – 5
R6	**R7**	**R8**	**R9**	**R10**
6 – 1	1 – 3	5 – 1	1 – 2	4 – 1
5 – 2	2 – 6	4 – 2	3 – 5	2 – 3
3 – 4	4 – 5	6 – 3	4 – 6	5 – 6

If a team plays against team *i* in one round, and against team *j* in the next round, we say that team *i* gives a *carry-over effect* (COE) to team *j*. If we define c_{ij} as the number of carry-over effects that *i* gives to *j*, we can compute the so-called *COE value* of the schedule as $\sum_{i,j} c_{ij}^2$. The problem of finding a schedule with the minimum COE value is the carry-over effects value minimization problem. A lower bound value is $rn(n-1)$, where *r* is the number of round robins; schedules that attain this lower bound are called *balanced schedules*.

III. The Sports Scheduling Problem

To solve a real-world sports scheduling problem it is apparent that a profound understanding of the relevant requests and requirements presented by the league is a prerequisite for developing an effective solution method. In most cases the most important goal is to minimize the number of breaks. There are various reasons why breaks should be minimized in a sports schedule: fans do not like long periods without home games, consecutive home games reduce gate receipts, and long sequences of home or away games might influence the team's current position in the tournament. Apart from minimizing the number of breaks, several other issues play a role in sports scheduling, e.g. minimizing the total traveling distance, creating a compact schedule, avoiding a team playing against all the strong teams consecutively.

We give next an outline of the typical constraints of the *sports scheduling problem*. We believe that these constraints are representative of many scheduling scenarios within the area of sports scheduling. We make no strict distinction between hard and soft constraints. They will be given by the instances themselves. The goal is to find a feasible solution that is the most acceptable for the sports league owner. That is, a solution that has no hard constraint violations and that minimizes the weighted sum of the soft constraint violations. The weights will also be given by the instances themselves. A league can use a mixture of the following constraints as a framework for its schedule generation:

- C01. There are at most *R* rounds available for the tournament.
- C02. A maximum of *m* games can be assigned to round *r*.
- C03. Each team plays at least m_1 and at most m_2 games at home.
- C04. Team *t* cannot play at home in round *r*.
- C05. Team *t* cannot play away in round *r*.
- C06. Team *t* cannot play at all in round *r*.
- C07. There should be at least m_1 and at most m_2 home games for teams $t_1, t_2, \dots$ on the same day.
- C08. Team *t* cannot play at home on two consecutive calendar days.
- C09. Team *t* wants to play at least m_1 and at most m_2 away tours on two consecutive calendar days.
- C10. Game *h-team* against *a-team* must be preassigned to round r.
- C11. Game *h-team* against *a-team* must not be assigned to round *r*.
- C12. A break cannot occur in round *r*.
- C13. Teams cannot have more than *k* consecutive home games.
- C14. Teams cannot have more than *k* consecutive away games.
- C15. The total number of breaks must not be larger than *k*.
- C16. The total number of breaks per team must not be larger than *k*.

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C17. Every team must have an even number of breaks.
C18. Every team must have exactly *k* number of breaks.
C19. There must be at least *k* rounds between two games with the same opponents.
C20. There must be at most *k* rounds between two games with the same opponents.
C21. There must be at least *k* rounds between two games involving team t_1 and any team from the subset t_2, t_3, ...
C22. Two teams play against each other at home and in turn away in 3RR or more.
C23. Team *t* wishes to play at least *m*1 and at most m_2 home games on $weekday_1$, $m_3 – m_4$ on $weekday_2$ and so on.
C24. Game *h-team* against *a-team* cannot be played before round *r*.
C25. Game *h-team* against *a-team* cannot be played after round *r*.
C26. The difference between the number of played home and away games for each team must not be larger than *k* in any stage of the tournament (a *k*-balanced schedule).
C27. The difference in the number of played games between the teams must not be larger than *k* in any stage of the tournament (in a relaxed schedule).
C28. Teams should not play more than *k* consecutive games against opponents in the same strength group.
C29. Teams should not play more than *k* consecutive games against opponents in the strength group *s*.
C30. At most *m* teams in strength group *s* should have a home game in round *r*.
C31. There should be at most *m* games between the teams in strength group *s* between rounds r_1 and r_2.
C32. Team *t* should play at least m_1 and at most m_2 home games against opponents in strength group *s* between rounds r_1 and r_2.
C33. Team *t* should play at least m_1 and at most m_2 games against opponents in strength group *s* between rounds r_1 and r_2.
C34. Game *h-team* against *a-team* can only be carried out in a subset of rounds r_1, r_2, r_3, ...
C35. A break of type *A/H* for team t_1 must occur between rounds r_1 and r_2.
C36. The carry-over effects value must not be larger than *c*.

