Distributed Medical Evacuation Planning: What Problem Should Each Agent Solve?

Victor Saks*, Gretchen Braidic*, Alexander Kott*, Corey Kirschner+
{saks, braidic, akott}@cgi.com, kirschnc@transcom.safb.af.mil
Carnegie Group, Inc*
Five PPG Place
Pittsburgh, PA 15211
USTRANSCOM/TCSG+
Bldg #1700, Room 1160
203 West Losey Street
Scott AFB, IL 62225-5209

Abstract

In the applied research being described here, there is a natural decomposition of a planning problem along geographic lines, where each sub-problem is to be solved by an agent whose organizational authority covers the geographic sector. However, the nature of the problem is such that each agent's solution has major impact on the problem to be solved by other agents, and multiple iterations of defining the problem solving process are required, until a process is agreed upon which is acceptable to the users as well as algorithmically sound. We formulate the concept of "constraint trespassing", which occurs when agents impose constraints on resources owned by other agents, and emphasize and illustrate the importance of minimizing it.

Introduction

In the applied research being described here, there is a natural decomposition of a planning problem along geographic lines, where each sub-problem is to be solved by an agent whose organizational authority covers the geographic sector. However, the nature of the problem is such that *each agent's solution has major impact on the problem to be solved by other agents*. First, during the problem solving process, demands of one agent become modified demands of other agents. In addition, the organizations represented by the planning agents own certain of the resources to be used to satisfy demands, including the demands of other agents. Thus the task of defining the overall problem solving process to be used by the collection of agents as a whole, and in particular the problem to be solved by each agent has been an ongoing challenge.

In this paper, we will begin by discussing the application problem, namely medical evacuation. Then we will discuss several different problem solving process definitions, and in particular, the definitions of the problem that each agent would solve, that we explored at a design level, together with their advantages and disadvantages, from both domain requirement and algorithmic perspectives. Then we will discuss which of the problem solving processes we implemented together with their user reactions and lessons learned and finally draw some conclusions.

We formulate the concept of "constraint trespassing", which occurs when agents impose constraints on resources owned by other agents. An owner/agent is willing to accept a demand from other agents, but not a constraint on its resources. Thus we formulate the following design principle: Design your problem solving process and supporting software to minimize constraint trespassing, that is, implicit or explicit posting of constraints by agents on non-owned resources.

Medical Evacuation Following a twenty year period during which time the Department of Defense collected factual and anecdotal accounts of seriously wounded patients being put at risk by having their care delayed due to evacuation planning and coordination, the Commander-in-Chief, US Transportation Command, resolved to correct this problem. As a result, In early 1993, the DoD - via Directive 5154.6 and Instruction 6000.11- tasked USTRANSCOM to consolidate the control of medical regulation and aeromedical evacuation under a single command. The resulting initiative, the TRAC^{2}ES (TRANSCOM Regulating and Command and Control Evacuation System) enterprise, codifies policies, procedures, doctrine, execution decision support, and advanced automated information technologies that permit resource constrained and unconstrained patient movement actions.

From its inception, TRAC^{2}ES has involved users in shaping its "to be" vision via national award winning business process re-engineering and the incorporation of multi-disciplinary user feedback. USTRANSCOM sponsored numerous Corporate Information Management (CIM) workshops, each of which focused on re-engineering a portion of the patient regulating and evacuation process into a seamless whole. Medical regulating is the process that selects and reserves a destination hospital bed, and the care associated with it, for a patient being moved from one Medical Treatment Facility (MTF) to another. Medical evacuation is the process of actually moving a patient once the patient is regulated.

Regulation/evacuation had been a two-step process where a regulator considers each patient and attempts to locate an available MTF bed. Once this is found, the patient is handed off to an evacuation planner who finds suitable airlift resources to move the patient to the MTF bed. One of the major changes in the "to-be" process is that the regulation and evacuation solutions should be integrated into one seamless decision process. TRAC^{2}ES provides automated support for this new business practice by proposing a lift-bed solution for moving the patients. Rather than seeking a bed first, and then looking for the lift, the TRAC^{2}ES planning algorithms consider lift and bed together.

The TRAC^{2}ES system will support medical regulation and evacuation on a global distributed network accessed by hundreds of users. The current release of TRAC^{2}ES is in use at exercises and sites around the world for evaluation purposes. It will replace the legacy systems used for regulation/evacuation in 1998.

