Operations Research

Publication details, including instructions for authors and subscription information:
http://pubsonline.informs.org

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To cite this article:
Robert A. Russell, Janny M. Y. Leung, (1994) Devising a Cost Effective Schedule for a Baseball League. Operations Research 42(4):614-625. https://doi.org/10.1287/opre.42.4.614

DEVISING A COST EFFECTIVE SCHEDULE FOR A BASEBALL LEAGUE

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(Received January 1993; revision received August 1993; accepted December 1993)

In this paper, we discuss the problem of devising a cost effective schedule for a baseball league. Sports scheduling is a notoriously difficult problem. A schedule must satisfy constraints on timing such as the number of games to be played between every pair of teams, the bounds on the number of consecutive home (or away) games for each team, that every pair of teams must have played each other in the first half of the season, and so on. Often, there are additional factors to be considered for a particular league, for example, the availability of venues on specific dates, home-game preferences of teams on specific dates, and balancing of schedules so that games between two teams are evenly-spaced throughout the season. In addition to finding a feasible schedule that meets all the timing restrictions, the problem addressed in this paper has the additional complexity of having the objective of minimizing travel costs. We discuss some structural properties of a schedule that meets the timing constraints and present two heuristics for finding a low-cost schedule. The methodology is used to develop an improved schedule for the Texas Baseball League.

The game of baseball is the national pastime of the United States, and is popular in many other countries as well. Baseball requires not only physical abilities but is also a game of strategy. One of the more difficult strategic problems in baseball occurs off the field—that of devising a season schedule for the league.

Each sport has its own set of scheduling objectives and constraints which define the characteristics of an effective schedule or timetable. Previous research on the sports league scheduling problem includes the graph-theoretic work of de Werra (1980, 1985, 1988) and Schreuder's (1992) construction of a timetable for the professional soccer leagues in The Netherlands. Ferland and Fleurent (1991) developed a decision support system which has been helpful in constructing the schedule for the National Hockey League. Campbell and Chen (1976) developed a minimum distance schedule for a collegiate basketball conference. Bean and Birge (1980) investigated reducing travel costs for the National Basketball Association.

The problem addressed in this paper is the scheduling problem of the Texas League. The Texas League is a double A minor league baseball organization. The scheduling of a minor league is similar to the scheduling of major league baseball, but it has a few important differences. Minor league attendance and revenue are considerably less than that of the major leagues and, consequently, travel cost minimization is of critical importance in the minor leagues. Historically, the Texas League has attempted to minimize travel costs by constructing schedules that consist of lengthy series between teams. These series or rounds typically consist of five consecutive games between the same teams with an occasional 6-game round. The rounds are longer than the typical 3- to 4-game rounds in the major leagues; however, longer rounds mean fewer road trips and reduced travel expenses.

The Texas League consists of eight baseball teams divided into two divisions. Teams from Arkansas, Jackson, Shreveport, and Tulsa comprise the East Division, while teams from El Paso, Midland, San Antonio, and Wichita comprise the West Division. During the course of a season, every pair of teams must play a required number of home and away games. Because a team must play teams in its own division as well as teams in another division, but for a different number of games, the problem of

Subject classifications: Production/scheduling, applications: heuristics for cost effective baseball timetables. Recreation and sports: heuristics for cost effective baseball schedules. Transportation, costs: minimizing baseball league travel costs.
Area of review: OR PRACTICE.

0030-364X/94/4204-0614 $01.25

devising a season schedule is more difficult than for other sports, such as soccer.

In the current Texas League schedule, teams in the same division play each other 16 games at home and 16 games away, and play every team in the other division 5 games at home and 5 games away. The games are played by meeting for 3 home and 3 away rounds with teams in the same division, and 1 home and 1 away round with teams from the other division.

Changing the current league schedule has become a factionalized and politicized issue within the Texas League. Some teams support the notion of a more varied and balanced schedule. Others prefer the lower travel costs associated with playing the majority of games against teams in the same division.

Quotes from intraleague correspondence illustrate the entrenched attitudes of the different teams' management. In 1987 one general manager said:

> I have just finished talking with some other league directors who, like myself, are disgusted with the fact that this is the third attempt by team A (not Tulsa) to change the Texas League schedule. ... How many times do people call your office and ask who are you playing? They ask what time is the game; when the team will return home; do you have a promotion?

In 1989 the president of team A wrote to the league saying:

> Six day visits to another city are ludicrous. The players, our staffs, and our farm directors hate them. More importantly, it is not the way to showcase our product and optimize our sales. I think that it is time that we take a step forward and improve the quality of the entertainment that we are offering.

In 1988, the Tulsa Drillers of the Texas League proposed a new schedule format that consisted primarily of 4-game rounds, more road trips, and more variety in the competition between teams. The proposed schedule was similar to the major league schedule and was intended to stimulate fan interest and increased attendance; however, the proposed schedule increased travel mileage by more than 53%. The schedule was rejected 6–2 at the annual owners' meeting. Subsequently, the general management of the Tulsa Drillers Organization approached the authors for help in developing a more cost effective schedule that would appeal to more teams in the league.

Developing a league schedule involves much more than minimizing travel costs. League rules require that each team play no more than 14 consecutive games on the road and no more than 14 consecutive home games. Additionally a team must have time off (a rest day with no games scheduled) every 21 days. It is also preferred that each team play every other team in the first half of the season and that consecutive rounds between the same teams be avoided.

Additionally, there are many other features of a schedule that are desirable. The Texas League would prefer that each team play a home series that spans either the third or Fourth of July. To sustain the interest of the fans (who are the major source of income for the teams), the schedule for the teams must be varied sufficiently. Since teams play each other so often, it is desirable that these games be evenly spaced throughout the season. These considerations increase the complexity of the scheduling problem. While the last feature is important, it is considered secondary and is not considered explicitly in this paper.

In addressing the Texas League scheduling problem, we developed a schedule in the format of the current 26-round schedule as well as a new schedule in a more varied 34-round format. In the next section we present the underlying methodology for schedule generation.