Next we consider some examples of these constraints. If the number of available rounds specified in constraint C01 is higher than the minimal number of rounds needed to complete the tournament, a relaxed schedule is allowed, and constraint C02 can be used to set the maximum number of games for each round. Constraint C03 is used when the number of home and away games is not the same for all teams (valid for 1RR and 3RR). A team cannot play at home (C04) if its venue is unavailable due to some other event. A team cannot play away (C05) if it has an anniversary on that day and it requests to play at home. If a team has a game in another league, it cannot play at all on certain round (C06). If two teams share a venue, constraint C07 can be used to avoid the two teams playing at home in the same round, by setting $m_1 = 0$ and $m_2 = 1$ for this pair of teams. Constraints C08 and C09 are used to schedule away tours.

Some games can be preassigned to certain rounds using constraint C10. The constraint is also useful for preassigning away tours or preassigning special mini-tournaments between some teams on weekends. When a game should not necessarily be played in a specific round, but rather in some period of the season, this can be expressed using constraint C34. When there is another important event on a specific day (round) that can compete in interest with a league game, there should not be any “popular” game in that round (C11).

Even if the main goal often is to find a schedule with the minimum number of breaks, constraints from C12 to C18 can also be used to set requirements concerning the number of breaks. Furthermore, quite often a break is not allowed in the second or in the last round (C12). In some cases, a break is desirable in some period of the season, which can be enforced using constraint C35.Two games between the same opponents cannot usually be played on close days (C19). Constraints C19 and C20 used together results in a mirrored schedule if *k* is set to $n – 1$. If a triple or quadruple round robin tournament is played, it’s common that two teams should play against each other at home and in turn away (C22).

Most of the teams prefer to play their home games at weekends to maximize the number of spectators. However, some teams might prefer weekdays to maximize the number of business spectators. Constraint C23 is used to limit a team’s number of home games on a weekday (e.g. Wednesday), assuming that the day on which it will be played is known for every round. Constraint C24 can be used in the latter 2RR when 4RR is solved by splitting it into two 2RRs. The constraint ensures that there are at least a given number of rounds between two games with the same opponents (see also C19). A team might also prefer home games against important opponents in the second half of the season, as these games are likely to be more attractive near the end of the competition. For the same reason, a game between local rivals might be preferred to be scheduled early in the season (C25).

Minimizing the difference between the number of played home and away games for each team at any stage of the season (C26) is an important fairness criterion. If not all teams play in each round, i.e. a relaxed schedule is to be generated, another fairness criterion is to minimize the difference in the number of played games between the teams (C27).

Another goal can be to avoid a team playing against extremely weak or extremely strong teams in consecutive rounds (C29), or to avoid consecutive games between teams located nearby (C28). A TV broadcaster might require that the most interesting teams should not all play at home on the same day (C30). Constraint C31 can be used to enforce a balanced spread of games between top teams over the season. Constraint C32 can be used to ensure that a team has a home game against a top team in each half of the season. Constraint C33 can be used to make sure that each team plays against a strong team in the first rounds of the season. Finally, for sports where carry-over effects could influence the result of the tournament, these effects can be balanced using constraint C36.

We model the sports scheduling problem using a simple text file format. The file format consists of a header section and a constraint section. The header section has eight elements:

\# *benchmark instance*, the name of the instance
\# *number of teams*
\# *team names*

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- # *number of round robins*
- # *additional games*, which can be used to set other games besides those in the round robins
- # *number of rounds*
- # *weekdays for rounds*
- # *strength groups*

The constraint section has one element for each constraint in use:

- # *C04. Team t cannot play at home in round r*
- # *C07. There should be at least m_1 and at most m_2 home games for teams t_1, t_2, ...*
- # *and so on.*

The detailed and up-to-date information on the file format and sample files can be found in [40]. We believe that this model helps researchers to evaluate, compare and exchange their solution methods.

Notice that some constraints are in fact generalizations of others (e.g. constraint C34 is a generalization of C24 and C25), or could be expressed using a series of other constraints (e.g. ensuring that a team does not play at all in a particular round (C06) can also be done by specifying that a team does not play at home (C04) or away (C05) in that round). However, we chose not to reduce the set of constraints to its most compact form because we think these redundant constraints make it easier to understand what the requirements for a tournament are, and/or reduce the number of lines in the described text file format.

