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An iterative switching heuristic to locate hospitals and helicopters

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Abstract

The Trauma Resource Allocation Model for Ambulances and Hospitals (TRAMAH) was created to guide health planners in locating important and expensive resources. The model's solution algorithm combines a mixed-integer linear program and a new "iterative switching" heuristic. The TRAMAH has the computational flexibility to optimally locate various numbers of aeromedical depots and trauma centers as separate resources or in tandem. It can be engineered to build a regional trauma system from "clean slate" or to accommodate well-developed trauma systems that are only seeking incremental changes. In this first application of TRAMAH using the Maryland Trauma System, the "iterative switching" heuristic allowed us to obtain solutions within reasonable computer processing times. The TRAMAH can thus help trauma systems improve the survival rates of their most severely injured patients. © 2001 Published by Elsevier Science Ltd.

1. Introduction

Throughout the world, injuries are the leading cause of death during half the human lifespan. In the United States, injuries are the leading cause of death from the first year of life to age 44 [1]. The lifetime costs per injury death are almost four times those for cancer, and more than six times those for cardiovascular disease [2].

In the past decade, guidelines have been developed to contend with injury as a public health problem. One arm of this injury prevention movement has been the development of trauma care systems [3–5]. Although trauma systems have been built on the strategic placement of both hospitals and ambulances, historical precedence and political bias have often hampered their

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organizational precision [6,7]. The need for a quantitative model of trauma systems has become evident.

The Trauma Resource Allocation Model for Ambulances and Hospitals (TRAMAH) is the first operations research model of its kind for use with trauma care systems. Its solution algorithm uniquely combines mixed-integer programming and a new “iterative switching” heuristic. In this first application of TRAMAH, the Maryland Trauma System is used as a test site. Sufficiently ubiquitous model parameters were, however, selected to promote the use of TRAMAH in other regions. With TRAMAH, planners can be directed to the resource configurations that will best prepare for the needs of their most severely injured residents.

2. Trauma hospitals and helicopters

Before the concept of a trauma system, severely injured patients were transported to the nearest hospital regardless of that hospital’s ability to address their level of injury [8]. Today, trauma systems involve coordinated response plans to ensure appropriate and timely access to dedicated and expert personnel at specialized trauma center hospitals [4,5]. This has been an effective strategy for reducing preventable death and disability due to injury [3,9–15].

Trauma centers were originally inner-city hospitals that had assumed de facto trauma center status [16]. Their development as regional resources, dedicated to serving severely injured patients, was predicated on the adaptation of existing resources in order to provide specialized trauma care services [17–19]. The conversion of community hospitals remains a common and economical strategy to create trauma centers. In Maryland, for example, the estimated cost to convert the typical community hospital into a trauma center in 1994 was \$2.3 million, substantially less money than outright construction [4,18,20–26].

Today, trauma centers function at the heart of the U.S. trauma system. They remain a “safety-net” for severely injured individuals despite inconsistent political and financial support [6,27]. Nevertheless, the question of exactly how many trauma centers are necessary to maintain an adequate safety-net remains largely unanswered. The American College of Surgeons estimates that one trauma center per million population is sufficient to address typical volumes of severely injured patients and maintain the expertise of medical providers [4]. This estimate is largely speculative, though, and only provides vague guidance in resolving where and how many trauma centers should be located for a particular region.

Urban areas are well-equipped with an abundance of hospital and ambulance resources while less populated regions continue to be plagued by sparse transportation resources and unusually long distances to trauma centers [28]. For the longest distances and the most severely injured patients, aeromedical services must be employed. The definition of “aeromedical” is the integration of medical treatment with the use of air ambulances. Although both ground and air ambulance services share common military origins, their evolution has been largely independent [29–32]. Single hospital aeromedical programs are most common followed by consortium/multiple-hospital operated programs and public use programs under the direction of police and fire departments [33].

Hospital-based aeromedical services began to multiply rapidly during the 1980s [33]. Air ambulances became highly visible marketing tools that expanded hospital catchment areas into

otherwise distant markets by literally flying patients past the competition. This market-based triage ran counter to traditional medical triage that had first justified the creation of many aeromedical services on the basis of the lives they saved [34–37].

With the advent of hospital reimbursement disincentives in the 1990s, single-hospital air medical programs were suddenly seen as financial burdens. Hospitals were discouraged from filling their beds thereby eliminating the reason to invest further in air ambulance programs [37,38]. Nevertheless, many hospitals still believed that their aeromedical programs had so successfully showcased their institutions that they were willing to continue operating at a loss. Other single hospital air ambulance programs, in order to remain solvent, merged to form free-standing aeromedical consortiums [39].

The costs of implementing a single helicopter program have been reported to be between \$2.5 and \$4.9 million per year [40,41]. The operating and implementation costs of air ambulance services have been shown to be as much as ten-fold those of ground ambulance services [42]. Collections from patients generally cover less than half of an aeromedical service's annual operating costs and, as such, programs are often heavily subsidized by their sponsoring hospitals or health systems [42,43]. In Maryland, the estimated cost to create an aeromedical depot was \$4.7 million in 1994 [20,26,40,41].

Helicopter response to an injury scene is limited by adverse weather conditions and the availability of a landing zone with adequate clearance for arrival and take-off. In about one-quarter of all flights, a landing zone cannot be established within a reasonable amount of time necessitating rendezvous with ground services at nearby clearings where safe transfer of injured patients can be made. In areas where hospital care is accessible by ground ambulance within 30 minutes, aeromedical transport is not suggested. The typical helicopter travel speed has been estimated to be 120 miles per hour when accounting for take-off time, landing zone appraisal, and on-scene time [43–45]. Except in cases of patient entrapment, it is unusual for time to be spent resuscitating patients on-scene since this can be successfully performed en route to the trauma center. Although helicopters can fly over 400 miles without refueling, most services limit their response distances to 120 miles. Fixed-wing aircraft are often used to transport patients more than 120 miles [34].

3. The trauma resource allocation model for ambulances and hospitals (TRAMAH)

Past emergency medical services analyses have addressed the location of ground ambulances and their destination hospitals [46–54]. Emergency medical services location analysis has, however, never been used to simultaneously locate ambulances and hospitals strictly for trauma. The incorporation of location techniques that have proven beneficial to the patient broadly in need of emergency care would also be of value in addressing the more specific needs of the trauma patient.