1. TWO-STAGE APPROACH

One way to approach the scheduling problem is to consider it in two stages: First, the generation of home-away patterns, and second, the assignment of teams to the home-away patterns. A *home-away pattern* (HAP) is a list for a team indicating the location and 'opponent' for each period. If there are m teams, then a *home-away timetable* (HAT) is a set of m home-away patterns. Following Schreuder, a HAT is represented by a matrix with m rows, where HAT $(i, k) = -j$ (respectively, $+j$) if the team with the ith HAP plays away (respectively, at home) in the kth period against the team with the jth HAP. An example of a HAT for a round robin for four teams is shown in Table I.

Table I
An Example of a HAT for a Round-Robin for 4 Teams

	Period 1	2	3
1	−3	+2	+4
2	−4	−1	+3
3	+1	+4	−2
4	+2	−3	−1

By assigning different teams to the set of HAPs in a HAT, we can obtain different actual schedules, as shown in Table II.

Using a two-stage approach to the scheduling problem, we first generate a home-away timetable (HAT) that meets the timing requirements for the teams, and then find the least total travel-cost assignment of the teams to the HAPs with respect to that HAT. Even with a fixed HAT, finding the least-cost schedule is NP-hard. While the constraints of matching m teams to m HAPs are easy to model as those of an assignment problem, the objective is highly nonlinear (in fact, it is a polynomial of degree m).

We next examine some combinatorial properties of a schedule. In Section 2, we discuss the construction of a low-cost schedule, obtain a lower bound for the travel costs, and apply our approach to the Texas League scheduling problem.

1.1. Combinatorial Properties of the Schedule

In the current schedule for the Texas League, each time two teams meet they play a series of 5 (or 6) games, which we will call a *round*. The league's current schedule divides the season into three segments. In the first and third segment, each team plays every other team in its *own* division for one round at home and one round away. In the middle segment, the two divisions mix and each team plays every other team (in both divisions) for one away and one home round. (The round consists of 6 games between teams from the same division and 5 games between teams from different divisions.) With 5- or 6-game rounds, the league rules will prohibit more than two consecutive away rounds.

Table II
An Example of Two Different Schedules From the Same HAT

Assignment				Period		
Team	⇔	HAP		1	2	3
A	⇔	1	A	−C	+B	+D
B	⇔	2	B	−D	−A	+C
C	⇔	3	C	+A	+D	−B
D	⇔	4	D	+B	−C	−A

Assignment				Period		
Team	⇔	HAP		1	2	3
A	⇔	1	A	−B	+D	+C
B	⇔	3	B	+A	+C	−D
C	⇔	4	C	+D	−B	−A
D	⇔	2	D	−C	−A	+B

The current format of 5- or 6-game rounds with the season divided into three segments is one that the Texas League has traditionally used. Dividing the season into three segments in this way simplifies the scheduling problem somewhat because each segment now becomes a double round robin, that is, each team plays every other team once away and once at home. (The second segment is a double round robin for 8 teams, whereas the first and third segment each consists of two double round robins, one for each division of 4 teams.) With each round consisting of 5 or 6 games, the league rules prohibit more than two consecutive away rounds and more than two consecutive home rounds for each team. One way to construct a schedule to ensure that each team plays every other team in the first half of the season is to construct a round robin schedule for the first half, then repeat the schedule with the home-away teams reversed for the second half.

Following Schreuder, we will call a team's round a (home, respectively away) *break* if the previous round is also a (home, respectively away) round. Clearly, to minimize travel costs, a team would like to maximize the number of away breaks.

Let us first consider the basic building block of a schedule, that of a round robin. Schreuder showed that for a round robin of $2n$ teams, the minimum number of breaks is $2n - 1$, and presented a construction of a schedule that achieves it. However, unlike Schreuder's problem, we are concerned with cost and we would like a schedule that *maximizes* the number of breaks. For $2n$ teams, each team must play $2n - 1$ rounds. Since there can be no more than two consecutive home or away rounds, the maximum number of breaks for a team is $\lfloor 2n - 1/2 \rfloor = n - 1$. The first question is whether there exists a schedule where every team achieves this maximum number of breaks. Such a schedule is possible for $n = 1$ and $n = 2$, but, unfortunately, impossible for $n \geqslant 3$. (For a proof, see Theorem 1 in Appendix A.)

Also in Appendix A, we describe an algorithm for constructing a HAT for a round robin for $2n$ teams which achieves $2n(n - 1) - (2n - 4)$ breaks for $n \geqslant 2$. This gives a lower bound on the maximum number of breaks that can be achieved. We note, however, that this bound is tight only for $n \leqslant 3$. The first seven rounds of the HAT in Table III is a round robin for $2n = 8$ teams that achieves $2n(n - 1) - 2 = 22$ breaks. Since breaks must occur in pairs, this achieves the maximum number of breaks possible.

The HAT for a double round robin can be obtained by repeating the HAT for a simple round robin with the signs reversed (that is, the home and away teams

Table III
A HAT for a Double Round Robin for 8 Teams With a Maximum Number of Breaks

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	+5	+2	−7	−4	+8	+3	−6	−3	+6	−5	−2	+7	+4	−8
2	+6	−1	−8	+3	+7	−5	+4	+5	−4	−6	+1	+8	−3	−7
3	+7	+4	−5	−2	+6	−1	−8	+1	+8	−7	−4	+5	+2	−6
4	+8	−3	−6	+1	+5	−7	−2	+7	+2	−8	+3	+6	−1	−5
5	−1	+6	+3	−8	−4	+2	+7	−2	−7	+1	−6	−3	+8	+4
6	−2	−5	+4	+7	−3	+8	+1	−8	−1	+2	+5	−4	−7	+3
7	−3	+8	+1	−6	−2	+4	−5	−4	+5	+3	−8	−1	+6	+2
8	−4	−7	+2	+5	−1	−6	+3	+6	−3	+4	+7	−2	−5	+1

reversed). In constructing the second half of a double round robin, the sequence of the rounds can be altered. This might be necessary for our problem so that no team plays three consecutive away or home games. It might also be desirable if more breaks are created. Table III shows a HAT for a double round robin for 8 teams where the rounds are sequenced so that the number of breaks are maximized. (Note that every team still plays every other team in the first half of the season, and no team plays more than two consecutive home or away rounds).

