SUSTAINMENT ROUTING FOR ORBITING SATELLITES

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ABSTRACT

Satellite systems are essentially consumable with no ability to service or repair them. This research formulates an initial two-stage optimization model to determine the on-orbit servicing logistics architecture and processes for a planned future satellite system. The study offers insights into a new and challenging application area.

Keywords: Vehicle routing, maintenance, satellite, service operations, optimization

INTRODUCTION

Many resources are used to acquire, launch, and operate space-born satellite systems for a wide variety of tasks, from weather forecasting and communications, to conducting military operations. Like the military, commercial space providers depend upon satellites to operate effectively and efficiently around the globe. However, satellite systems are treated as essentially a consumable item with no ability to service satellites in orbit. Except in rare cases like the Hubble space telescope, there is currently no ability to maintain, repair, or upgrade satellites while in orbit, and if a satellite fails, it must be replaced or the capability that satellite provides is lost. The U.S. military and the Defense Advanced Research Projects Agency (DARPA) have considered employing on-orbit servicing systems as an alternative to replacement. One satellite system under development is the Space-Based Radar, or Space Radar system, resurrected from the cancelled Discoverer II program (Tirpak, 2002). The Air Force and DARPA considered on-orbit servicing as part of an analysis of alternatives for a Space-Based Radar (SBR) constellation projected for deployment in 2015 (McCormick et al. 2003). China has similar plans to develop in-orbit servicing by 2016 (Pasztor, 2010).

This research provides an approach to determine the optimal on-orbit servicing architecture for a client satellite constellation, and notionally applies it to SBR. A servicing architecture is composed of a variable number and type of autonomous servicing vehicles using varying routes to visit a set of client satellites with specific time windows for servicing, and an available set of spacecraft for commodity supply. The problem resembles a simultaneous facility location (Daskin, 2008) and vehicle routing problem with time windows (Yan et al. 2006; Qi et al. 2012), and similar research for airborne military operations considers time windows and payload capacity constraints (Murray and Karwan, 2010). While a very large problem to solve using optimization techniques, a network flow structure facilitates the use of integer linear programming to efficiently determine the optimal solution.

LITERATURE

On-orbit servicing can include anything from upgrade, repair, or cleaning solar panels to assembly of very large spacecraft (Waltz, 1993). However, an on-orbit servicing system will be expensive, and the resources devoted to it should be used as efficiently as possible (Rexius, 2009). Although on-orbit servicing operations are not currently being used, development efforts are focused on making on-orbit servicing a technological possibility. Although the technology to make servicing a reality may be in place within the next decade, the policies of how to operate such a system need to be explored before fielding any new capability.

Previous studies have been conducted to determine the cost feasibility of on-orbit servicing (Divinic et al. 1997; Saleh et al. 2003; Perez et al. 2002) . These studies examined the cost of servicing a satellite in terms of its commercial, civil, and military utility, direct servicing costs, and even the value of increased capability or flexibility. Few studies have examined the different servicing architectures available to large client satellite constellations (Reilly and Mata, 1990). There is a need to examine the management alternatives for costly on-orbit servicing resources by looking at what architecture(s) would most efficiently utilize servicing assets. This research provides an approach to determine the optimum servicing architecture for a given client satellite constellation with an associated set of demands. As a frame of reference on the expense of placing new satellites, rather than servicing existing ones, Germany launched the fifth and final satellite in its SARLupe X-Band constellation in 2008 (Taverna, 2008). The 1,700-pound satellite completed the European Union's first fully space-based radar network. Launching one of these satellites costs approximately 50 million Euros with an expected life for the network of 10 years (Krebs, 2009). Additional satellite construction costs range from relatively inexpensive models, to larger missile warning satellites with costs approaching $1 billion (Banke, 2000; Castel 2000). While historically the U.S.'s Space Shuttle has been able to service limited, high value orbiting assets, the average cost for each shuttle mission is $450 million (Isakowitz 2004; Dunbar 2010; Robertson 2008). Given NASA will no longer be sending Space Shuttles into orbit after 2010, there is a greater need than ever to investigate alternative options of satellite servicing (Yembrick, 2008).