IV. Artificial Benchmark Instances

The generation of standard benchmark problems has not received much attention. Some test instances for round robin tournaments have been introduced in [41]. Kyngäs and Nurmi [38] presented a set of artificial test instances for the constrained minimum break problem. For the traveling tournament problem, test instances can be found in [42]. No set of standard test instances has previously been published for the real-world constrained minimum break problem.

Researchers quite often only solve some special artificial cases or one real-world case. The strength of random test instances is the ability to produce many problems with many different properties. Still, they should be sufficiently simple for each researcher to be able to use them in their test environment. The strength of practical cases is self-explanatory. However, an algorithm performing well on one practical problem may not perform satisfactorily on another practical problem; which is why we present a collection of test instances for both artificial and real-world cases. We start with artificial cases.

Table II shows 22 test instances some of which have earlier been introduced in [38]. All but two must be compact schedules (see constraint C01). Most of the instances are double round robin tournaments (RR = 2). The number of teams (n) varies between 8 and 100. The challenge is to find either a round robin tournament (C15 = empty) or a round robin tournament that minimizes the number of breaks (C15 = Min). In some instances there must be at least k rounds before two teams meet again (see constraint C19). Additional constraints may include place constraints (see constraints C04 and C05) and complementary constraints (see constraint C07). The only soft constraints in these instances are C15, all other constraints are hard.

Also note the following points:

- R14K7P208 has four home game restrictions and four away game restrictions in each round totaling a number of 208 C04 and C05 constraints.
- In the instances where C07 constraints exist, teams 1 and 2, teams 3 and 4, and so on cannot play at home at the same day - that is, $m_1 = 0$ and $m_2 = 1$.
- R16P116C23 and B16K12P116C1 are constructed using data from one season of the Finnish major ice hockey league for players under 20 years of age. The games should be scheduled for 57 rounds instead of the 45 rounds needed for a compact schedule. Furthermore, the home teams for the third round-robin are given.
- The home teams for B16C30 are given.

Table II
Artificial benchmark instances: R14K7P208 (1), R16P116C23 (2), R100C8 (3), B8 (4), B8K0P30 (5), B8K2P30 (6), B10 (7), B10K2C4 (8), B10K3 (9), B12 (10), B12K3 (11), B12K8 (12), B12K8C4 (13), B12K8P30 (14), B12K8P30C3 (15), B12K8P30C4 (16), B12K10 (17), B14 (18), B16 (19), B16K3 (20), B16C30 (21), B16K12P116C1 (22).

ID	RR	*n*	C 01	C 15	C 19	C 04+05	C 07	C 10	Best sol
1	2	14			7	208			found
2	3	16	57			116	23		found
3	2	100					8		found
4	2	8		Min					6*
5	2	8		Min		30			10
6	2	8		Min	2	30			12
7	2	10		Min					8*
8	2	10		Min	2		4		10
9	2	10		Min	3				16
10	2	12		Min					10*
11	2	12		Min	3				16*
12	2	12		Min	8				24
13	2	12		Min	8		4		24
14	2	12		Min	8	30			30
15	2	12		Min	8	30	3		34
16	2	12		Min	8	30	4		1H+42
17	2	12		Min	10				30
18	2	14		Min					12*
19	2	16		Min					14*
20	2	16		Min	3				20*
21	1	16		Min		30			36
22	3	16	57	Min	12	116	1	45	30

* known optimum

The optimal number of breaks is only known for seven

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instances [7]. The other best solutions were found while preparing this article. These solutions provide a good starting point for communications between sports scheduling researchers. The next section introduces another set of instances which further widens this aim.

V. Real-World Benchmark Instances

There are not many cases where academic researchers have been able to close a contract with a sports league owner. The real-world instances introduced in this section are based on such cases. In order not to reveal league secrets the instances might slightly differ from the actual problems solved for the league owners. The instances are derived from Finnish, Austrian, German, Argentine, Chilean, Belgian and Brazilian leagues. We give a short description of these leagues. In all the leagues the most important goal is to minimize the number of breaks.