Concepts borrowed from previous location models were combined to formulate a new model of trauma resource location, the TRAMAH [55–59]. The TRAMAH considers both trauma center (TC) and aeromedical depot (AD) resources as simultaneous pairings. Coverage is measured by the number of severely injured persons having access to one or both resource types in a two-level hierarchy (numbered as (1) and (2) as follows). A severe injury lacking access to both levels of

service (ground service and air service) within some time standard, S , must be counted as lacking coverage in the statement of the objective function. That is, an injury, i , is considered covered if:

1. at least one TC is sited within a time standard, S , by ground, or
2. an (AD, TC) pair is sited in such a way that the sum of the flying time from the AD to i plus the flying time from i to the TC is within the same time standard, S .

Using this definition for coverage, TRAMAH can be stated as the maximization of the sum of covered demands,

$$\begin{aligned} \text{Maximize } Z_{\text{TRAMAH}} &= \sum_{i \in I} a_i y_i && (1) \text{ Objective} \\ \text{subject to:} &&& \\ \sum_{j \in J} x_j^{\text{TC}} &= p^{\text{TC}} && \forall j \in J && (2) \text{ Number of TCs Constraint} \\ \sum_{k \in K} x_k^{\text{AD}} &= p^{\text{AD}} && \forall k \in K && (3) \text{ Number of ADs Constraint} \\ y_i - v_i - u_i &\leq 0 && \forall i \in I && (4) \text{ Ground/Air Logical Constraints} \\ v_i - \sum_{j \in N_i} x_j^{\text{TC}} &\leq 0 && \forall i \in I, j \in J && (5) \text{ Ground Constraints} \\ u_i - \sum_{(j,k) \in M_i} z_{kj} &\leq 0 && \forall i \in I, j \in J, k \in K && (6) \text{ Air Constraints} \\ z_{kj} - x_j^{\text{TC}} &\leq 0 && \forall j \in J, k \in K && (7) \text{ Ground Logical Constraints} \\ z_{kj} - x_k^{\text{AD}} &\leq 0 && \forall j \in J, k \in K && (8) \text{ Air Logical Constraints} \\ 0 \leq y_i &\leq 1 && \forall i \in I && (9) \text{ Bounds} \\ x_j^{\text{TC}}, x_k^{\text{AD}} &\in \{0, 1\} && \forall j \in J, k \in K && (10) \text{ Integers} \end{aligned}$$

where:

$y_i = 1$ if demand node i is covered by air or ground, 0 otherwise;

a_i = population demand at node i ;

$v_i = 1$ if demand node i is covered by ground, 0 otherwise;

$u_i = 1$ if demand node i is covered by air, 0 otherwise;

I = the set of demand nodes, i ;

$x_j^{\text{TC}} = 1$ if a TC is sited at node j , 0 otherwise;

J = the set of eligible TC locations;

$x_k^{\text{AD}} = 1$ if an AD is sited at node k , 0 otherwise;

K = the set of eligible AD locations;

$z_{kj} = 1$ if an AD is sited at node k and a TC is sited at node j , 0 otherwise;

p^{TC} = the number of TCs to be sited;

p^{AD} = the number of ADs to be sited;

$N_i = \{j | t_{ij}^{\text{G}} \leq S\}$ = TC sites within the time standard, S , of node i by ground; and

$M_i = \{(j, k) | (t_{ki}^{\text{A}} + t_{ij}^{\text{A}}) \leq S\}$ = TC/AD pairs within the time standard, S , of i by air.

The problem was assessed on a network of travel arcs and geographic nodes where t_{ij}^{G} is the driving time from node i to node j , t_{ij}^{A} is the flying time from node i to node j , and t_{ki}^{A} is the flying time from node k to node i . (See Fig. 1.) The previously mentioned (AD, TC) pairs are denoted above as z_{kj} . It is also important to note that only constraints (5) and (6) above were calculated relative to the time standard, S ; the remaining constraints were not influenced by the selection of S . The time standard, S , could also be changed to reflect different levels of coverage urgency. Not all nodes in the network were necessarily considered eligible to have a TC or an AD located on

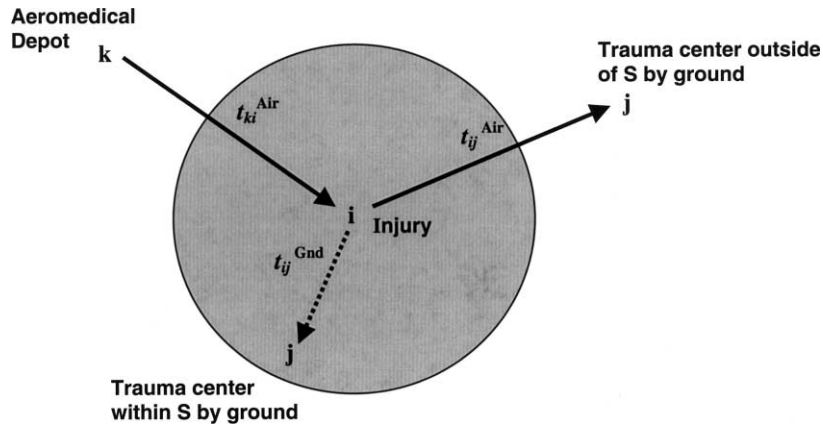


Fig. 1. Schematic defining coverage for TRAMAH. The solid arrows represent coverage by air and the broken arrow represents coverage by ground.

them, although all nodes in the network were considered as potential locations where an injury could occur and would thus require coverage by the trauma system.

4. Testing the solution algorithm

The TRAMAH was solved using the revised simplex algorithm, a variant of the original simplex procedure [60]. For purposes of this study, CPLEX Version 1.2 (1990 CPLEX Optimization Incorporated, Houston, Texas) with a branch-and-bound add-on was used to solve TRAMAH. In most cases, the application of the revised simplex algorithm to solve TRAMAH ended in fractional, noninteger solutions. The CPLEX Mixed-Integer Optimizer recognizes mixed-integer submissions and automatically resorts to a branch-and-bound algorithm to resolve fractional solutions although special steps need to be taken in most cases to insure solutions within reasonable processing times [61].

Submissions to CPLEX were written using Fortran 77. Each submission was formulated for two different time standards, 15 and 30 min, and 100 different combinations of numerical resources up to ten TCs and ten ADs. Using Maryland ZIP codes, 32 eligible TC sites (because of either existing TCs or adaptable community hospitals) and 385 eligible AD sites were considered in testing TRAMAH. Hospital discharge data were obtained from the Maryland Health Services Cost Review Commission and vital statistics data were obtained from the Maryland Department of Health and Mental Hygiene for the years 1992, 1993, and 1994 [20]. Injury Severity Scores were calculated using a computerized conversion table that translates ICD-9-CM discharge diagnoses into Abbreviated Injury Scale Scores [62]. Severely injured patients were defined as those having an Injury Severity Score of greater than 15 or as having died due to trauma [63].