2. FINDING LOW-COST SCHEDULES

The minimum cost schedule for a fixed HAT can be found by evaluating the total travel costs for all possible assignments of teams to the HAPs. For example the HAT for the 1990 schedule for the Texas League is shown in Table IV. Notice that the teams assigned to the first four HAPs must be in the same division (and similarly for the last four HAPs). Table V (the upper triangle) shows the distances between the locations of the teams in the Texas League. The lower triangular half of the table shows the estimated travel costs. Using these costs between the team locations, the minimum travel cost schedule for the Texas League for the HAT shown in Table IV is obtained by computing the total travel cost for all the $2(4!)(4!) = 1{,}152$ possible assignments of the teams to the HAPs. The optimal team-HAP assignments are shown in Table VI. The optimal assignment yields a savings of \$5,512 and 734 miles.

2.1. Generating Home-Away Timetables

By evaluating all the possible assignments of teams to the HAPs we can obtain the minimum total travel costs schedule for a given HAT. However, it may be possible that there are other HATs that may provide a lower-cost schedule. Recall that the sequence of the rounds can be altered as long as every pair of teams plays a sufficient number of games in the first half of the two rounds in the sequence. Such exchanges are feasible as long as they do not create three consecutive home or away games for any team. Appendix B describes a more general exchange heuristic for generating a new HAT from a given HAT.

Table IV
The HAT for the 1990 Schedule for the Texas League

Round	1	1	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	−2	4	−3	−4	3	2	−6	−7	6	7	−4	2	3	−3	4	−2	8	5	−8	−5	2	4	−3	−4	3	−2
2	1	3	−4	−3	4	−1	5	8	−5	−8	3	−1	4	−4	3	1	−6	−7	6	7	−1	3	−4	−3	4	1
3	−4	−2	1	2	−1	4	−7	−6	7	6	−2	4	−1	1	−2	−4	5	8	−5	−8	4	−2	1	2	−1	−4
4	3	−1	2	1	−2	−3	8	5	−8	−5	1	−3	−2	2	−1	3	−7	−6	7	6	−3	−1	2	1	−2	3
5	−7	8	7	−6	−8	6	−2	−4	2	4	−6	8	7	−8	−7	6	−3	−1	3	1	−6	−8	7	8	−7	6
6	8	7	−8	5	−7	−5	1	3	−1	−3	5	7	−8	−7	8	−5	2	4	−2	−4	5	−7	−8	7	8	−5
7	5	−6	−5	8	6	−8	3	1	−3	−1	8	−6	−5	6	5	−8	4	2	−4	−2	8	6	−5	−6	5	−8
8	−6	−5	6	−7	5	7	−4	−2	4	2	−7	−5	6	5	−6	7	−1	−3	1	3	−7	5	6	−5	−6	7

Total travel cost = \$414,992; total travel distance = 77,198 miles.

Division	East				West			
Team	ARK	JAC	SHR	TUL	ELP	MID	SAN	WIC
HAP	6	8	5	7	1	3	4	2

Table V
Mileage (Upper Triangle) and Estimated Travel Costs (Lower Triangle) Between the Texas League Cities

City	ARK	ELP	JAC	MID	SAN	SHR	TUL	WIC
Arkansas	– –	947	246	627	570	195	271	446
El Paso	4,168	– –	1,008	302	570	814	778	742
Jackson	970	5,120	– –	703	599	218	543	718
Midland	3,272	975	4,840	– –	325	508	552	631
San Antonio	3,132	975	4,700	1,050	– –	383	530	635
Shreveport	945	3,454	945	2,880	1,150	– –	377	552
Tulsa	970	3,132	4,700	2,936	2,712	1,100	– –	175
Wichita	1,400	4,700	4,700	4,840	3,412	4,000	900	– –

2.2. The Texas League

The HAT for the 1990 schedule of the Texas League is shown in Table IV. With the assignment of teams as indicated and using the costs (distance) shown in Table V, the total travel cost is $414,992 and the distance is 77,198 miles. Applying the exchange heuristic, but only allowing exchanges that do not create three consecutive home or away rounds and that reduces the overall travel distance (with respect to the current assignment of teams to HAPs), we can generate a new HAT. The minimum total distance assignment for this new HAT can be computed. We can then seek new improved exchanges in the new HAT (with respect to the new assignments) and iterate between assignment and exchange stages until no further reduction in the total travel distance is found. This two-stage iterative approach can be applied to the search for a low-cost schedule, starting with several different HATs. Table VII shows a different HAT with an assignment of teams where the total travel cost is $388,152 and the total distance is 72,906 miles, which is a 6.5% reduction in cost and a 5.6% reduction in the total travel distance as compared to the 1990 schedule shown in Table IV.

2.3. Lower Bound

Consider a double round robin of $2n$ teams where each team cannot have more than two consecutive away rounds. For each team the ideal minimum travel distance is one where the team makes $n - 1$ trips of two away rounds (visiting two teams) and one trip with one away round. The pairing of the teams for these trips, which minimizes the travel distance for the team, can be found *simultaneously for all teams* by finding a minimum-weight matching with respect to the distances shown in Table V (see Section 3). With the three-segment format of a season schedule, the single round trip in the first and second segments or the second and third segments (but not both) can be combined to realize additional reduction in the travel distance for a team (see the example in Figure 1). The sum of these ideal minimum travel distances for all the teams provides a lower bound on the total travel distances for a feasible schedule. For the Texas League, the lower bound so obtained is 68,314 miles, and $346,849 if the lower bound is computed with respect to the travel costs in Table V. In view of Theorem 1, it is unlikely that these ideal minimum cost trips can be combined to give a feasible schedule, so this lower bound is unlikely to be tight. Campbell and Chen discuss the scheduling of a basketball league (a double round robin) where they present a schedule in which it appears that all the teams achieve the ideal minimum travel distance. However, their schedule is not compact in the sense that not all teams play in every round. In the Texas League season schedule, no team is allowed to be idle in any round.