The Finnish Major Ice Hockey League (FIN1) has 14 teams. The basis of the schedule is a quadruple round robin tournament resulting in 52 games for each team. In addition, the teams are divided into two groups of seven teams to get a few more games to play. These teams play a single round robin tournament resulting in 6 games. Therefore, there are 58 games for each team and a total of 406 games to be scheduled. The three most important goals are to have no home games on the same day for some team pairs (C07), to have at least 5 rounds between two games with the same opponents (C19) and to have an equal number of home games on Saturdays for all teams (C23). For more details, refer to [37]. The Finnish 1st Division Ice Hockey League (FIN2) has 12 teams. The basis of the schedule is a quadruple round robin tournament resulting in 44 games for each team. In addition, each team plays at home against the Finnish U20 team (national team for players under 20 years of age). Therefore, there are 45 games for each team and a total of 276 games to be scheduled. Distances between the home venues of some of the teams are quite significant. The three most important goals are to generate away tours (C09), to have at least 7 rounds between two games with the same opponents (C19) and to have an equal number of home games at weekends for all teams (C23). For more details, refer to [38].

The basis of the schedule for the Austrian Soccer Championship (AUS1), the German Soccer Championship (GER1) and the German Handball Championship (GER2) are mirrored double round robin tournaments. The number of teams is 10, 18 and 18, respectively. The most important goal is to reach the minimum number of breaks. The set of rounds teams can play at home or away may be restricted. Specific matches of a home team against an away team can only be carried out in a subset of rounds. In AUS1 some pairs of teams cannot play at home in parallel; thus one of them must play at home in each round. In GER1, subsets of teams cannot play an arbitrary number of home games in parallel in some rounds. In GER2 the number of matches between the six strongest teams is restricted to one per round. For more details, refer to [32].

The major volleyball league in Argentina was composed of 12 teams in 2007/2008, and 11 teams in 2008/2009 and 2009/2010. Although the main interest of the schedule design is the minimization of the global travel distances [36], the instance ARG1 has been adapted to suit the framework introduced in this work. Another feature of this league that has been simplified consists of a paired schedule design. In such a schedule, the teams' respective matches are grouped into pairs called couples. Each weekend, one couple visits another couple, and the four possible matches between the corresponding teams are played.

Table III
Real-world benchmark instances.

ID	RR	*n*	Mirrored	Hard constraints	Soft constraints
FIN1	2*	14	No, k=7	01,04,07,10, 12	07,13,14,15, 16,19,22,23, 24,26,27
FIN2	2	12	No, k=5	01,04,10,12	04,13,14,15, 16,19,23,26
AUS1	2	18	Yes	01,07,15,19, 20,34	04
GER1	2	18	Yes	01,05,07,15, 19,20,34	04
GER2	2	18	Yes	01,05,15,19, 20,31,34,35	04
ARG1	2	12	Yes	01,04,07,10, 12,19,20,23, 26	13,14,15
CHI1	1	20	Yes	01,03,04,05, 12,16,24,25, 31	13,14
BEL1	2	18	Yes	01,04,07,12, 13,14,15,16, 19,20,31	04,05,07,24, 25,29,30,32, 33,34
BEL2	2	18	Yes	01,04,07,12, 13,14,15,16, 19,20,31	04,05,07,24, 25,29,30,32, 33,34
BEL3	2	18	Yes	01,04,07,12, 13,14,15,16, 19,20,31	04,05,07,24, 25,29,30,32, 33,34
BRA1	2	20	Yes	01,03,07,13, 14,15,17,18, 24,25,28,29, 31,32,34	11

The Chilean first division tournament was composed of 20 teams until 2008; since 2009, there have been just 18 teams. There are two tournaments per year: the Opening Tournament and the Closing Tournament. Both competitions consist of a single round robin tournament and then the eight teams with the highest points advance to the playoffs of the championship (until 2008 the teams were divided into groups and the best two teams in each group would advance to the playoffs). The problem has some constraints that are not considered in the test instance, mainly related to the Chilean geography. Chile is a very long and thin country, and for that reason there are constraints related to the trips that teams should or should not make. There are also constraints related to security issues and international competitions. For more details, refer to [33].

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The instances BEL1, BEL2, and BEL3 represent the scheduling problem in the highest soccer league in Belgium for the seasons 2006-2007, 2007-2008, and 2008-2009 respectively. This league is played as a mirrored double round robin tournament with 18 teams, involving 306 games that need to be played in 34 rounds. It is imperative that these schedules have the minimal number of 48 breaks (C15), and no team should start or end the league with a break (C12). Furthermore, the two teams that share a stadium cannot play at home in the same round (C07). Apart from that, there are various constraints, originating from Belgacom TV, (the company that broadcasts the league), the police, the clubs and the association itself. For instance, a mayor can forbid a game being played in his or her city in one or more rounds if he/she feels public safety cannot be guaranteed (C04). Clubs may have a number of wishes related to the fairness of the schedule, especially related to the timing of their encounter with strong teams: no team wishes to face all traditionally strong opponents in a row (C33), or likes to host a top game in the summer, when many fans are abroad for holidays (C24). According to Belgacom TV, one way to increase the viewing figures is a schedule where at least one (and preferably two) of four teams that are considered to be top teams plays an away game in each round (C30). The underlying motivation is that a top team's home games are less interesting, since the top team tends to win these games without much effort. Moreover, the top games should be spread over the season (C31). The association itself requests, among other things, that every team receives a top team at home at least once in each half of the season (C32). For more details on the constraints that play a role, and the motivation for these constraints, werefer to [34].