Rand-McNally TripMaker Version 1.0 (1994 Rand-McNally and Company, Skokie, Illinois) was used to calculate optimized shortest driving times. This was done by setting the interstate road travel speed to 60 miles per hour, the US highway travel speed to 50 miles per hour, and the

state road travel speed to 40 miles per hour. These speeds were set lower than usual in an attempt to account for ground ambulance scene times and delays enroute. Town names and landmarks (for larger cities and towns) were used to calculate the inter-ZIP code driving times of a (32×385) ground travel matrix.

Using TRAMAH, trauma centers were placed with respect to severely injured patients and the explicit location of aeromedical depots. The locations of ground ambulance depots were implicitly considered. This is a consideration that is both realistic and advantageous in analyzing state trauma systems because the number of ground ambulance depots at the state level is prohibitively large and only a relatively small percentage of ground ambulance transports are devoted to severe trauma. The explicit placement of ground ambulances is, thus, a mathematically impractical endeavor at the present time.

In subregions with trauma centers, the accompanying proliferation of ground ambulances allows for depot-to-scene response times that average approximately 5 minutes [64,65]. Because ground ambulance depot-to-scene information was excluded in the first half of the TRAMAH algorithm, it was assumed that in subregions where trauma centers were sited, ground ambulance depots would be a few minutes away from the scene of injury. These few minutes were considered negligible lengths of time compared to the overall standard for both ground and air and were rationalized by setting ground ambulance travel speeds lower than usual. In this way, TRAMAH indirectly accounted for an otherwise impractical task — the location of an unwieldy hierarchy of ground ambulances for the entire State of Maryland.

Longitude and latitude coordinates were used to calculate Euclidean distances between ZIP code centroids. Inter-ZIP code flying times were then calculated in a (385×385) air travel matrix assuming an air-speed of 120 miles per hour [43]. All computations were done using a Silicon Graphics MIPS R4400 mini-computer (1987–1994 Silicon Graphics Inc., Mountain View, California) with a 200 MHz processor and 64 megabytes of RAM.

CPLEX permits the assignment of branching priorities to some or all of the integer variables in a problem. Priority ordering of several different integer variable groupings was attempted in more efficiently solving TRAMAH. In a few of the problems that sited small numbers of TCs and ADs, priority ordering of the branch-and-bound method resulted in reduced solution times. However, the remaining majority of problems did not have their solution times reduced by priority ordering. Rather, no solutions were attainable within a reasonable amount of time for these problems. Therefore, most problem solutions were unattainable within a reasonable amount of computer processing time using the CPLEX variant of the simplex algorithm and branch-and-bound.

To remedy this, a heuristic incorporating vertex substitution (one-opt interchange) with an iterative switching mechanism was developed for two purposes [66]. The first was as a stand-alone methodology for very large problems. The second purpose was to obtain a reduced set of eligible AD and TC sites for resubmission to CPLEX as condensed integer programming formulations. This “heuristic concentration” approach produced all nonfractional solutions within acceptable computer processing times [67,68].

The iterative switching heuristic was intended to be equivalent in concept to the subjective elimination of eligible AD and TC sites typically performed by a trauma systems administrator. Subjective elimination might be undertaken in addition, however. The heuristic was written to accept any number of eligible TC and AD sites in order to suit the problem at hand. Resubmissions to CPLEX incorporated both AD and TC concentration sets.

The basic mechanism of the iterative switching heuristic was a series of one-opt substitutions. In the first of these, the best AD sites were identified, holding the TC sites fixed. The best TC sites were then identified, holding the AD sites fixed. These two steps were then repeated until no one-opt substitutions yielded further improvement. The sites were locally optimal in the sense that further repetition of the exchange procedure in the heuristic produced no improvement of the objective value. (See Fig. 2.) The specific steps of the iterative switching heuristic proceeded as follows:

4.1. Create the first matrix $(A_1)_{ki}$

Formulation of the first matrix $(A_1)_{ki}$ was begun by randomly selecting m TC sites. These m TC sites remained fixed throughout the manipulation performed on $(A_1)_{ki}$. The $(A_1)_{ki}$ matrix contained the minimum values between g_i and $(t_{ki}^A + h_i)$ in each cell. It appeared as follows:

$$(A_1)_{ki} = \begin{pmatrix} \min(g_1, t_{11}^A + h_1) & \min(g_1, t_{12}^A + h_1) & \cdots & \min(g_1, t_{1,385}^A + h_1) \\ \min(g_2, t_{21}^A + h_2) & \min(g_2, t_{22}^A + h_2) & \cdots & \min(g_2, t_{2,385}^A + h_2) \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \min(g_i, t_{ki}^A + h_i) & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \min(g_{385}, t_{385,1}^A + h_{385}) & \min(g_{385}, t_{385,2}^A + h_{385}) & \cdots & \min(g_{385}, t_{385,385}^A + h_{385}) \end{pmatrix}$$

where g_i is the driving time from demand node i to the closest eligible TC, and h_i is the flying time from demand node i to the closest eligible TC. To each h_i was added the flying time from the ZIP code it represented to each of the other 385 ZIP codes, t_{ki}^A . Thus, $(A_1)_{ki}$ contained the fastest travel times, by either ground or air, given the fixed positions of a random set of m TC sites.

4.2. Perform a one-opt substitution using the first matrix $(A_1)_{ki}$

A one-opt substitution algorithm was then performed using the $(A_1)_{ki}$ matrix. The procedure began by randomly selecting an initial set of n out of the 385 columns in $(A_1)_{ki}$ to represent eligible AD sites. Correspondingly, ZIP codes were represented as rows in $(A_1)_{ki}$. For each row, if any of its elements intersecting the selected n columns was less than the time standard, then the ZIP code that this row represented was considered covered. The populations of severely injured patients within all covered ZIP codes were then summed to obtain a current objective value as achieved by the current collection of n columns.

Following this, the first of the n selected columns was successively replaced with each of the remaining nonselected columns, and the objective value recalculated each time until the nonselected column replacement that most improved the objective was obtained. This substitution procedure was then repeated column by column for all n columns. The final best objective that resulted from the substitution procedure was recorded alongside the final set of n columns, representing the n locally best eligible AD sites that produced it given the initial placement of TCs. Although not performed, it would also have been possible to do multiple passes at replacement until no local improvements occurred.