Problem Statement

The world is divided into theaters, which are geographic areas of responsibility. Each theater is assigned to a Commander-in-Chief (CINC) who is allocated military resources and organizations located within his geographic area in support of a broad continuing military mission (e.g., PACOM, the Pacific theater). A Supported Combatant Theater CINC produces patients that require medical support outside of the theater. A Supporting Theater CINC is designated to receive and treat patients from one or more supported theaters.

Each operational theater has a Theater Patient Movement Requirements Center (TPMRC). The TPMRC is the organization/local agent responsible for movement of patients both within and out of the theater that it supports. The organization/global agent that monitors world-wide patient movement and addresses resource conflicts between theaters is called the Global Patient Movement Requirements Center (GPMRC).

A patient begins movement at an Originating Military Treatment Facility (MTF). This is where patients receive their initial treatment and are prepared for transit. The Destination MTF is the hospital that the patient will be moved to. This hospital must support the medical specialty (e.g., cardiac care) required by the patient.

Patients are moved between MTFs within a theater. This is called an Intra-Theater move. They also can be moved from an MTF in one theater to an MTF in another theater. This is called an Inter-Theater move.

Each TPMRC has the responsibility to satisfy a collection of Patient Movement Requests (PMRs) that have been entered at numerous originating MTFs. Some PMRs can be satisfied within the theater, through an intra-theater move, and some must be sent to another theater. Most patients with serious injuries are sent to the U.S., perhaps after short stays in MTFs in supporting theaters until they are stabilized.

The following requirements are levied on the TRAC^{2}ES planning algorithm in addition to the standard requirements of quickly producing acceptably good plans and ensuring the highest quality medical care for patients:

1. Respect organizational authority, do not make organizations request or give up use of resources (airlift and bed) they own.

2. Minimize conflicts for shared resources, or resources which are potentially shared.

3. The end result of the process must produce a full itinerary for patients including assignments to the destination MTF and the air mission or missions to deliver them there.

4. One system in peace and war.

Resource Ownership, Management and Contention

Each MTF can report the number of beds that it has available to handle incoming patients. The beds are managed by the theater in which the MTF is located. If different TPMRCs can assign patients to MTFs in the same theater, for example CONUS (the U.S.), then they will contend for the same beds

TPMRCs may assign patients to both dedicated airlift, which is solely used for the movement of patients and opportune airlift, which may be moving cargo or passengers.

All intra-theater airlift is owned by the theaters, for example, EUCOM, the European theater has a dedicated fleet of C-9 airplanes for flying patients within Europe. The TPMRC in Europe controls the stops, medical crew and patient manifest for these missions..

In practice, the division of the world into theaters is not a strict partition, and theaters can have dual roles and hierarchical relationships with each other. The most important theater is CONUS. In CONUS, the GPMRC serves two roles: Global Arbiter for inter-theater lift and CONUS TPMRC. Inter-theater lift is owned by the TRANSCOM CINC and aero-medical missions are planned and managed by the GPMRC. Depending on the problem solving process, different TPMRCs can contend for the same inter-theater lift.

In addition, the large theaters commands, EUCOM in Europe and PACOM in the Pacific, really contain the smaller theaters near them. Thus, EUCOM can be said to contain the Bosnia theater, as well as CENTCOM, and PACOM includes Korea. Perhaps the main point to be made here is it that has been extremely difficult to precisely identify resource ownership by the different theaters, which has severely complicated the task of defining problem solving process and obtaining user buy-in.

Problem Formulated as CSP

We now formulate the planning problem as a Constraint Satisfaction Problem, emphasizing the capacity constraints which are the key constraints affecting agent interaction:
GIVEN:

- a list of patients to move to an MTF which can treat them
- a list of airports
- a list of missions connecting the airports
- a list of MTFs, each of which is co-located with at least one airport
- a list of ASFs, Aeromedical Staging Facilities, which are temporary holding facilities at airports for patients changing missions

The SOLUTION consists of specifying, for each patient, an acceptable destination MTF and a sequence of missions which will take the patient from their current location to the destination MTF.

The SOLUTION is subject to the following constraints:

- mission aircraft capacity cannot be exceeded
- MTF bed capacity cannot be exceeded
- ASF bed capacity cannot be exceeded

This formulation ignores many of the constraints that make the medical evacuation problem so complex, for example, patient medical conditions that must be treatable by the destination MTF, restrictions on patient itineraries such as a maximum number of stops the patient can tolerate and maximum altitude at which the patient can fly. Here we are interested in listing the capacity constraints which are the key constraints affecting agent interaction, and will discuss each of the problem solving definitions in terms of capacity constraint.