METHODS

The on-orbit servicing system used in this research is based on Boeing's Orbital Express program (Boeing, 2010). Orbital Express is an advanced technology demonstrator that in 2009 showcased the feasibility of fully autonomous on-orbit servicing. The SBR analysis of alternatives uses the Orbital Express system as the enabling technology for the on-orbit servicing system alternative. As such, this research is also based upon the capabilities of the Orbital Express system as a system baseline. The SBR constellation orbital parameters were derived from Hoy (2004). The satellite constellation used in our model consists of 18 client satellites in six orbital planes. Each orbital plane is assumed circular at an altitude of 1,000 nautical miles, or 1,842 Km and an inclination of 50°. The specific pattern of the satellite constellation has not yet been finalized. Therefore, a commonly used pattern was employed for client satellites, spacing them evenly, with a mean anomaly difference of 120° between each client. Further, the Right Ascension of each client plane was evenly spaced with a 60° difference. Each of the depot spacecraft locations was arbitrarily chosen to be equidistant between two client satellites in each of the six planes. Figures 1 and 2 are generalized illustrations of the orbital planes and client satellite relative locations within each plane. In order to service the SBR satellites, servicing vehicles must travel to each of the client satellites. Servicing vehicles can travel from any client satellite to any other, as well as to any of six depot spacecraft. Each client satellite may have a different demand for servicing and the time required for a servicing vehicle to move from one node to another will vary based on mass, fuel, and previous orbit. Given the types of variables, nodes, and restrictions involved, a complex routing problem appears to be representative of the SBR on-orbit servicing problem.

There are several methods that can be applied to solving vehicle routing problems (VRPs). Enumerative approaches can guarantee optimality, but large scale and complex problems have too many variables to make enumerative solution techniques efficient. Tabu search and other meta-heuristics have been widely applied to solve complex VRPs, and a comparison of meta-heuristic methods for solving the VRP has been presented by Laporte (2007). However, most heuristic techniques cannot guarantee the optimality of a determined solution. Therefore, by using a network flow problem, an optimal solution may be found via the linear programming.

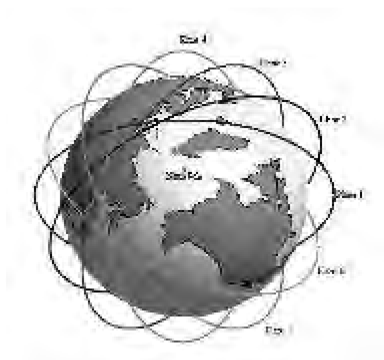


Fig. 1. SBR orbital planes as seen from above the North Pole

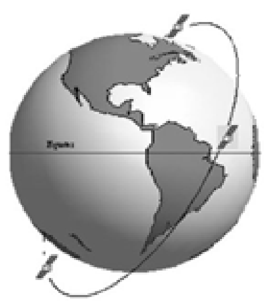
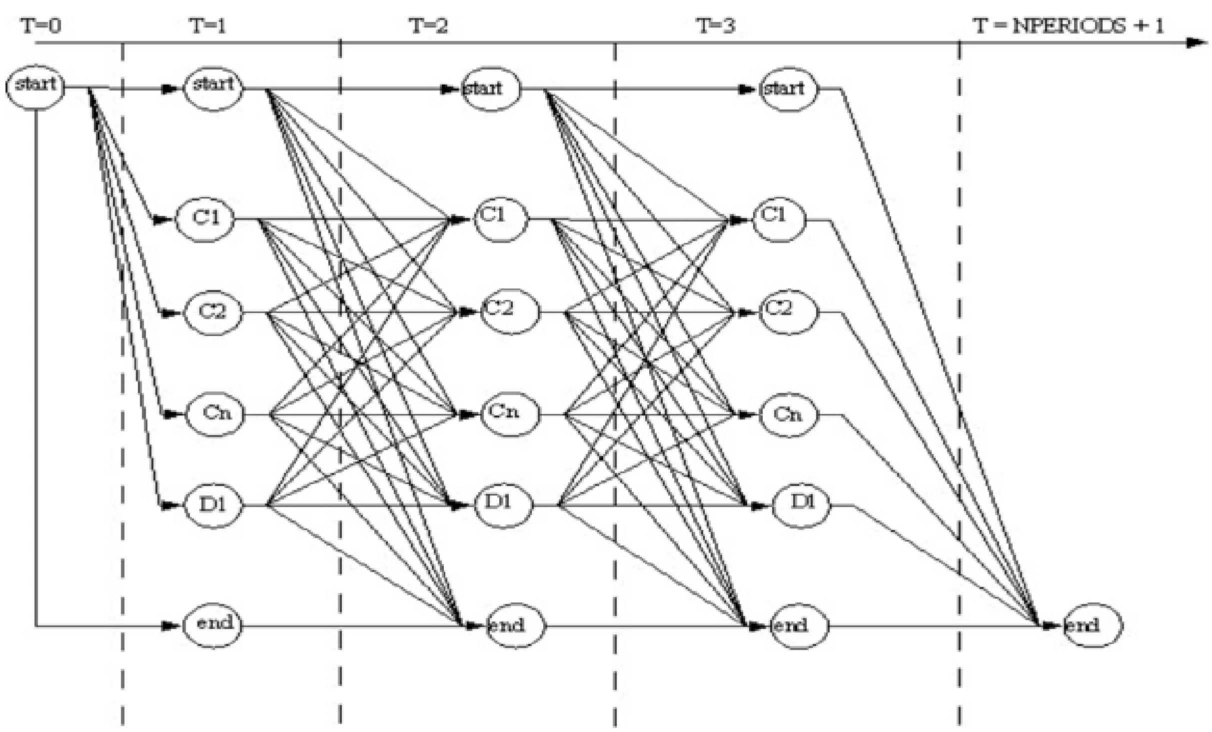