Using the lower bound, the schedule in Table VII is guaranteed to be within 6.7% of the optimum distance and 11.9% of the optimum cost.

2.4. Travel Costs

The travel costs for the various teams in the Texas League are varied and nonlinear. Highway distance

Table VI
Optimal Assignment of Teams to the HAT for the 1990 Season

Division	East				West			
Team	ARK	JAC	SHR	TUL	ELP	MID	SAN	WIC
HAP	1	4	2	3	5	6	7	8

Table VII
A Low-Cost Schedule for the Texas League

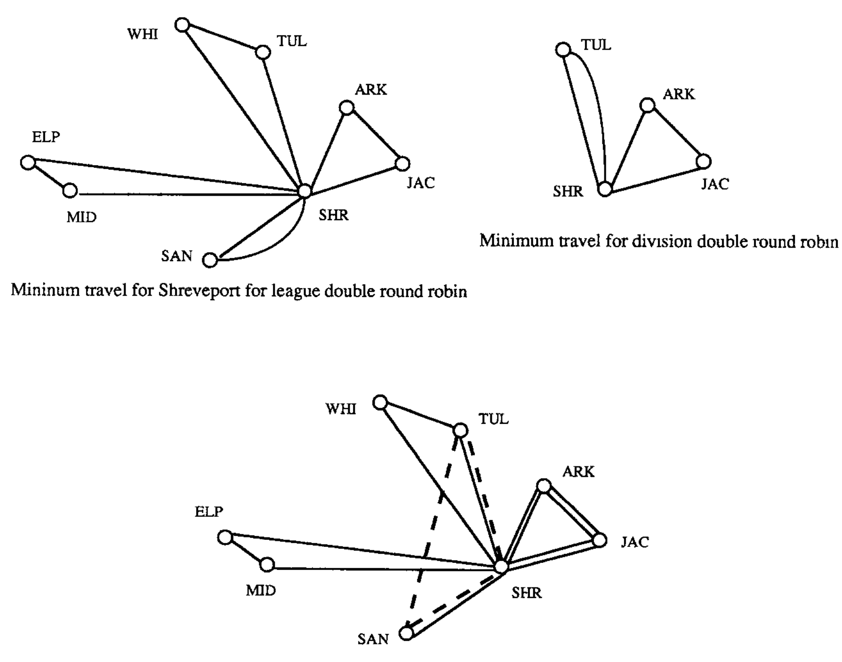
Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	−3	4	−2	−4	2	3	−6	−7	6	7	−4	3	2	8	4	−2	−3	5	−8	−5	4	2	−3	−2	3	−4
2	−4	3	1	−3	−1	4	5	8	−5	−8	3	4	−1	−4	3	1	−6	−7	6	7	3	−1	−4	1	4	−3
3	1	−2	−4	2	4	−1	7	−6	−7	6	−2	−1	4	5	−2	−4	1	−8	−5	8	−2	4	1	−4	−1	2
4	2	−1	3	1	−3	−2	8	5	−8	−5	1	−2	−3	2	−1	3	−7	−6	7	6	−1	−3	2	3	−2	1
5	−7	8	7	−6	−8	6	−2	−4	2	4	−6	8	7	−3	−7	6	−8	−1	3	1	−6	−8	7	8	−7	6
6	8	7	−8	5	−7	−5	1	3	−1	−3	5	7	−8	−7	8	−5	2	4	−2	−4	5	−7	−8	7	8	−5
7	5	−6	−5	8	6	−8	−3	1	3	−1	8	−6	−5	6	5	−8	4	2	−4	−2	8	6	−5	−6	5	−8
8	−6	−5	6	−7	5	7	−4	−2	4	2	−7	−5	6	−1	−6	7	5	3	1	−3	−7	5	6	−5	−6	7

Total travel cost = $388,152.

Division	East				West			
Team	ARK	JAC	SHR	TUL	ELP	MID	SAN	WIC
HAP	1	4	2	3	5	6	7	8

can be used as a surrogate for travel cost, but a more accurate travel cost matrix can be developed by determining when a team would bus or fly. Travel policies among teams vary widely. El Paso flies most of the time and Arkansas almost always uses buses. Tulsa leases a bus for a fixed cost of $3,900 per month, Jackson owns their own bus, and Arkansas incurs a variable cost per round trip.

Our travel cost matrix was developed based on proposed league rules that require flying for one-way trips in excess of 500 miles. Flight costs were based on the lowest in-advance air fares for 28 players and staff. Bus costs were based on variable costs obtained from the Arkansas team. Since using a bus is much less expensive, we assumed that teams used a bus whenever the trip was less than 500 miles one way. An attempt was made to solicit exact bus costs from all eight teams, but only Arkansas and Tulsa responded. The estimated travel costs between Texas League cities is shown in the lower triangular half of Table V. Evaluating proposed schedules for the Tulsa and Arkansas teams yielded total travel costs that were very close to the actual totals calculated by the teams.



Mininum travel for Shreveport for league double round robin

Minimum travel for division double round robin

Minimum travel for Shreveport with two one-stop trips combined

Figure 1. The ideal minimum travel distance for Shreveport.

We emphasize that our two-stage scheduling approach is not restricted to a single distance or cost matrix. If available, individual team travel costs can be incorporated in both the assignment and exchange phases of the algorithm. Once a schedule is developed, each individual team can assess the exact travel costs associated with the schedule according to its preferred mode of transport for a given trip and its particular travel cost.

3. DEVISING A MORE VARIED SCHEDULE FORMAT

The management of the Tulsa Drillers of the Texas League was interested in developing a new schedule format that consisted of 4-game rounds and provided more variety in competition between teams. In 1988, their manually derived schedule consisted of 34 rounds in which each team would play three home and three away rounds with teams in their division and two home and two away rounds with teams in the other division. Unfortunately, the new format required the league to travel a total distance of 118,094 miles at a cost of approximately $651,145. This distance increase was 53% more than the previous format.