The TPMRC Planning Algorithm

Our basic planning and scheduling technology is Constrained Heuristic Search (Fox, Sadeh & Baykan, 1989) using the texture measures of contention and reliance (Sadeh 1991) which were originally defined in the Micro-Boss system to solve the job-shop scheduling problem.. We first adapted this approach to solve the military logistics distribution problem in the KBLPS Distribution Planner (Saks, Kepner & Johnson 1992; Saks, Johnson & Fox 1993). Our approach is based on Sadeh in which resources maintain demand profiles which allow contention over time to be measured. The algorithm first selects the resource which is most heavily contended for at a specific time within the planning horizon, and assigns those resources to the demands which rely on them most critically, taking demand priority into account.

The logistics distribution problem includes many complex resource constraints not normally dealt with in job-shop scheduling, such as product inventory, and complex demand constraints such as splittable orders. To reason effectively on these kinds of constraints, we had to significantly generalize Sadeh's earlier research. See (Beck et. al. 1997) for some different approaches to reinterpreting contention texture measurements.

Later, in solving the medical evacuation problem in the TRAC^{2}ES (Kott and Saks 1996) system, we took the KBLPS Distribution Planner as a starting point, since both problems focus on transporting commodities through a distribution network. However, patient evacuation again requires reasoning on a new collection of complex constraints. For example, in the KBLPS problem, the distribution network could be represented as a tree, whereas for TRAC^{2}ES, mission routing is fairly unconstrained. Thus in the KBLPS Distribution Planner, we pre-calculated all routes, whereas in TRAC^{2}ES, mission routes and patient path/itineraries are dynamically calculated.

In the TRAC^{2}ES planning algorithm, each patient has a "Path Preference Manager (PPM)", which functions like a travel agent, searching the lift-bed network to construct good candidate path/itineraries for the patient. Each PPM has knowledge of how to take into account the patient's constraints and preferences in its path search, as well as in computing the contention and reliance measures. For example, in case the patient is Urgent, the PPM adjusts the reliance for the patient to guarantee that the Urgent patient will be scheduled ahead of all Routine patients who are contending for the same resources. In addition, the PPM has the authority to bump already scheduled routine patients from their assigned itinerary. For routine patients, in case the patient is running out of acceptable paths, the PPM raises the patient's reliance, increasing the likelihood that the patient will be chosen for assignment sooner.

Distributed Planning Process

As part of developing TRAC^{2}ES, Carnegie Group and TRANSCOM personnel explored many different approaches for defining the overall problem solving process and defining the roles of the TPMRCs and GPMRC and their interactions.

Very little attention was given to negotiation schemes between the TPMRCs, since, in the military, peer-to-peer negotiation to resolve conflicts is simply not the normal way of doing business. Thus we were most interested in approaches which would minimize, and if possible, eliminate conflicts between different TPMRC plans. In case of conflicts and/or suboptimalities, the GPMRC must get involved and arbitrate a solution or negotiate with the TPMRCs.

Decomposition with truly limited interaction is impossible because theaters send patients to each other: one theater's patients end up in another theater, consuming resources, and possibly becoming new movement requirements, according to several, but not all, of the processes we explored.

We also were required to work within the constraints of resource ownership in order to reduce the amount of authorization (e.g., CONUS granting permission for EUCOM patients to occupy CONUS MTF beds) necessary to implement a plan that is created by our algorithms. Understanding and accommodating the ownership of beds and lift is not a trivial problem.

In addition, as discussed before, TRANSCOM has been and still is re-engineering the business practice of patient regulation and evacuation. Thus we have been attempting to design a system to solve a problem for a process which is itself incompletely defined, and is still a moving target. To say the least, that has made our task that much more difficult.

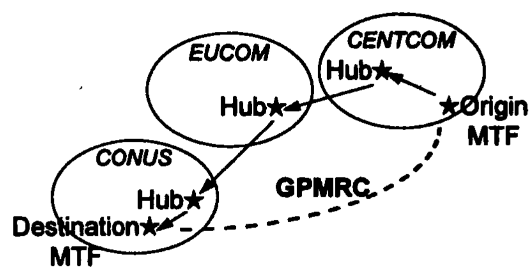
An important simplification is the Hub and Spoke concept. This is similar to the hub concept used by commercial airlines in the U.S (see, for example, Aykin, 1995). Each theater designates certain airfields as hubs, and inter-theater flights into the theater would enter the theater through a hub. Interaction between the TPMRCs is substantially simplified by the use of hubs. In particular, the impact of incoming patients to a theater, usually the U.S., for subsequent redistribution to a destination MTF, would be unmanageable if those patients could fly in to any airport, as opposed to a relatively small number of hubs from which they will be redistributed as required. See (Steppe et al., 1997) for an in depth model of redistribution of patients arriving into hubs in the CONUS,.