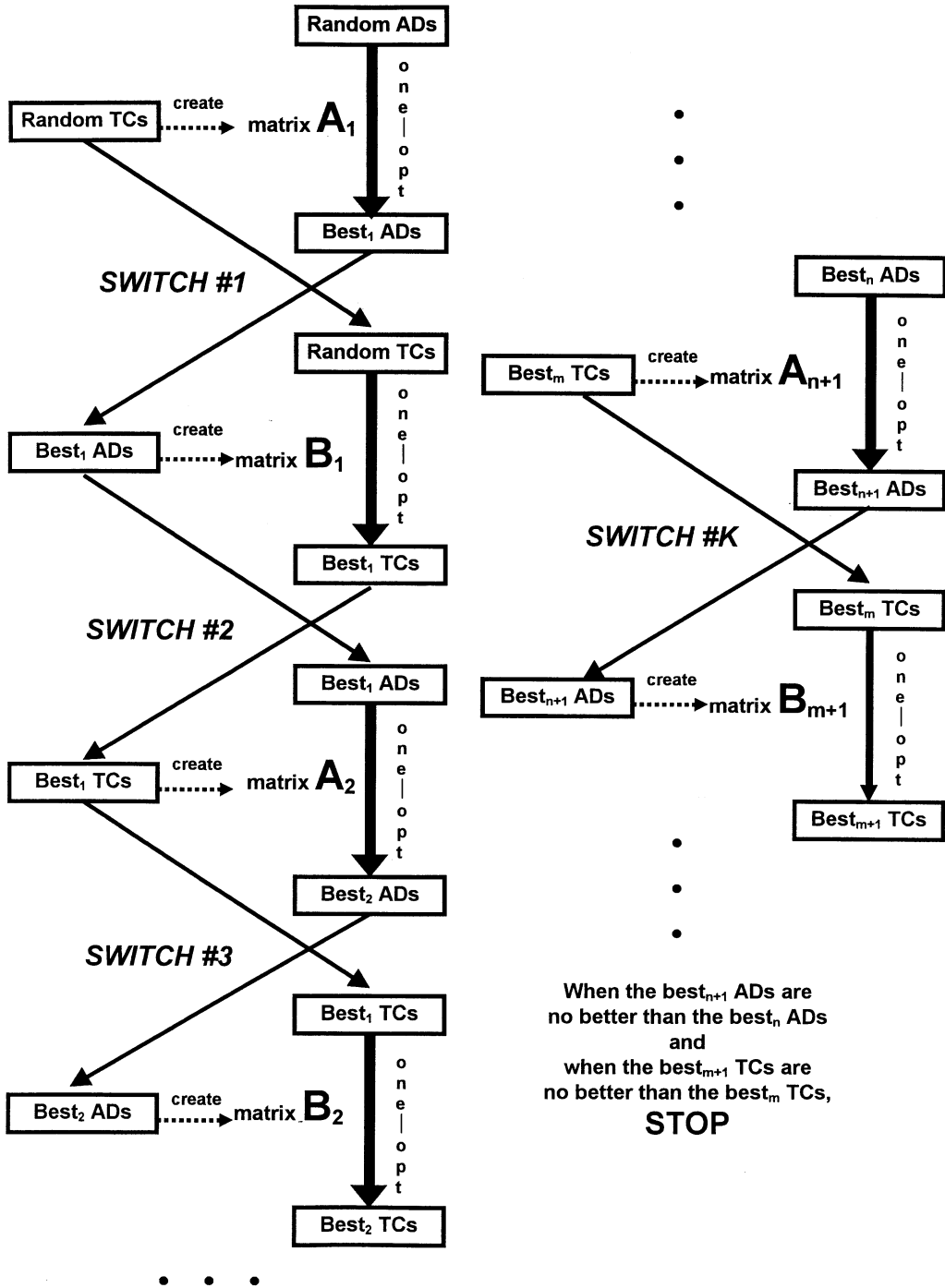


Fig. 2. Flow diagram of the iterative switching heuristic used to reduce the number of eligible TC and AD sites.

4.3. Execute switch #1 and create the second matrix $(B_1)_{ij}$

The n best AD sites found using the previous one-opt substitution were then used to create a second matrix, $(B_1)_{ij}$. These n AD sites remained fixed throughout the manipulation of $(B_1)_{ij}$. The $(B_1)_{ij}$ matrix contained the minimum values between q_i and $(r_i + t_{ij}^A)$ in each cell. It appeared as follows,

$$(B_1)_{ij} = \begin{pmatrix} \min(q_1, r_1 + t_{11}^A) & \min(q_1, r_1 + t_{12}^A) & \cdots & \min(q_1, r_1 + t_{1,385}^A) \\ \min(q_2, r_2 + t_{21}^A) & \min(q_2, r_2 + t_{22}^A) & \cdots & \min(q_2, r_2 + t_{2,385}^A) \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \min(q_i, r_i + t_{ij}^A) & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ \min(q_{385}, r_{385} + t_{385,1}^A) & \min(q_{385}, r_{385} + t_{385,2}^A) & \cdots & \min(q_{385}, r_{385} + t_{385,385}^A) \end{pmatrix}$$

where q_i is the driving time from demand node i to the closest eligible TC and r_i is the flying time from the closest eligible AD site to demand node i . To each r_i was added the flying time from the ZIP code it represented to each of the other 385 ZIP codes, t_{ij}^A . Thus, $(B_1)_{ij}$ contained the fastest travel times, by either ground or air, given the fixed positions of a best set of n AD sites.

4.4. Perform a one-opt substitution using the second matrix $(B_1)_{ij}$

A second one-opt substitution algorithm was then performed using the $(B_1)_{ij}$ matrix. This began by randomly selecting an initial set of m out of the 385 columns in $(B_1)_{ij}$ to represent eligible TC sites. Correspondingly, ZIP codes were represented as rows in $(B_1)_{ij}$. For each row, if any of its elements intersecting the selected m columns was less than the time standard, then the ZIP code that this row represented was considered covered. The populations of severely injured patients within all covered ZIP codes were then summed to obtain an objective value.

Following this, the first of the m selected columns was successively replaced with each of the remaining nonselected columns, and the objective value recalculated each time until the nonselected column replacement that most improved the objective was obtained. This substitution procedure was then repeated column by column for all m columns. The final best objective that resulted from the substitution procedure was recorded alongside the final set of m columns, representing the m best eligible TC sites that produced it given the initial set of ADs.