In deriving a more cost effective 34-round schedule, two approaches were taken. One schedule was derived using the two-stage approach explained in Section 1 through subsection 3. In this case, the 14-round HAT from Table III was repeated to create a 34-round schedule. Lastly, the schedule was augmented by a 6-round schedule in which each team played home and away rounds with every other team in its division. This schedule design attempted to maximize the number of away breaks while limiting the maximum number of consecutive home or away breaks to two. After applying the exchange heuristic, the minimum total distance achieved was 101,200 miles.

The limiting of each round to four games allows the scheduling of three consecutive road trips without violating the league constraint of fourteen consecutive road games. A second approach to the construction of a 34-round schedule is based on the method of Campbell and Chen. Their approach generates schedules with up to three consecutive home or away rounds. The resulting schedules also contain open dates or byes in which some teams are idle. A preferred solution to the Texas League problem will have no byes. Thus, the Campbell and Chen schedule generation approach must be modified for the Texas League problem.

This second approach consists of three phases:

1. Solve a matching problem on n teams.
2. Determine an ordering in the scheduling of paired teams by using a symmetric Latin square.
3. Eliminate open dates or byes by combining rounds with byes.

The objective of the matching problem is to create pairs of teams that are "close together" and are visited in sequence by other pairs of teams. Mathematically, the matching problem for n teams is to find x_{ij} for $i = 1, 2, \ldots, n-1, j = i+1, \ldots, n$ where

$$x_{ij} = \begin{cases} 1 & \text{if city } i \text{ (team } i\text{) is paired with city } j \text{ (team } j\text{)}, \\ 0 & \text{otherwise,} \end{cases}$$

in order to

$$\text{minimize} \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} d_{ij} x_{ij} \qquad (1)$$

subject to

$$\sum_{i=1}^{k-1} x_{ik} + \sum_{j=k+1}^{n} x_{kj} = 1 \quad k = 1, 2, \ldots, n. \qquad (2)$$

The d_{ij}'s in (1) are the costs between city i (team i) and city j (team j). The optimal matching for the Texas League problem is (1, 4), (2, 7), (3, 8), (5, 6), where 1 = Arkansas, 2 = Shreveport, 3 = Tulsa, 4 = Jackson, 5 = El Paso, 6 = Midland, 7 = San Antonio, and 8 = Wichita. The symmetric Latin square in Table VIII can be used to associate team pairings indicated by the optimal matching with a schedule sequence. The numbers in the Latin square represent the sequence in which associated pairs play each other. For example, the first row indicates that teams 1 and 4 play each other first and, subsequently, teams 1 and 4 play teams 2 and 7, and so on. The partial schedule derived from the Latin square is shown in Table IX. Note that rounds 2 and 6 consist of byes for four teams. In the case of eight teams it is possible to combine rounds to eliminate all byes.

Combining rounds 2 and 6 and reversing home and away games for the next seven rounds yields the feasible partial schedule shown in Table X. Extrapolating the 14-round schedule into a 28-round schedule augmented by a 6-round within-division season-ending competition yields the final HAT shown in Table XI.

Table VIII
A Schedule for 4 × 2 Rounds

	(1, 4)	(2, 7)	(3, 8)	(5, 6)
(1, 4)	1	2	3	4
(2, 7)	2	3	4	1
(3, 8)	3	4	1	2
(5, 6)	4	1	2	3

Table IX
Derived Schedule With Byes

Round	1	2	3	4	5	6	7	8
1	−4		−2	−7	+3	+8	−5	−6
2	−5	−6	+1	+4	−7		−3	−8
3	−8		+5	+6	−1	−4	+2	+7
4	+1		−7	−2	+8	+3	−6	−5
5	+2	+7	−3	−8	−6		+1	+4
6	+7	+2	−8	−3	+5		+4	+1
7	−6	−5	+4	+1	+2		−8	−3
8	+3		+6	+5	−4	−1	+7	+2

Enumerating all possible assignments of teams to HAPs yields a minimum total league travel cost of $434,588 (distance = 91,279 miles). This is a projected $216,557 savings (33.3% reduction) compared to the 34-round manual schedule derived by the Tulsa Drillers.

The proposed schedule was further refined by the general manager of the Tulsa Drillers, who also serves as Secretary of the Texas League. Schedule details, such as calendar dates and assignment of travel dates and days off, were added. The final schedule was enthusiastically endorsed by the Tulsa Drillers.

At the July 1992 owners' meeting, the new schedule format was formally proposed. The initial vote to accept the new format resulted in a 4–4 tie. Subsequent deliberations resulted in a defeat of the proposed schedule based primarily on known travel cost increases versus unknown revenue increases. The new format schedule increased travel costs by approximately $20,000 and travel distance by 14,000 miles (or 18%) compared to the old format.

The league is considering expansion to ten teams. If expansion occurs, the league will have to accept a new schedule format at that time.

4. OBSTACLES TO IMPLEMENTATION AND LESSONS LEARNED

The failure to accept the new schedule format was the sixth unsuccessful attempt to change the Texas League schedule. The political and equity of burden issues play a major role in this group decision. The eight estimated team travel costs of the current schedule in ascending order are $32,104, $32,432, $41,640, $50,700, $55,807, $59,257, $65,857, and $77,195. Most attempts to improve the old schedule resulted in cost increases for the lowest cost teams and cost decreases for the highest cost teams. In the limited time available between obtaining the travel costs and the latest owners' meeting, we were not able to construct a schedule that has the desired features and *simultaneously* reduces the travel costs for *all* the teams.

The improved version of the old 26-round schedule format was not presented to the league by the Tulsa general manager. He did not want to confuse the issue by diverting the focus from the new format. It is clear from examining the distribution of travel costs that some teams have a vested interest in maintaining the status quo and an inequity of burden.