Numerous paradigms were explored for structured problem solving approach for TRAC^{2}ES and the GPMRC/TPMRC interaction. Together with each paradigm, we will discuss its advantages and disadvantages, as well as the extent of its constraint trespassing.

Different Problem Definitions

In order to clarify the distinctions between the different problem definitions, each will be accompanied by a diagram, which shows the movement of a patient from CENTCOM to CONUS through EUCOM. Each movement leg is highlighted, showing which TPMRC or GPMRC made the decision to move the patient along that leg. As mentioned before, CENTCOM functions like a sub-theater of EUCOM, and thus the CENTCOM to EUCOM leg is considered to be *intra*-theater, with EUCOM owning the lift. The identification of the GPMRC and CONUS TPMRC means that either of them can plan resources owned by CONUS without constraint trespassing.

<u>I. Global Solve</u>



GPMRC creates all patient itineraries for patients needing movement. In many distributed planning contexts, global solve is not an option, because each agent may have specialized knowledge which is not, and should not be, accessible to other agents. Also, certain agents may have access to private data which may not be revealed to other agents. In the current context, none of these disqualifications apply, and so global solve could be a viable option. Global solve is how a non-distributed planner would produce a plan.

Advantages:

- This ensures an integrated conflict-free solution.

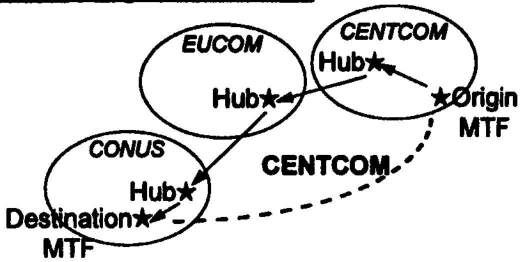
Disadvantages:

- It could potentially become an unmanageable data problem and risk of computational explosion. However, recent contingencies (e.g., Operation Desert Storm) have generated a patient load that could reasonably be planned by a single process at the GPMRC.
- TPMRCs do not control their own assets.

Constraint Trespassing:

- Maximum constraint trespassing on all TPMRCs, on the missions into CENTCOM and EUCOM, and on the ASFs at the hubs in those theaters.

II. TPMRC plans end-to-end.



The originating TPMRC plans its patients all the way through to their destination MTF.

Advantage

- Simple solution process that allows one organization to be responsible for the creation of a full patient itinerary.

Disadvantages

- Conflicts for lift and beds can occur anywhere along the way, and especially in CONUS.
- This approach does not respect the resource ownership of each theater.

Constraint Trespassing:

- CENTCOM is trespassing on missions in EUCOM and CONUS, on the MTF beds in CONUS and on the ASF beds in the hubs

We explored several variations here to reduce conflicts. First, that the TPMRCs share data so that the TPMRC internal algorithm can take a global view. The TPMRC would produce its portion of a plan, taking into account the global situation (current and forecasted) so that it can be integrated with other theater plans without major rework.

The foundation of this approach is based on the ideas of Distributed Micro-Boss (Sycara et al. 1991) which expands the concepts of Micro-Boss so that they can be applied to a distributed scheduling problem. Distributed Micro-Boss has focused on the manufacturing domain and this effort would be the first application of its demand-based coordination protocols techniques to transportation and distribution problems.

The key concept here is to improve overall system performance by developing protocols through which agents exchange information about their demands and available capacities. In (Sycara et al. 1991) it has been shown that by exchanging demand profiles, agents can focus on the most critical decisions within the overall system rather than focus on locally critical decisions.