Fig. 2. Notional relative locations of SBR satellites within orbital planes

Given the nature of the on-orbit servicing process, the design of an optimal architecture can be looked at as determining an optimal path through a network. In the on-orbit servicing network, nodes represent client satellites, and depot spacecraft. The arcs represent the maneuvers between different orbits, and servicing vehicles move between nodes on the network arcs. Each arc will have costs (termed delta-V, a proxy cost for propellant usage in a space environment, and time) associated with the chosen maneuver (Kobel, 2004). Servicing vehicles are initiated by selecting their launch into the network from the supply node (launch facility on Earth) on the far left of the network. It is possible to launch any number of each type of servicing vehicle either directly to a client or to a depot spacecraft. If a servicing vehicle is launched to a depot spacecraft, it is launched “dry” with only enough fuel to get it to the depot spacecraft where it will be fueled in preparation for its servicing mission. If a servicing vehicle is launched directly to a client satellite, it must be launched “wet” with a full load of fuel. Servicing vehicles travel through the network visiting client satellites until their delivery capacity is reached, then they exit the network or visit a depot spacecraft to re-fuel. In order to track the inventory of each servicing vehicle throughout its route, it is necessary to track the vehicle routes with respect to time. By creating discrete time units equivalent to the total time to maneuver from one node to another in the network it becomes possible to look at each servicing vehicle’s inventory at any given time. It also becomes possible to track the balance of supply parts called orbit-replaceable units (ORU) and delta-V propellant (e.g., demand) for each client at any given time. Incorporating time as a way to help structure the network results in vehicle routes being combined strings of binary choices, whether or not to choose specific arcs at specific instances in time. The continuous variables representing flow of delta-V and ORUs across arcs are also examined at specific instances in time. Figure 3 is a generalized diagram of the network and the arcs available for use at any given time period. In the network diagram in Figure 3, the servicing vehicle can choose to use any arc at the beginning of the current period. For example, at the beginning of period 0, the only arcs available to choose from leave the start node to any other node. At the beginning of the next period the arcs available depend on what choice was made at the beginning of the last period. The nodes labeled “C” represent client satellite nodes and “D” represents the depot spacecraft node. Once an arc out of the start node is chosen, it is not possible to go back to the start node. Also, once an arc is taken to the exit node, it is not possible to leave for another.



3. Simplified diagram of on-orbit servicing network

For the SBR on-orbit servicing problem the sets of objects in the network considered are client satellites, depot spacecraft, servicing vehicles, and the transfer orbits (arcs) along which servicing vehicles can travel. There are three types of servicing vehicles characterized as small, medium, or large with their associated capacities varying accordingly. Client satellites requiring servicing are the "customers" or "demand" nodes. Each of the customers has a specific location given by its specific orbit. Each client satellite has a specific demand in terms of orbit-replaceable unit (ORU) mass and propellant (delta-V) mass. The time windows are important as early arrivals may result in too-frequent servicing and induced failures (Ebeling, 1997). Late arrivals may result in too-infrequent servicing and client satellite failures. Depot spacecraft in orbit serve as "supply" nodes where a servicing vehicle can replenish its propellant and ORU stores. Like the client satellites, the orbits in which these depot spacecraft can be located are given as part of the problem definition. For the SBR on-orbit servicing problem, travel costs considered are time and delta-V. In order for any body in orbit to maneuver, it requires a change in velocity, or delta-V. As described earlier, delta-V is used as a proxy for maneuver cost for propellant usage because it ignores the mass of the object (Kobel, 2004). By calculating the delta-V required for a specific maneuver, planners can consider the mass of the vehicle later in calculating the total propellant needed to achieve the desired delta-V. The added complexity of where to initially locate servicing vehicles requires a definition of the cost to use specific locations. The cost of locating a servicing vehicle either "dry" at a depot or "wet" at a client is reflected in the launch cost, based on the generally accepted figure of $10,000 per pound (Air University, 2002). The following is a list and description of the specific parameters used in the SBR on-orbit servicing problem:

$Txdelta_{(j,k)}$:= delta-V required for a servicer to move from node *j* to node *k*
$costwet_{st}$:= cost to launch servicer type *st* fully loaded
$costdry_{st}$:= cost to launch servicer type *st* unfueled
$demDV_{c}$:= demand for delta-V propellant of client *c*
$demORU_{c}$:= demand for ORU mass of client *c*
$timeearly_{v,c}$:= early time allowed for visit *v* to client *c* by a servicer
$timelate_{v,c}$:= late time allowed for visit *v* to client *c* by a servicer
$Ttime_{(j,k)}$:= time (quarters) required for a servicer to move from node *j* to node *k*
$arc_{st,s,(j,k).t}$:= The decision to move servicing vehicle type *st*. number *s* from node *j* to node *k* at the beginning of period *t* is allowed/not allowed
$DeltaCap_{st}$:= delta-V capacity of servicer type *st* (for maneuver and delivery)
$ORUCap_{st}$:= ORU carrying capacity of servicer type *st* (for delivery only)
$RHSBAL_{(n,t)}$:= Servicing vehicle balance for node *n* at the beginning of period *t*
$DVBAL_{(n,t)}$:= Delta-V flow balance for node *n* at the beginning of period *t*
$ORUBAL_{(nt,)}$:= ORU flow balance for node *n* at the beginning of period *t*

For the SBR on-orbit servicing problem the sets of objects in the network considered are client satellites, depot spacecraft, servicing vehicles, and the transfer orbits (arcs) along which servicing vehicles can travel. Servicing vehicles are characterized as small, medium, or large with their associated capacities varying accordingly. The variable sets include nodes, clients, servicing vehicle types, arc lengths and the number of time periods, as defined below:

NODES := {0, 1, 2, . . ., 25} All nodes

CLIENTS (*C*) := {1, 2, 3, …, 18} Subset of nodes where clients 1 through 3 are in the first orbital plane, and clients 4 through 6 are in the second orbital plane, etc. There are 6 orbital planes with 3 client satellites in each (Hoy, 2004).

DEPOTS (*D*) := {19, 20, 21, …, 24} Subset of nodes where one depot spacecraft is assigned per client orbital plane.

DSNODE := {0} Subset of nodes, dummy start node

DENODE := {25} Subset of nodes, dummy end node

STYPES := {1, 2, 3} Servicing vehicle types

S := {1, 2, 3, …, 6} Servicing vehicle index number

V := {1,2} Required servicing visits to each client satellite

NPERIODS := {0, 1, 2, …, 13} Time periods

DSPERIOD := {0) Subset of periods

DEPERIOD := {14} Subset of periods

$$Arcs(i,j) := \begin{Bmatrix} (0,0) & (0,1) & (0,2) & \cdots & (0,25) \\ (1,1) & (1,2) & (1,3) & \cdots & (1,25) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ (24,1) & (24,2) & (24,3) & \cdots & (24,25) \end{Bmatrix} \quad \begin{matrix} i \in NODES \\ j \in NODES \end{matrix}$$

The primary decision variables in the on-orbit servicing problem are binary variables that determine which servicing vehicles to use, and when and along which routes to send them. There are also continuous variables that determine the amount of each commodity to flow along the chosen servicing vehicle routes. The flow variables can range anywhere from 0 to the capacity of the servicing vehicle type chosen for that route. The decision variables are:

$w_{st,s,(j,k),t}$:= 1 if servicer type *st* number *s* travels along arc (*j*,*k*) at the beginning of time period *t*, 0 otherwise

$flowDV_{st,s,(j,k),t}$:= amount of delta-V transferred by servicer type *st* number *s* along arc (*j*,*k*) at the beginning of time period *t*

$flowORU_{st,s,(j,k),t}$:= amount of ORU mass transferred by servicer type *st* number *s* along arc (*j*,*k*) at the beginning of time period *t*