One positive outcome of the latest owner's meeting was a commitment to study the scheduling issue further. In the next six months, the League agreed to

Table X
Feasible 14 Round Schedule

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	−4	+8	−2	−7	+3	−5	−6	+5	+6	−3	+7	+2	−8	+4
2	−5	−6	+1	+4	−7	−3	−8	+3	+8	+7	−4	−1	+6	+5
3	−8	−4	+5	+6	−1	+2	+7	−2	+7	+1	−6	−5	+4	+8
4	+1	+3	−7	−2	+8	−6	−5	+6	+5	−8	+2	+7	−3	−1
5	+2	+7	−3	−8	−6	+1	+4	−1	−4	+6	+8	+3	−7	−2
6	+7	+2	−8	−3	+5	+4	+1	−4	−1	−5	+3	+8	−2	−7
7	−6	−5	+4	+1	+2	−8	−3	+8	+3	−2	−1	−4	+5	+6
8	+3	−1	+6	+5	−4	+7	+2	−7	−2	+4	−5	−6	+1	−3

Table XI
Proposed 34-Round HAT for the Texas League

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	-8	4	7	2	-3	5	6	-5	-6	3	-2	-7	-8	4	8	-4	-2
2	5	6	-4	-1	7	3	8	-3	-8	-7	1	4	-6	-5	6	5	1
3	4	-8	-5	-6	1	-2	-7	2	7	-1	5	6	-4	8	4	-8	-5
4	-3	-1	2	7	-8	6	5	-6	-5	8	-7	-2	3	-1	-3	1	7
5	-2	-7	3	8	-6	-1	-4	1	4	6	-3	-8	7	2	-7	-2	3
6	-7	-2	8	3	5	-4	-1	4	1	-5	-8	-3	2	7	-2	-7	8
7	6	5	-1	-4	-2	8	3	8	-3	2	4	1	-5	-6	5	6	-4
8	1	3	-6	-5	4	-7	-2	-7	2	-4	6	5	1	-3	-1	3	-6

Round	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1	7	-3	5	6	-5	-6	3	-2	-7	-4	8	-3	2	4	2	-4	3
2	-4	7	3	8	-3	-8	-7	1	-4	-5	-6	4	-1	-3	-1	3	4
3	-6	1	-2	-7	2	7	-1	5	6	8	-4	1	4	2	-4	-2	-1
4	2	-8	6	5	-6	-5	8	-7	2	1	3	-2	-3	-1	3	1	-2
5	8	-6	-1	-4	1	4	6	-3	-8	2	7	6	-8	-7	8	7	-6
6	3	5	-4	-1	4	1	-5	-8	-3	7	2	-5	-7	-8	7	8	5
7	-1	-2	8	3	-8	-3	2	4	1	-6	-5	-8	6	5	-6	-5	-8
8	-5	4	-7	-2	7	2	-4	6	5	-3	-1	7	5	6	-5	-6	7

Total travel cost = \$434,588; distance = 91,279 miles.

Division	East				West			
Team	ARK	JAC	SHR	TUL	ELP	MID	SAN	WIC
HAP	4	2	7	3	6	5	8	1

explore the development of a 4-year cycle of schedules for the 1995–1998 seasons. Additionally, a league-wide travel pool will be considered in which the teams would share equally in the travel costs.

Although the new schedule format was not adopted, several lessons were learned in the process:

1. Never underestimate the influence of political factors in any group decision process.
2. Use highly accurate costs in the objective function whenever possible.
3. Implementing change will be more difficult in a group decision process when some members of the group have a vested interest in maintaining the status quo.
4. A proposal for change will have a higher probability of success if it is proposed by a neutral agent rather than a member of the group with a vested interest in the outcome.

In light of the last observation, future schedule changes probably should be initiated through the league president rather than from one of the Texas League teams directly.

5. SUMMARY

In this paper, we presented two methods for finding low-cost schedules for a baseball league. The first method is a two-stage approach. In the first stage, a home-away timetable (HAT) that meets all the timing restrictions is generated. In the second stage, the least-cost schedule for that HAT is found by evaluating all possible assignments of teams to HAPs. Further improvements can be sought by iterating between the two stages. Since the cost evaluation is rather fast for a league with a small number of teams, we did not investigate methods of solving the assignment stage faster. The major reduction in costs is obtained by finding "good" HATs. The data from the Texas League suggest that the exchange heuristic presented in this paper might be effective in generating low-cost schedules. Further refinements of this approach might be to relax the restriction that only cost-reducing exchanges are allowed, so that more HATs may be generated.

The second method presented in this paper is a modification of the Campbell and Chen approach for the construction of a basketball league schedule. This approach relaxes the restriction of a maximum of two consecutive away rounds. This approach was effective in generating a minimum cost schedule for a new format for the Texas League. However, for a league with more than eight teams, this approach will result in byes or open dates for some teams. This might not be acceptable in some league scheduling applications.

The changing of the Texas League schedule is an economically sensitive and politically charged undertaking. A few teams strongly prefer the current format in spite of the fact that the burden of travel costs is inequitable. The future acceptance of a new schedule format will depend on the individual teams' ability to recognize and accept what would be good for the league as a whole.

APPENDIX A

Theorem 1. *For a round robin of* $2n$ *teams with* $n \geq 3$, *where each team can play no more than two consecutive home or* 2 *consecutive away rounds, the maximum number of breaks is strictly less than* $2n(n-1)$.

Proof. Without loss of generality, suppose that teams $1, 2, \ldots, n$ play away and teams $n+1, n+2, \ldots, 2n$

play at home in the first round. If every team has $n - 1$ breaks, then the locations (i.e., home or away) of all the teams in odd-numbered rounds are fixed. The HAPs of all the teams have the following sign pattern for odd-numbered rounds:

Round	1	2	3	4	5	6	7	...
Teams $1, \ldots, n$	−		+		−		+	...
Teams $n+1, \ldots, 2n$	+		−		+		−	...