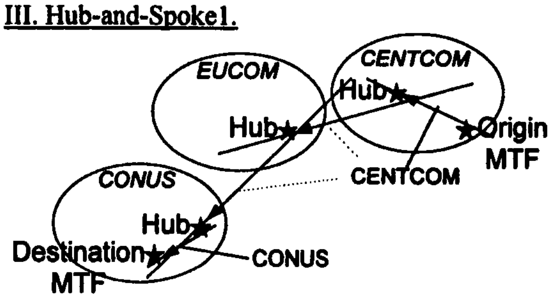
In this earlier work, each agent makes one request at a time, and as many as possible of the requests are granted. However, this mechanism is too simplistic, since TPMRC users require as complete a solution as possible from one run, and this type of extended collaborative solve is unacceptable. In addition, in our problem where the agents have different priorities based on supported/supporting relationships, it is crucial that agents with higher priority have their requests honored as fits their priority. Moreover, patients themselves have different priorities which must be respected. Thus this approach is technically risky, requiring major new ideas which take priority and other domain specific concepts into account, and was never fully designed.

We also explored imposing an ordering on different TPMRCs planning, so each sees what the others before it have planned. The ordering could be based primarily on supported TPMRCs planning first, because they have first priority for using shared resources. However, TPMRC users would not accept being forced to plan at specific times. Moreover, if a TPMRC user needs extra time to edit a plan and/or explore what-if possibilities, the schedule is thrown off.

This paradigm would certainly introduce conflicts for beds any time more than one TPMRC is sending patients to CONUS, and for lift any time more than one TPMRC is sending patients to CONUS from the same direction. This paradigm is the simplest for TPMRC users, since they can plan a full ticket for patients on their own. However, even with explicit GPMRC deconfliction, it may require many iterations to reach a feasible plan, let alone an optimal one.

The flaws accompanying the previous approaches, and in particular the extensive constraint trespassing, convinced all the involved parties to work together to find better approaches which now follow.

III. Hub-and-Spoke1.



Each TPMRC plans patients only to a hub in the destination theater. The destination TPMRC, usually CONUS, is then responsible for incorporating the patients who require onward movement from the reception point in with their organic theater requirements, developing a composite lift-bed plan, and notifying the sending TPMRC of a completed itinerary for their patients prior to their departure from the sending theater.

Advantage

- Eliminates conflicts for beds and intra lift in destination theater.

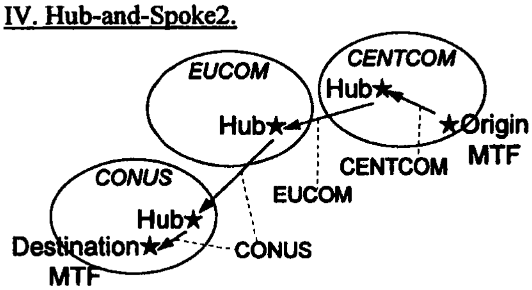
Disadvantages

- If each TPMRC selects destination hubs without coordination among the TPMRCs, the CONUS redistribution problem may be unduly difficult and the final solution may be suboptimal, because extra missions may be required due to patients being scattered at different hubs. Alternatively, one hub may be clogged with too many patients to handle while other hubs have excess available patient handling capability.
- Two TPMRCs must be involved in the creation of a single inter-theater itinerary.

Constraint Trespassing:

- A significant improvement over the previous approaches. Destination theater no longer has trespassing on its MTF beds and intra-lift. But the sending TPMRC is still trespassing on the inter-lift into the other theaters and their ASF beds.

IV. Hub-and-Spoke2.



Each TPMRC plans patients only to a hub in its own theater. Each TPMRC is responsible for planning the patient moves into its own theater on its own lift. The destination TPMRC is responsible for developing a lift-bed plan from its own hub to final destination MTF in its theater. Since most patients go to CONUS, most inter-theater planning is done by the CONUS TPMRC. Thus this paradigm is very similar to a paradigm for which each TPMRC performs its own intra-theater planning, and all inter-theater planning is done by a single agent

Advantages

- A TPMRC has total control for planning patients on the lift and bed resources that they own.
- There will be no conflicts for resources because each TPMRC plans all patients (regardless of their originating theater) who need access to their resources.

Disadvantages

- Fragmented solve - multiple TPMRCs must work to complete a single itinerary
- A bad decision may be made when staging a patient to a hub, since the originating theater does not have visibility into the remaining legs of the patient's trip.

Constraint Trespassing:

- Constraint trespassing has been eliminated.

Experience To Date

An operational prototype of the planning algorithm was presented to the users for evaluation in 1995. This algorithm utilized the concept described in Hub-and-Spoke1 (paradigm III). The software would not present the itinerary for viewing until all legs of the patient's itinerary had been planned. This meant that the itinerary was not available until both theaters had completed their planning. This is different than the current manual process, because they can currently view each half of the itinerary as soon as it is created. The users stated that this was not acceptable.