4.5. Execute switch #2 and repeat steps (1) to (2)

A second “switch” was then performed to recreate the first matrix $(A_2)_{ki}$ as before using the m best TC sites (as opposed to m random TC sites) obtained previously. The one-opt substitution algorithm was then performed on the $(A_2)_{ki}$ matrix using the n best AD sites obtained previously (as opposed to n random AD sites) to produce a new set of n best AD sites.

4.6. Execute switch #3 and repeat steps (3) to (4)

A third “switch” was then performed to recreate the second matrix $(B_2)_{ij}$ as before using this new set of the n best AD sites. After another one-opt substitution algorithm on the $(B_2)_{ij}$ matrix using the m best TC sites obtained previously, a new set of the m best TC sites was produced.

4.7. Continue repeating until the objective values do not improve

When the best set of $m+1$ TC sites was no better than the previous best set of m TC sites, and the best set of $n+1$ AD sites was no better than the previous best set of n AD sites (as determined by their accompanying objective values), the iterative switching procedure was viewed as stabilized and thus stopped. The best m TC and n AD sites were then recorded alongside the accompanying best objective value.

4.8. Repeat steps (1) to (7) 100 times and union the top ten results

The entire process was repeated 100 times. The union of the sets of m TC and n AD sites was formed for the top ten out of the 100 best objective values that resulted. These unioned sets were the final concentration sets of eligible AD and TC sites, these were then used for resubmission to CPLEX.

In the event that the concentration set obtained for use with one of the time standards was too large, a new run of the heuristic was performed using a smaller number of initial TCs and ADs, such as seven and seven as opposed to 10 and 10. A new run of the heuristic was also used when maximally covered objective values repeated themselves, making the union of the top ten objective values of little consequence in obtaining sufficiently reduced concentration sets of AD and TC sites.

5. Results from Maryland

A total of 26,774 severe injuries were considered for coverage. Two high-volume clusters, in the Baltimore and metropolitan Washington, DC areas, formed a bicentric distribution of serious injuries in Maryland (see Fig. 3). The TRAMAH always sited a TC near Baltimore because of the high number of serious injuries that had occurred there over the three-year study period. Because service capacity considerations were outside the scope of TRAMAH, we made the assumption that the four TCs currently in Baltimore were necessary due to the potential for congestion at any single facility. The TC site that covered Baltimore was therefore constrained to represent four TCs.

Applying TRAMAH to the Maryland Trauma System produced two types of results. The first type assumed that no existing trauma care resources were present: TCs and ADs were thus located as if the state were a “clean slate”. The second type began with the existing configuration of TCs and ADs and utilized TRAMAH to make incremental changes.

The full “clean slate” problem with all 385 eligible AD sites and all 32 eligible TC sites contained 25,733 constraints and 13,860 variables. For a 30-min response time standard, the

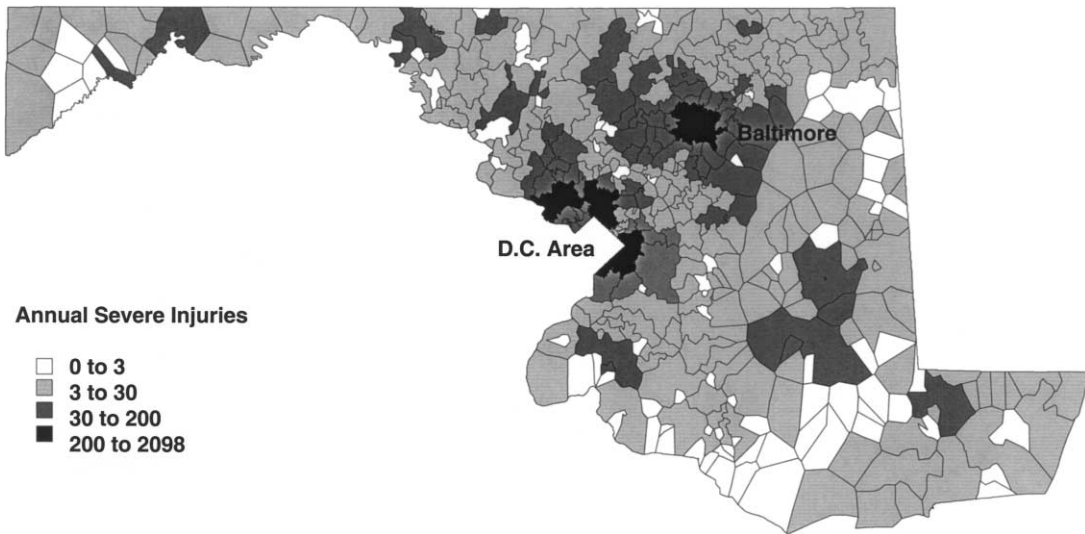


Fig. 3. Spatial profile of serious injuries across Maryland.

iterative switching heuristic successfully reduced the numbers of eligible sites. Beginning with five TC sites and five AD sites, the union of the top 10 out of 100 objective values produced a TC concentration set of 15 sites and an AD concentration set of 37 sites. These two concentration sets produced solutions in all of the 100 problems for the 30-min response time standard. The problem utilizing the concentration sets of 15 eligible TC and 37 eligible AD sites contained 2266 constraints and 1764 variables.

The number of branch-and-bound nodes among all 100 problems for the 30-min response time standard ranged from 22 to 20,497 nodes. Solution times ranged from 3 min for the 22-node problem to over 2 h for the 20,497-node problem. The number of nodes increased and then decreased as more TCs and ADs were sited. The highest numbers of nodes were among problems from six to seven TC sites and from three to five AD sites.

The percentage of serious injuries covered within 30 min ranged from a low of 74.7% to a maximum of 100% for ten TC and ten AD sites (see Table 1). The citing of seven TC and seven AD sites using TRAMAH achieved complete coverage of all ZIP codes. Resource configurations for greater than seven TC and seven AD sites also achieved 100% coverage, although sometimes with completely different resource configurations. This same information is displayed as an investment-versus-coverage graph assuming that the cost of a typical AD site is approximately twice the cost of converting the typical Maryland community hospital into a TC (see Fig. 4).

As a stand-alone analysis, the heuristic procedure sampled a relatively small number of the potential solutions in each clean slate problem. A comparison between the heuristic in a stand-alone capacity and the previous percent coverage figures for the 30-min response time standard was performed for ten select, noninferior solutions. As more facilities were sited, the disparity between the heuristic alone and the integer program plus the heuristic increased (see Table 2).