This means that the first n teams either all play away or all play at home in odd-numbered rounds, and can only play each other (and must play each other) on even-numbered rounds. If n is odd, the even-numbered rounds would be impossible to schedule because an odd number of teams must play among themselves. Even if n is even, no schedule is possible. Since $n \geqslant 3$, at least two of the first n teams must play at home in round 2; let teams 1 and 2 play at home. For both these teams to have $n - 1$ breaks, the HAP for both teams must have the following sign pattern: round $2k$ is the same sign as round $2k + 1$ for $k = 1, 2, \ldots, n - 1$. With the HAP for both teams 1 and 2 having the identical sign pattern, the game between these two teams cannot be scheduled. Therefore, it is impossible for every team to achieve the maximum number of breaks.

Next, we present a construction of a HAT for a round-robin for $2n$ teams with $2n(n - 1) - (2n - 4)$ breaks.

Case: *n* is Odd

Let the $2n$ teams be divided into two groups, $D = \{1, 2, \ldots, n\}$ and $D' = \{1', 2', \ldots, n'\}$. In our construction, all the games are intergroup on the even-numbered periods, whereas we schedule exactly one intergroup game in the odd-numbered periods. The intragroup games in the first period are represented by the graphs in Figure 2. That is, team 2 plays at home against team n, team 3 plays away against team $n - 1$, and so on. The intragroup games for the third period are obtained by 'rotating' the arcs clockwise in the graphs in Figure 2. Thus, in the third period team 3 plays at home against team 1, team 4 plays away against team n, team 5 plays at home against team $n - 1$, and so on. Continuing this way, all the intragroup games are scheduled in the odd-numbered periods. In addition, we schedule the following intergroup game in each odd-numbered period:

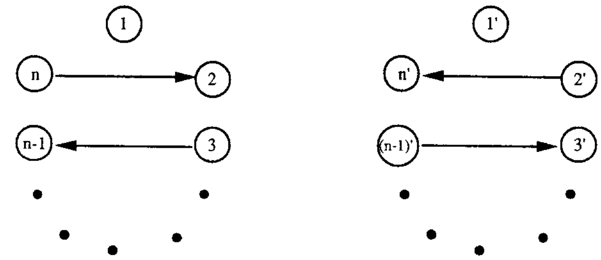


Figure 2. Graph representation of intragroup games in the first period.

- in the kth period for $k = 1, 3, \ldots, n$, team $\lceil k/2 \rceil$ plays team $\lceil k/2 \rceil'$;
- for periods $k = 1, 3, \ldots, n - 2$, if $k \equiv 1 \pmod 4$, team $\lceil k/2 \rceil$ plays at home, otherwise, it plays away;
- for period $k = n$, if $k \equiv 1 \pmod 4$, team $\lceil k/2 \rceil$ plays away, otherwise, it plays at home.

The other intergroup games are scheduled in the even-numbered periods. Specifically, for periods $h = 2, 4, \ldots, 2n - 2$,

- team 1 plays team $(h/2 + 1)$; and team $(h/2 + 1)$ plays team 1′;
- for periods $h = 2, 4, \ldots, 2n - 6$ if $h \equiv 0 \pmod 4$, teams 1 and $(h/2 + 1)$ play away, otherwise, they play at home;

Table XII
A Round-Robin for $2n = 10$ Teams With $2n(n - 1) - (2n - 4) = 34$ Breaks

Period	1	2	3	4	5	6	7	8	9
1	+1′	+2′	−3	−3′	+5	−4′	−2	+5′	+4
2	+5	+1′	−2′	+5′	−4	−3′	+1	+4′	−3
3	−4	−4′	+1	−1′	+3′	−5′	−5	+2′	+2
4	+3	−5′	−5	+2′	+2	−1′	−4′	+3′	−1
5	−2	−3′	+4	+4′	−1	−2′	+3	+1′	−5′
1′	−1	−2	+3′	+3	−5′	+4	+2′	−5	−4′
2′	−5′	−1	+2	−4	+4′	+5	−1′	−3	+3′
3′	+4′	+5	−1′	+1	−3	+2	+5′	−4	−2′
4′	−3′	+3	+5′	−5	−2′	+1	+4	−2	+1′
5′	+2′	+4	−4′	−2	+1′	+3	−3′	−1	+5

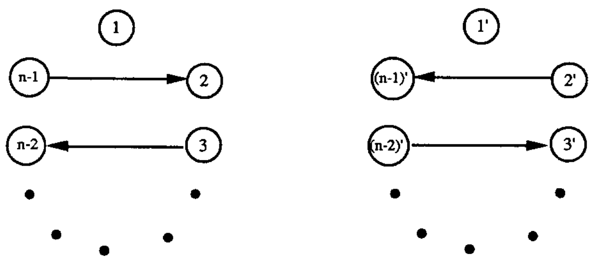


Figure 3. Graph representation of intragroup games in the second period.

- for periods $h = 2n - 4$ and $2n - 2$, if $h \equiv 0 \pmod 4$, teams 1 and $(h/2 + 1)$ play at home, otherwise, they play away.

We will not give the details here but the remaining intergroup games can be scheduled in the even-numbered periods so that in the hth period (h even), the remaining teams in D play at home and the remaining teams in D' play away if $h \equiv 0 \pmod 4$, and vice versa otherwise. The total number of breaks of a schedule so constructed is $2n(n - 1) - (2n - 4)$. Such a schedule for $n = 5$ is shown in Table XII.