The objective function of the SBR on-orbit servicing problem seeks to minimize the total launch costs for servicing vehicles while at the same time finding the least expensive (in terms of delta-V) path through the network visiting clients at the latest time possible. Mathematically, it is written as follows:

$$\min \sum_{st\in stypes} \sum_{s\in servicers} \sum_{c\in clients} \sum_{t\in periods} \left(costwet_{st} + (.01 * s)\right) * arc_{st,s,(0,c),t} w_{st,s,(0,c),t} + \qquad (1a)$$

$$\sum_{st\in stypes}\sum_{s\in servicers}\sum_{d\in depots}\sum_{t\in periods}\left(costdry_{st}+(.01*s)\right)*arc_{st,s,(0,d),t}w_{st,s,(0,d),t}+ \quad (1b)$$

$$\sum_{st\in stypes}\sum_{s\in servicers}\sum_{(j,k)\in nodes}\sum_{t\in periods}(Txdelta_{(j,k)}*.01)*arc_{st,s,(j,k),t}*w_{st,s,(j,k),t}+ \quad (1c)$$

$$\sum_{st\in stypes}\sum_{s\in servicers}\sum_{(j,k)\in nodes}\sum_{t\in periods}0.1*(NPERIODS-t)*arc_{st,s,(j,k),t}*w_{st,s,(j,k),t} \quad (1d)$$

Expressions 1a and 1b include the cost of launching a servicing vehicle either fully fueled (wet) to a client satellite, or un-fueled (dry) to a depot spacecraft. Multiplying the cost value by .01 times the servicing vehicle number drives the choice of smaller indexed servicing vehicles. This was done to differentiate otherwise equivalent solutions, thus speeding overall solution time. Expression 1c seeks the minimum total delta-V cost for the solution. This term is multiplied by .01 in order to scale down the importance of delta-V relative to launch costs. In future research, once exact costs are better known, the delta-V term can be re-calculated in terms of a dollar cost by calculating the actual propellant used, and so match the units of this term to the rest of the objective function. Expression 1d drives servicing to as late in the time window for each client as possible, to delay maintenance actions as long as possible (Ebeling, 1997). The on-orbit servicing model includes a number of constraints that limit the choices made. These constraints include the capacity for the flow of delta-V and ORUs along arcs between nodes (2-3). There are also balance constraints for the servicing vehicles (4), delta-V (5-7), and ORUs (8-10) moving to and from the nodes. Finally, there are time window constraints for the arrival and departure of servicing vehicles (11-12). The constraints are:
The flow of delta-V propellant along arcs must be less than the capacity of the servicing vehicle type used.

$$flowDV_{st,s,(j,k),t} \le DeltaCap_{st}*arc_{st,s,(j,k),t}*w_{st,s,(j,k),t} \quad (2)$$

$$\forall st\in stypes, s\in servicers, (j,k)\in arcs, t\in periods$$

The flow of ORU mass along arcs must be less than the capacity of the servicing vehicle type used.

$$flowORU_{st,s,(j,k),t} \le ORUCap_{st}*arc_{st,s,(j,k),t}*w_{st,s,(j,k),t} \quad (3)$$

$$\forall st\in stypes, s\in servicers, (j,k)\in arcs, t\in periods$$

Servicing vehicle node and time period balance constraint:

$$\sum_{k\in nodes}\sum_{t\in periods}arc_{st,s,(j,k),tp}*w_{st,s,(j,k),tp}-\sum_{k\in nodes}\sum_{t\in periods}arc_{st,s,(j,k),t}*w_{st,s,(j,k),t}=RHSBAL_{(j,t)} \quad (4)$$

$$\forall\ st\in stypes,\ s\in servicers,\ (j,k)\in n$$

Delta-V node and time period balance constraint for clients:

$$\sum_{j \in nodes} \sum_{tp \in periods: tp+Ttime(j,c)=t} arc_{st,s,(j,c),tp} * flowDV_{st,s,(j,c),tp} - \sum_{k \in nodes} arc_{st,s,(c,k),t} * flowDV_{st,s,(c,k),t} =$$

$$demDV_{c,t} * \sum_{k \in nodes: c \neq k} arc_{st,s,(c,k),t} * w_{st,s,(c,k),t} + \sum_{k \in nodes} Txdelta_{(c,k)} * arc_{st,s,(c,k),t} * w_{st,s,(c,k),t} \quad (5)$$

$$\forall st \in stypes, s \in servicers, c \in clients, t \in periods$$

Delta-V node and time period balance constraint for depots:

$$\sum_{j \in nodes} \sum_{tp \in periods: tp+Ttime(j,d)=t} arc_{st,s,(j,d),tp} * flowDV_{st,s,(j,d),tp} - \sum_{k \in nodes} arc_{st,s,(d,k),t} * flowDV_{st,s,(d,k),t} \geq$$