The existing Maryland Trauma System, consisting of six TC sites (nine TCs) and eight AD sites, covers 94.8% of severe injuries within 30 min (see Fig. 5). For the same number of resources, nine

Table 1

Percent coverage within 30 min for different combinations of trauma centers and aeromedical depots (bold cells represent noninferior solutions). Note that the first trauma center site represents four trauma centers

TC sites (#)	AD sites									
	1	2	3	4	5	6	7	8	9	10
1(4)	74.74%	79.66%	83.81%	85.16%	86.12%	87.09%	87.50%	87.77%	87.94%	88.007%
2(5)	81.10	86.67	88.64	89.62	90.70	91.70	92.62	92.90	93.03	93.079
3(6)	86.58	89.73	92.11	93.22	94.35	94.98	95.26	95.74	96.01	96.146
4(7)	88.87	92.02	94.40	95.51	96.63	97.59	98.10	98.41	98.68	98.738
5(8)	90.69	94.19	96.16	97.33	98.29	99.13	99.59	99.69	99.75	99.79
6(9)	92.50	96.01	97.35	99.07	99.27	99.87	99.93	99.97	100.0	100.0
7(10)	93.61	96.81	97.99	99.14	99.83	99.94	100.0	100.0	100.0	100.0
8(11)	94.24	97.46	98.58	99.59	99.91	100.0	100.0	100.0	100.0	100.0
9(12)	94.80	97.87	98.99	99.65	99.97	100.0	100.0	100.0	100.0	100.0
10(13)	95.27	98.11	99.10	99.70	99.97	100.0	100.0	100.0	100.0	100.0

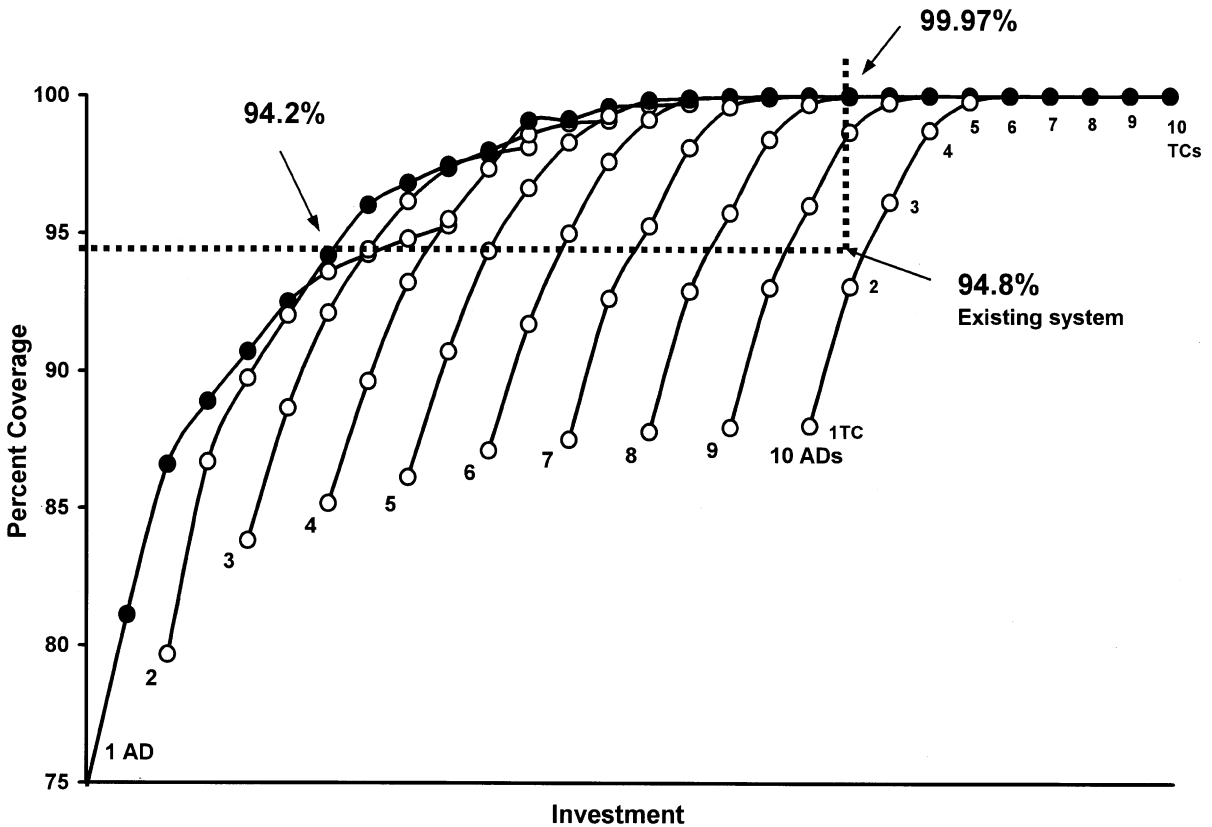


Fig. 4. Trade-off assuming that an AD site costs twice that of a TC. Closed circles are noninferior solutions.

Table 2

Comparison of solutions between heuristic-assisted integer programming and the heuristic procedure as a stand-alone analysis

Number of TC sites	Number of AD sites	Percent coverage with heuristic-assisted IP	Percent coverage with heuristic alone
1	1	74.74%	74.61%
2	1	81.10	81.10
3	1	86.58	84.46
4	1	88.87	86.12
5	1	90.69	87.39
5	2	94.19	91.17
6	2	96.01	91.51
7	2	96.81	94.76
8	2	97.46	95.49
7	3	97.99	96.06