Case: *n* is Even

Again, let the $2n$ teams be divided into two groups, $D = \{1, 2, \ldots, n\}$ and $D' = \{1', 2', \ldots, n'\}$. In this case, all the intergroup games are scheduled in the odd-numbered periods and the intragroup games are scheduled in the even-numbered periods. The intragroup games not involving teams n and n' in the second period are represented by the graphs in Figure 3. The other intragroup games are scheduled in the subsequent even-numbered periods by 'rotating' the arcs clockwise (similar to the previous case) in the graphs in Figure 3. The unmatched team in each group during the even-numbered periods, for example, teams 1 and 1′ in the second period play teams n and n', respectively. For periods $h = 2, 4, \ldots, 2n - 2$, team n plays away and team n' plays at home if $h \equiv 0 \pmod 4$, and vice versa otherwise. In addition, we schedule the following the intergroup games:

in periods $k = 3, 7, \ldots, 2n - 5$,

$$\text{team } \lceil k/2 \rceil \text{ plays away against team } \lceil k/2 \rceil'. \qquad (*)$$

The remaining intergroup games are scheduled in the odd-numbered periods, where the teams $D = \{1, 2, \ldots, n\}$ are matched with cyclic permutations of $D' = \{1', 2', \ldots, n'\}$ in compliance with (*) above and such that for periods $k = 1, 3, \ldots, 2n - 1$, the teams in D (except the one assigned by (*)) play away if $k \equiv 1 \pmod 4$, and play at home otherwise. Again, the total number of breaks of a schedule constructed in this way is $2n(n - 1) - (2n - 4)$. Such a construction for $n = 6$ is shown in Table XIII.

APPENDIX B

Exchange Heuristic

The games for a round can be represented by a graph $G = (T, A)$ where the node-set $T = \{1, 2, \ldots, 2n\}$ represents the teams and an arc $(i, j) \in A$ denotes that team i plays away against team j. Since a team can only play against one other team in each round, no two arcs in A are incident to each other. Instead of exchanging every game in two rounds in a HAT, we can consider exchanging only some of the games, as follows. Let $G_h = (T, A_h)$ and $G_k = (T, A_k)$ represent the games for rounds h and k in a HAT. Let $G = (T, A_h \cup A_k)$ be the union of the two graphs. The arcs of G are a collection of (undirected) cycles with the arcs in each cycle being alternately in G_h and G_k. Let $C =$

Table XIII
A Round-Robin for $2n = 12$ Teams With $2n(n - 1) - (2n - 4) = 52$ Breaks

Period	1	2	3	4	5	6	7	8	9	10	11
1	−4′	−6	+3′	−3	−2′	+5	+1′	−2	−6′	+4	+5′
2	−3′	+5	−2′	+6	−1′	−4	+6′	+1	−5′	−3	+4′
3	−2′	−4	+1′	+1	−6′	−6	+5′	−5	−4′	+2	+3′
4	−1′	+3	+6′	−5	−5′	+2	−4′	+6	−3′	−1	+2′
5	−6′	−2	+5′	+4	−4′	−1	+3′	+3	−2′	−6	+1′
6	−5′	+1	+4′	−2	−3′	+3	+2′	−4	−1′	+5	+6′
1′	+4	+6′	−3	+3′	+2	−5′	−1	+2′	+6	−4′	−5
2′	+3	−5′	+2	−6′	+1	+4′	−6	−1′	+5	+3′	−4
3′	+2	+4′	−1	−1′	+6	+6′	−5	+5′	+4	−2′	−3
4′	+1	−3′	−6	+5′	+5	−2′	+4	−6′	+3	+1′	−2
5′	+6	+2′	−5	−4′	+4	+1′	−3	−3′	+2	+6′	−1
6′	+5	−1′	−4	+2′	+3	−3′	−2	+4′	+1	−5′	−6

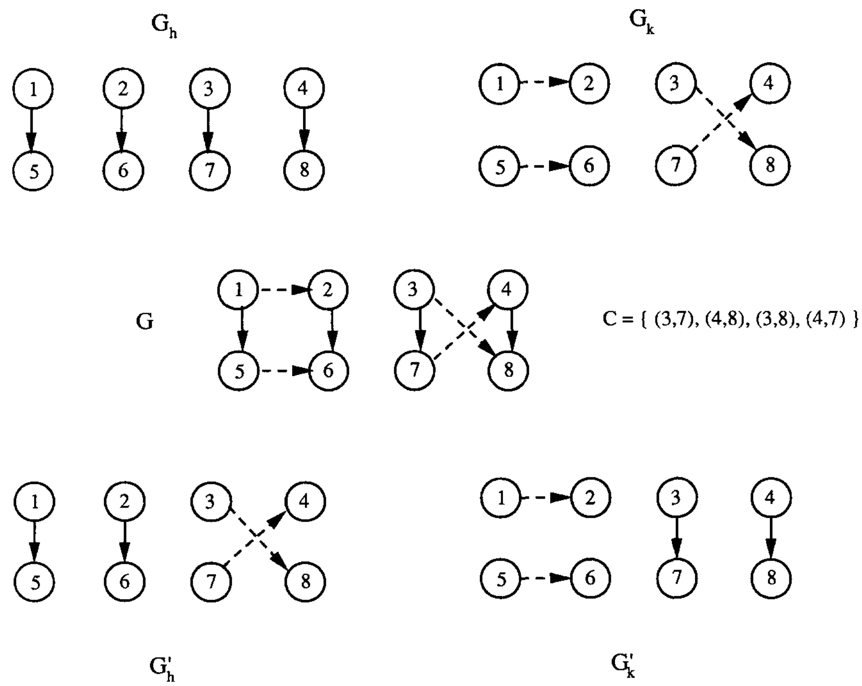


Figure 4. Generating two new rounds using the exchange procedure.

$A_h^C \cup A_k^C$ with $A_h^C \subseteq A_h$ and $A_k^C \subseteq A_k$ be a subcollection of such cycles. By exchanging the arcs in these cycles, we obtain two new sets of games for the two rounds. In other words, the games represented by $G'_h = (T, (A_h \backslash A_h^C) \cup A_k^C)$ and $G'_k = (T, (A_k \backslash A_k^C) \cup A_h^C)$ can be used to replace rounds h and k in the HAT. Figure 4 illustrates this exchange procedure. The complete exchange of all the games for the two rounds is equivalent to the case where $A_h^C = A_h$ and $A_k^C = A_k$. Using the partial exchange, many more HATs can be generated.

ACKNOWLEDGMENT

We thank Mr. Joe Preseren, general manager of the Tulsa Drillers, for his assistance in developing a schedule for the Texas League. We also thank the anonymous referees for their constructive comments and suggestions which improved the paper, and Dr. Richard E. Stone of Northwest Airlines for his assistance.

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