$$DVBAL_{ct} * \sum_{k \in nodes: d \neq k} arc_{st,s,(d,k),t} * w_{st,s,(d,k),t} + \sum_{k \in nodes} Txdelta_{(d,k)} * arc_{st,s,(d,k),t} * w_{st,s,(d,k),t} \quad (6)$$

$$\forall st \in stypes, s \in servicers, d \in depots, t \in periods$$

Delta-V initial node and time period balance constraint:

$$\sum_{k \in nodes} arc_{st,s,(DSNODE,k),t} * flowDV_{st,s,(DSNODE,k),t} \geq \quad (7)$$

$$\sum_{j \in nodes: j \neq DSNODE} \sum_{tp \in periods: tp+Ttime=t} arc_{st,s,(j,DSNODE),tp} * flowDV_{st,s,(j,DSNODE),tp} -$$

$$DVBAL_{dt} * \sum_{k \in nodes} arc_{st,s,(DSNODE,k),t} * w_{st,s,(DSNODE,k),t} \mid tp + Ttime_{(j,DSNODE)} = t \text{ and } j \neq DSNODE$$

$$\forall st \in stypes, s \in servicers, t \in periods$$

ORU node and time balance constraints for clients:

$$\sum_{j \in nodes} \sum_{tp \in periods: tp+Ttime=t} arc_{st,s,(j,c),tp} * flowORU_{st,s,(j,c),tp} - \sum_{k \in nodes} arc_{st,s,(c,k),t} * flowORU_{st,s,(c,k),t} = \quad (8)$$

$$demORU_{c,t} * \sum_{k \in nodes: c \neq k} arc_{st,s,(c,k),t} * w_{st,s,(c,k),t} \forall st \in stypes, s \in servicers, c \in clients, t \in periods$$

ORU node and time balance constraints for depots:

$$\sum_{j \in nodes} \sum_{tp \in periods: tp+Ttime=t} arc_{st,s,(j,d),tp} * flowORU_{st,s,(j,d),tp} - \sum_{k \in nodes} arc_{st,s,(d,k),t} * flowORU_{st,s,(d,k),t} \geq \quad (9)$$

$$-ORUCap_{st} * \sum_{k \in nodes: d \neq k} arc_{st,s,(d,k),t} * w_{st,s,(d,k),t} \forall st \in stypes, s \in servicers, d \in depots, t \in periods$$

ORU initial node and time balance constraint:

$$(10)$$

$$\sum_{j \in nodes} \sum_{tp \in periods: tp+Ttime=t} arc_{st,s,(j,DSNODE),tp} * flowORU_{st,s,(j,DSNODE),tp} -$$

$$\sum_{k \in nodes: DSNODE \neq j} arc_{st,s,(DSNODE,k),t} * flowORU_{st,s,(DSNODE,k),t} \geq$$

$$-ORUCap_{st} * \sum_{k \in nodes} arc_{st,s,(DSNODE,k),t} * w_{st,s,(DSNODE,k),t} \forall st \in stypes, s \in servicers, t \in periods$$

All clients must have a servicing vehicle arrive between the early time and the beginning of the late time for that visit.

$$\sum_{st \in stypes} \sum_{s \in servicers} \sum_{j \in nodes} \sum_{t \in periods} arc_{st,s,(j,c),t} * w_{st,s,(j,c),t} = 1 \quad (11)$$

$$\forall c \in clients, v \in visits \mid timeearly_{v,c} \leq t + Ttime_{(j,c)} \leq timelate_{v,c} \text{ and } 0 < k \neq c$$

All clients must have a servicing vehicle leave between the early time and the beginning of the late time for that visit.

$$\sum_{st \in stypes} \sum_{s \in servicers} \sum_{k \in nodes} \sum_{t \in periods} arc_{st,s,(c,k),t} * w_{st,s,(c,k),t} = 1 \quad (12)$$

$$\forall c \in clients, v \in visits \mid timeearly_{v,c} \leq t \leq timelate_{v,c} \text{ and } 0 < k \neq c$$