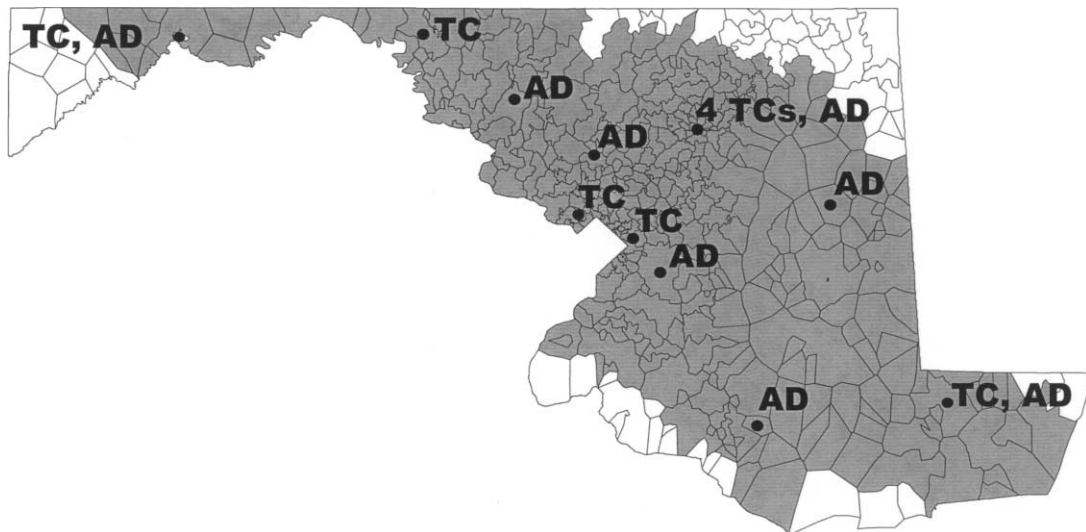


Fig. 5. The existing Maryland Trauma System, consisting of six TC sites (nine TCs) and eight AD sites, covers 94.8% of severe injuries within 30 min.

TCs and eight ADs, the clean slate approach achieved a coverage objective of 99.97% within 30 min. Only one small, north-central ZIP code with about three severe injuries per year was left uncovered (see Fig. 6). The existing system had 56 uncovered ZIP codes. For one less TC and six fewer ADs, TRAMAH achieved a coverage objective of 94.2% within 30 min, roughly the same as the existing system (see Fig. 7).

Using TRAMAH, incremental changes to the Maryland Trauma System were assessed with the nine TCs in the system stationary and then with the eight ADs stationary. In both cases, reduced

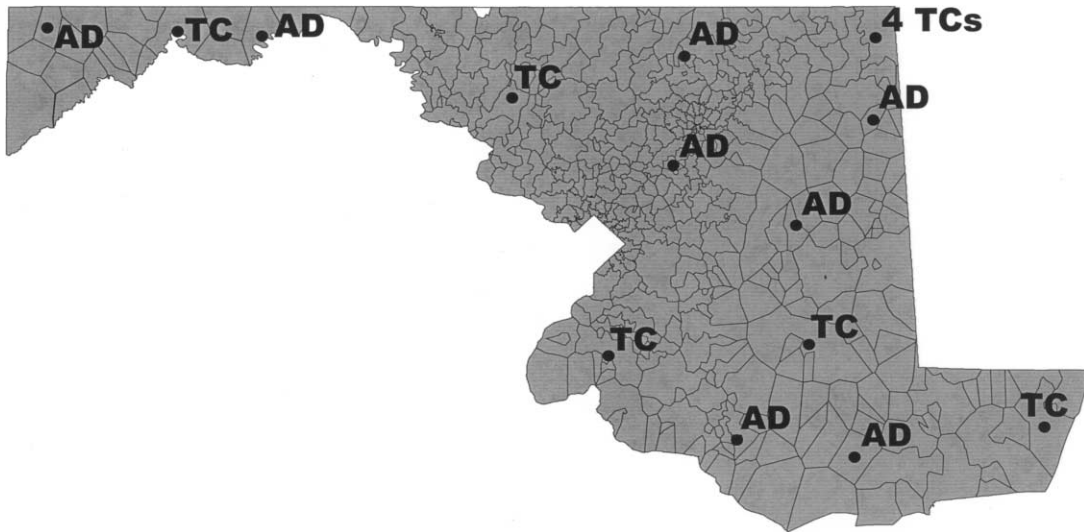


Fig. 6. For the same number of resources as the existing system, the clean slate approach achieved a coverage objective of 99.97% within 30 min.

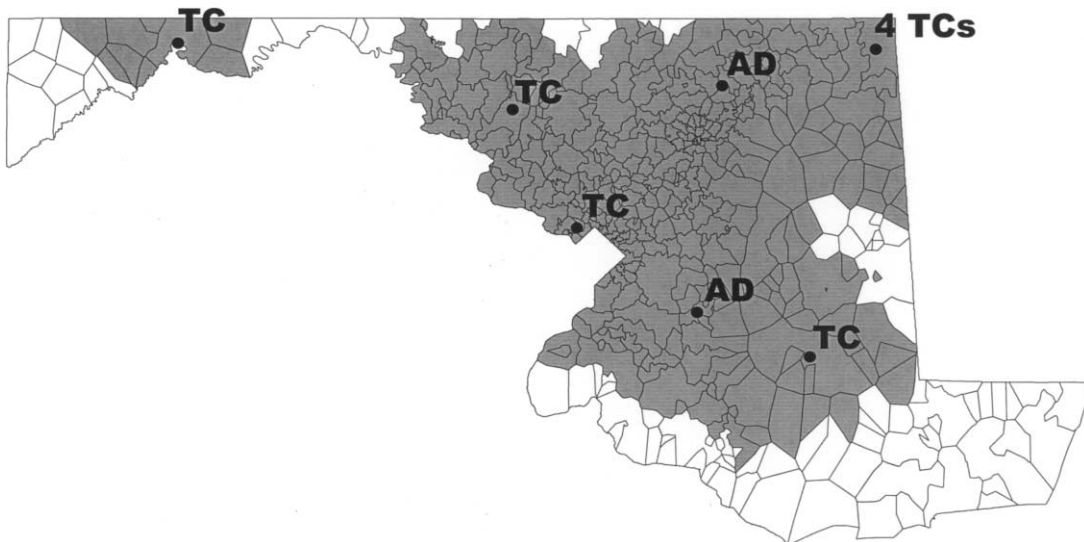


Fig. 7. The clean slate approach 94.2% of severe injuries within 30 min, roughly the same as the existing system, using one less TC and six fewer ADs.

problem sizes made fully optimal solutions possible, obviating the assistance of the iterative switching heuristic.

Holding in place the nine TCs of the existing system, approximately the same percent coverage as the existing system was achieved within 30-min by optimally locating two to three ADs, as opposed to retaining the eight of the existing system (see Table 3 and Fig. 8).