The next version of TRAC^{2}ES software was built to support contingency operations like Operation Desert Storm and Operation Joint Endeavor. This version employed the TPMRC Plans End-To-End (paradigm II). Although in this version, TPMRC users were able to plan a full ticket itinerary for a patient without waiting for another TPMRC to complete the itinerary, TPMRCs did not accept it, primarily because they could not control the assets that they own.

The version of TRAC^{2}ES that is currently in development will utilize the Hub-and-Spoke2 (paradigm IV). It will be deployed world-wide in 1998 and will become the definitive system for planning patient movement. Current users are supporting this paradigm because it most allows the theater that "owns" the resources to allocate them to patients.

This is also the preferred algorithmic paradigm, since it eliminates resource conflicts between different TPMRCs.

The user interface will be improved so that TPMRC users can view each part of the itinerary as soon as it is created.

Conclusions

In complex real-world distributed planning problems, defining a structured problem solving approach and agent interaction is a challenging task and a critical key to successful system development. When the relationships between the different agents are not well defined by an already existing business practice, then requirements to respect agent authority and other agent needs which may not be well specified can be the drivers of the system architecture definition process, overriding pure algorithmic considerations.

In particular, when the nature of the problems is such that during the planning process, demands of one agent become transformed into demands of other agents, then great care must be given to defining agent interactions which are acceptable to the different organizations, and which also support a workable planning process in which agent conflicts are minimized. It should be expected that multiple iterations of defining the problem solving process will be required, until a process is defined which is acceptable to the users as well as algorithmically sound.

We formulate the concept of "constraint trespassing", which occurs when agents impose constraints on resources owned by other agents. We illustrate the concept of "constraint trespassing" by showing how it applies to several problem solving process definitions. Our experience has shown us that an owner/agent is willing to accept a demand from other agents, but not a constraint on its resources. Thus we formulate the following design principle: Design your problem solving process and supporting software to minimize constraint trespassing, that is, implicit or explicit posting of constraints on non-owned resources. We illustrate this design principle by finally defining a problem solving process which incorporates it and which users have indicated they will accept.

The views expresses in this article are those of the authors and do not reflect the official policy or position of the United States Transportation Command, the Department of Defense, or the United States Government.

Acknowledgments. We thank the United States Transportation Command for the support to develop TRAC²ES and for permission to publish this paper. The first three authors thank Lt. Col. Corey Kirschner for his dedication to the medical evacuation process and for his leadership in managing the TRAC²ES project. Many thanks also to all of our colleagues who we have enjoyed working with, including Bill Elm, Ivan Johnson, Michael Bett, Bob Erhard, Ron Ball, Jeff Stonebrook, Jerry Agin, Andy Hollencamp, Rick Ragsdale, and especially to Phil Mahlum for helping to clarify and write some of the domain information.

References

Aykin, T. 1995. Networking Policies for Hub-and -Spoke Systems with Application to the Air Transportation System. In Transportation Science 29(3).

Beck, J.C., Davenport, A.J., Sitarski, E., and Fox, M.S. 1997. Beyond Contention: Extending Texture-Based Scheduling Heuristics. In Proceedings AAAI-97.

Fox, M.S., Sadeh, N. and Baykan, C. 1989. Constrained Heuristic Search. In Proceedings of the Eleventh International Joint Conference on Artificial Intelligence.

Kott, A. and Saks, V. 1996 Continuity-Guided Regeneration: An Approach to Reactive Replanning and Rescheduling, In Proceedings of the Florida Artificial Intelligence Research Symposium, FLAIRS-96, Key West, Florida.

Sadeh, N. 1991. Look-ahead Techniques for Micro-opportunistic Job Shop Scheduling. Ph.D. thesis, School of Computer Science, Carnegie Mellon University.

Saks, V., Kepner, A. and Johnson, I. 1992. Knowledge Based Distribution Planning, In Proceedings of the American Defense Preparedness Association AI conference.

Saks, V., Johnson, I. Fox, M. S. 1993. Distribution Planning: A Constrained Heuristic Search Approach, In Proceedings of the Canadian DND Workshop on Advanced Technologies in Knowledge-Based Systems.

Steppe, J., Lorraine, J., Saks, V., and Mahlum, P. CONUS Model Design Document, in preparation.

Sycara, K., Roth, S., Sadeh, N., and Fox, M, 1991. Distributed Constrained Heuristic Search, In IEEE Transactions on Systems, Man, and Cybernetics.21(6):1446-1461