Each servicing vehicle type has a different delta-V capacity. These capacities are derived from Boeing's Orbital Express demonstrator. The range of each servicing vehicle is determined by the maneuvers it makes, or in terms of a network problem, the arcs over which it travels. Each maneuver arc has a unique delta-V and time cost, which was provided by the Aerospace Corporation (Kobel, 2004, Appendix A). The total maneuver costs for a servicing vehicle's route cannot exceed its delta-V capacity. Servicing vehicles have the option to replenish their ORU payload and re-fuel by visiting a depot spacecraft. The time windows associated with servicing needs create additional constraints on the problem. Each client satellite must be serviced between year 4 and 5. This requirement matches the optimal frequency of servicing determined by Waltz (1993). Waltz calculated several "breakpoints" at which servicing is better than satellite replacement. He determined that servicing should be favored over satellite replacement when the following occur:

- ORUs cost less than or equal to 50% of total satellite replacement cost
- Servicing equipment charges are less than 50% of total satellite replacement cost
- Servicing intervals are at least one-third of the time required to replace a satellite
- Servicing intervals are at least 4 to 5 years

For the purposes of this research, it is assumed that the first three of Waltz's criteria will already have been met. The Space-Based Radar constellation will have a baseline (without any servicing) expected life span of 10 years (Hoy, 2004). With servicing every 4 years, the constellation can be upgraded at least twice with the possibility of extending its lifespan.

In order to solve the problem, reasonable reductions in size must be considered. The first reduction is in the number of servicing vehicles available to use. The number of available servicing vehicles is limited to no more than six of any type. For the SBR constellation, clients occupy six orbital planes with three satellites in each plane. Because the time window was set at four quarters for the first visit, and any maneuver takes one quarter to complete, a servicing vehicle can only visit four nodes within the first time window. This limits the number of clients that any servicing vehicle can visit within the first time window to four or fewer. Even the smallest servicing vehicle type has enough capacity to service all client satellites in any plane. Although it is feasible to use more than one servicing vehicle per client plane, if one servicing vehicle can meet the demand, using more than one is not a logical alternative, given the objective, parameters, and assumptions of this problem. Limiting the number of depot spacecraft locations to one per client plane reduces the number of nodes in the network to 26 (one per client, one per depot, a start or "launch" node, and an exit node). Maneuvers from one orbital plane to another are very costly in terms of delta-V. By having a depot spacecraft located in each of the client planes, the need to travel to a different plane just to replenish a servicing vehicle is eliminated. The inactive time between servicing windows can be eliminated because it is not necessary to make any decision to move during this time, and so not necessary to model it. Further limiting the time from the beginning of the fourth year of the client's lifetime to the last year for servicing brings the number of time variables (quarters) from 40 down to 13. This greatly reduces the number of variables in the problem, and although still very large, a problem of this size can be successfully solved by using a two-stage integer linear programming approach. After determining the relative positions of each client satellite and depot spacecraft, the delta-V required for a servicing vehicle to move from any node to any other node was calculated using data provided by the Aerospace Corporation (Kobel, 2004). The delta-V required for any maneuver was calculated as the least amount of delta-V required to make the maneuver in 90 days. From these data, a matrix was constructed for use by the program used to generate solutions.

RESULTS

After solving for the first servicing visit, the routing for each servicing vehicle was fixed as a starting solution for the second stage. The servicing vehicle type used in the second stage run was allowed to vary. This allowed for the possibility of using a larger, more capable servicing vehicle for the first visit and using fewer vehicles for the second visit. The linear programming (LP) relaxation of the problem took only 0.1 seconds and gave an objective function lower bound of 201.564. A branch-and-bound global search took 169.5 seconds, examined 10 nodes, and found the first integer solution optimal and equal to the lower bound. The first stage solution used one small servicing vehicle per client plane, launched the vehicles dry to the depot, then visited each of the three clients in the plane, and and returned to depot (Table 1).

Servicing vehicle type, index #				Servicing vehicle type, index #			
Servicer 1.1	Travel to	Flow delta-V	Flow ORU	Servicer 1.4	Travel to	Flow delta-V	Flow ORU
Time 0	Depot 20	0	0	Time 0	Depot 22	0	0
Time 1	Client 5	154.2	450	Time 1	Client 11	154.2	450
Time 2	Client 6	102.5	300	Time 2	Client 12	102.5	300
Time 3	Client 4	50.8	150	Time 3	Client 10	50.8	150
Time 4	Depot 20	0	0	Time 4	Depot 22	0	0
Servicer 1.2	Travel to	Flow delta-V	Flow ORU	Servicer 1.5	Travel to	Flow delta-V	Flow ORU
Time 0	Depot 23	0	0	Time 0	Depot 21	0	0
Time 1	Client 13	154.2	998	Time 1	Client 8	154.2	450
Time 2	Client 15	102.5	848	Time 2	Client 9	102.5	300
Time 3	Client 14	50.8	698	Time 3	Client 7	50.8	150
Time 4	Depot 23	0	548	Time 4	Depot 21	0	0
Servicer 1.3	Travel to	Flow delta-V	Flow ORU	Servicer 1.6	Travel to	Flow delta-V	Flow ORU
Time 0	Depot 24	0	0	Time 0	Depot 19	0	0
Time 1	Client 17	154.2	450	Time 1	Client 1	154.2	450
Time 2	Client 18	102.5	300	Time 2	Client 3	102.5	300
Time 3	Client 16	50.8	150	Time 3	Client 2	50.8	150
Time 4	Depot 24	0	0	Time 4	Depot 19	0	0