Table 3

Percentage coverage achieved for the optimal location of up to eight aeromedical depots assuming that the nine trauma centers of the existing Maryland Trauma System have not been moved

Optimally located aeromedical depots	Percent coverage within 30-min
0	80.52%
1	88.37
2	93.53
3	96.02
4	97.59
5	98.42
6	99.13
7	99.51
8	99.71

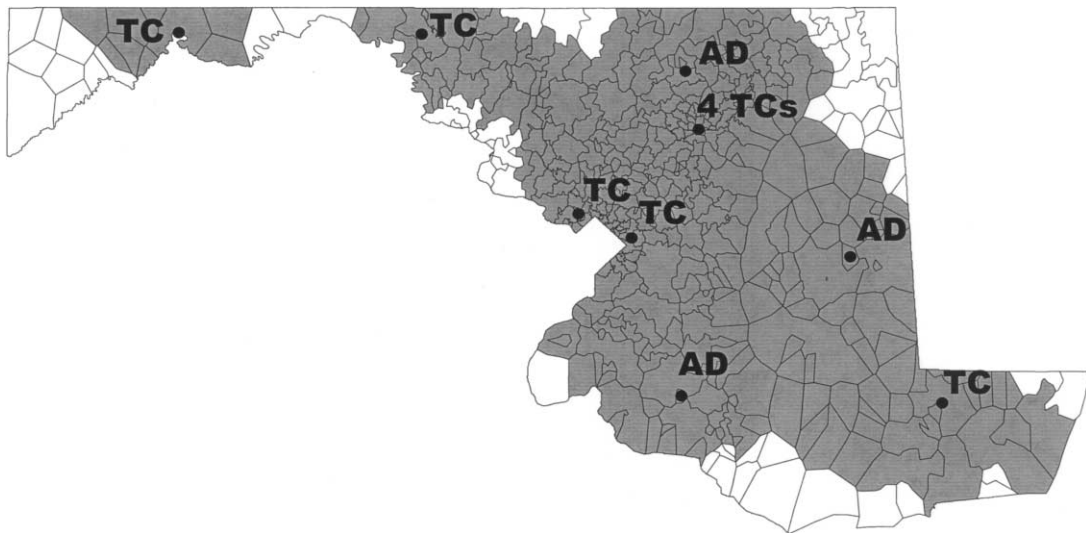


Fig. 8. Optimal aeromedical depot location within 30 min holding existing trauma centers in place (96.0% coverage).

Optimally locating the eight ADs used in the existing system would provide coverage to 99.7% of the serious injuries in Maryland within 30-min. This is an improvement of 4.9%, or 438 serious injuries additionally covered per year, over the existing system.

Holding in place the eight ADs of the existing system, TC sites were eliminated one and two at a time and then optimally replaced using TRAMAH. On average, the optimal replacement of a single TC site increased coverage by 1.68% for the 30-min response time standard. Similarly, the optimal replacement of two TC sites increased coverage by an average of 2.85%. The most effective TC replacement was shown to cover an additional 415 severely injured persons per year.

6. Conclusions

The “medical arms race” among trauma systems has produced organizational hypertrophy yet offered little marginal benefit to the public health [69–73]. Failure to limit the number of trauma centers based on demonstrated geographic need remains the most common trauma system deficiency [6,7,74]. Hospitals that satisfy clinical intra-facility requirements continue to be granted trauma center status with little systematic assessment of their relationship to ambulance facilities or their likely impact on regional demands.

Attempts in the early 1980s to recognize and close surplus trauma facilities did little to restrain the growth of trauma systems. As of 1993, 21 states were served by legally authorized statewide or regionally-based trauma systems. The short-lived funding provided by the 1990 Trauma Systems Development Act (PL-101-590) encouraged an additional 19 states to initiate publicly administered trauma systems of their own [5,6,75]. Geographic standards and reduction of duplicative resources are vital to the continued existence of solvent trauma systems.

The technical tools used to geo-spatially assess trauma system resources are often crude. Even a moderately sized region with the intent of citing a small number of resources can generate many more configuration choices than can effectively, much less optimally, be evaluated by the current technology. Quantitative location techniques, such as TRAMAH, produce optimal or near-optimal solutions faster and more efficiently compared with human judgment alone. In the case of Maryland, the full TRAMAH assessed over 50,000 possible location combinations for the citing of five aeromedical depot/trauma center pairs. Systems of linear equations this large are beyond the scope of human judgment alone.

The TRAMAH has the computational flexibility to optimally locate various numbers of aeromedical depots and trauma centers as separate resources, or in tandem. It can thus be engineered to build a regional or state trauma system from a “clean slate” as well as to accommodate partially-developed or well-developed systems that are only seeking incremental changes to their system.

From “clean slate”, TRAMAH produced near-optimal results using an iterative switching heuristic and integer programming. The use of TRAMAH to relocate the existing nine TCs and eight ADs from clean slate covered nearly all the state’s severely injured residents. Conversely, Maryland could have retained its current level of coverage with eight optimally located TCs and two optimally located ADs.

The iterative switching heuristic allowed us to obtain solutions within reasonable computer processing times for the clean slate analysis which, by its nature, was designed to locate different numbers of two types of facilities, TCs and ADs. The heuristic always produced concentrated sets of eligible facilities, of both types, within a negligible amount of computer processing time. Comparatively, the GRASP meta-heuristic [76] achieved generally similar results when applied to the maximum covering problem, although it should be noted that it was tested for a single facility type. The entire solution algorithm for TRAMAH, including the iterative switching heuristic and the reduced mixed-integer linear program, took over 2 h at its longest. This was about 30 min more than the time taken to obtain the longest GRASP metaheuristic solution largely because our solution algorithm had to contend with the citing of multiple facility pairs. The use of (AD, TC) pairs increased computer processing times vastly more than increases in the numbers of either facility type sited alone as with GRASP. In this way, our iterative switching heuristic was

specifically tailored for use with a maximum covering problem that sought to locate two types of facilities making a single-facility heuristic inapplicable.

A well-developed trauma system like Maryland's could also use TRAMAH to guide incremental decisions. However, this would not require the iterative switching heuristic because only one facility type is incrementally sited while the locations of the other facility type are held in place. In this regard, optimally relocating all eight existing ADs with TRAMAH could offer access to hundreds of severely injured residents each year for the relatively small price of moving resources that pose relatively few obstacles to relocation. At the very least, Maryland could reap the financial benefits of eliminating five of its existing eight ADs, optimally relocate the remaining three, and still maintain approximately the same level of access within 30 min. Although the relocation of TCs is more difficult than that of ADs, TRAMAH could also guide health planners to the best candidate sites should the decision be made to de-designate existing trauma centers and/or newly designate existing community hospitals as trauma centers.

Trauma systems must be balanced by trauma resource investments that efficiently protect the health of the community. The TRAMAH, which incorporates integer programming and a new iterative switching heuristic, is a powerful tool that can help trauma systems achieve this balance and improve the survival of their most grievously injured patients.

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