Soccer is the most widely practiced sport in Brazil. The Brazilian national soccer tournament organized every year by the Brazilian Soccer Confederation (CBF) is the most important sporting event in the country. Its major sponsor is TV Globo, the largest media group and television network in Brazil. The most attractive games are those involving teams with more fans and better players, and, consequently, also with larger broadcast shares [19]. Games involving teams from São Paulo and Rio de Janeiro are of special interest for broadcasting through open TV channels due to their corresponding larger revenues from advertising. The competition lasts for seven months (from May to December) and is structured as a compact mirrored double round robin tournament played by 20 teams. Every team has a home city and some cities host more than one team. There are at most two rounds of games per week: mid-week rounds are played on Wednesdays and Thursdays, while weekend rounds are played on Saturdays and Sundays. Elite teams are those with larger numbers of fans, better records of previous participations in the tournament, and more valuable players. The most important games involve elite teams and, as far as possible, should be played during the weekends, when they can attract larger attendances and TV audiences. The participating teams and the dates available for playing the games change from one year to the next.

Table III shows the above mentioned eleven real-world instances. Most of the instances are mirrored double round robin tournaments. In non-mirrored instances there must be at least *k* rounds before two teams meet again. The number of teams varies between 12 and 20. The table lists all the hard and soft constraints that are in action for the instances.

VI. Best Solutions to Five Real-World Instances

In this section we publish the best solutions we have found for some of the real-world instances introduced in Section 5. We invite the sports scheduling community to find solutions to the unsolved instances. We also briefly discuss our solution methods.

The overall goal of the real-world cases is to find a feasible solution that is the most acceptable for the sports league owner. That is, a solution that has no hard constraint violations and that minimizes the weighted sum of the soft constraint violations. The importance of the soft constraints is handled by giving them different weights. The values of the weights are decided based on the negotiations with the league owner and the teams. We refer to [40] for what the values of the weights for the real-world instances are. We also refer to [40] for how the constraint violations are calculated. As an example, a violation is counted for the constraint C04 if team t plays at home in round r, and one violation is counted for the constraint C07 for each home game less than m_1 or more than m_2.

FIN1 and FIN2 were solved by a cooperative local search metaheuristic [22]. BEL1, BEL2, BEL3 were solved using a multiphase decomposition approach ending up with a mixed integer programming model that was solved using CPLEX [34]. Table IV shows the best solutions we have found for FIN and BEL instances. Together with the solutions for the artificial benchmark instances in Section 4, these solutions provide a good starting point for communications between sports scheduling researchers.

Table IV
Best solutions for five of the real-world benchmark instances.

ID	Best solution	Solution method	Found by
FIN1	1 hard + 52	Metaheuristic	Kyngäs and Nurmi
FIN2	16	Metaheuristic	Kyngäs and Nurmi
BEL1	1918	Multiphase approach	Goossens and Spieksma
BEL2	2002	Multiphase approach	Goossens and Spieksma
BEL3	2316	Multiphase approach	Goossens and Spieksma

We also briefly mention how the other instances were originally solved. AUS1, GER1 and GER2 instances were solved using a combination of a graph coloring algorithm, a semi-greedy algorithm and a truncated branch-and-bound algorithm [32] ARG1 was solved by a straightforward integer programming model, resorting to ILOG CPLEX for the computational solution of the model [36]. CHI1 was solved using a two phase approach. First, home-away patterns were created and then the constraint programming model was solved using CPLEX [33]. BRA1 was solved using a multiphase approach similar to that presented in [31]. The key to success is in considering the constraints as early as possible in order to reduce the number of patterns as much as possible, leaving the IP solver with as light a problem possible [20].

VII. CONCLUSIONS

We defined a framework for a highly constrained sports scheduling problem, which was modeled from the requirements of various professional sports leagues. A set of artificial and real-world instances were introduced. We have published the best solutions for the artificial instances and five of the real-world instances. The sports scheduling community is invited to challenge our solutions as well as to find solutions to the unsolved instances. The instances are available online.

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