Table 1. First stage solution

Following the first stage, the servicing vehicle routes were fixed and the model re-run looking at 13 periods to cover both servicing visits. Using Xpress-MP optimization software, the model was translated into the Mosel programming language, which allows an almost direct translation of mathematical equations. The LP relaxation took 0.9 seconds and found the lower bound for the objective function of 239.67. The branch-and-bound global search examined 82 nodes, with the second integer solution found being the optimal solution in 281.7 seconds. The second stage solution maintained the use of small servicing vehicles to complete the first stage's fixed routes and continued their use for the routes determined for the second servicing visit. Table 2 lists the solution to the second-stage model run.

Servicing vehicle type, index #				Servicing vehicle type, index #			
Servicer 1,1	Travel to	Flow DV	Flow ORU	Servicer 1,4	Travel to	Flow DV	Flow ORU
Time 0	Depot 20	0	0	Time 0	Depot 22	0	0
Time 1	Client 5	154.2	450	Time 1	Client 11	154.2	450
Time 2	Client 6	102.5	300	Time 2	Client 12	102.5	300
Time 3	Client 4	50.8	150	Time 3	Client 10	50.8	150
Time 4	Depot 20	0	0	Time 4	Depot 22	0	0
Time 5	Client 4	153.4	450	Time 6	Client 11	153.4	450
Time 7	Client 5	101.7	300	Time 8	Client 10	101.7	300
Time 8	Client 6	50	150	Time 11	Client 12	50	150
Time 12	exit	0	0	Time 12	exit	0	0
Servicer 1,2	Travel to	Flow DV	Flow ORU	Servicer 1,5	Travel to	Flow DV	Flow ORU
Time 0	Depot 23	0	0	Time 0	Depot 21	0	0
Time 1	Client 13	154.2	450	Time 1	Client 8	154.2	450
Time 2	Client 15	102.5	300	Time 2	Client 9	102.5	300
Time 3	Client 14	50.8	150	Time 3	Client 7	50.8	150
Time 4	Depot 23	0	0	Time 4	Depot 21	0	0
Time 9	Client 14	328	450	Time 6	Client 7	153.4	998
Time 10	Client 15	276.3	300	Time 9	Client 8	101.7	848
Time 11	Client 13	224.6	150	Time 10	Client 9	50	698
Time 12	exit	174.6	0	Time 12	exit	0	548
Servicer 1,3	Travel to	Flow DV	Flow ORU	Servicer 1,6	Travel to	Flow DV	Flow ORU
Time 0	Depot 24	0	0	Time 0	Depot 19	0	0
Time 1	Client 17	154.2	450	Time 1	Client 1	154.2	450
Time 2	Client 18	102.5	300	Time 2	Client 3	102.5	300
Time 3	Client 16	50.8	150	Time 3	Client 2	50.8	150
Time 4	Depot 24	0	0	Time 4	Depot 19	0	0
Time 6	Client 16	153.4	998	Time 6	Client 2	328	998
Time 8	Client 18	101.7	848	Time 8	Client 1	276.3	848
Time 10	Client 17	50	698	Time 11	Client 3	224.6	698
Time 12	exit	0	548	Time 12	exit	174.6	548

Table 2. Second stage solution

CONCLUSION

The two-stage solution approach offered in this paper appears to achieve the optimal solution for the given data set. Therefore, it can be used as an initial starting point to assist planners of an on-orbit servicing system before the final numbers of servicing vehicles and depot spacecraft have been determined during the acquisition and construction of a satellite system. The solution provided by the model can also be used to facilitate calculation of break-even points for the decision to design new satellite systems for on-orbit servicing. This research provides a first step in solving the difficult problem of finding optimal on-orbit servicing architectures for a client satellite constellation. By defining the problem as a minimum cost flow network, it was possible to apply integer programming and find an optimal solution.

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