SIMULATION ANALYSIS OF AN AUTOMATED HOSPITAL MATERIALS HANDLING SYSTEM

John J. Marsh, III and Ralph W. Swain
The Ohio State University Hospitals
Health Systems Research Division
University of Florida

ABSTRACT

A prototype simulation of the operations of an automated hospital materials handling system is constructed in GASP IV to investigate the feasibility of the modeling scheme employed and to evaluate some alternative rules to be used in system operation. This paper describes the structure used in the model and illustrates two types of investigations and operation of the actual system.

INTRODUCTION

The Ohio State University Hospitals is a 1,000 bed teaching institute serving as the major referral center for Central and Southeastern Ohio. The services available include twenty-six surgical and medical specialties, comprehensive psychiatric treatment programs and long term physical medicine and rehabilitation services. The Hospital operates on an annual budget of $70,000,000 and currently employs 3,500 full time equivalent personnel. Admissions total more than 29,000 resulting in over 300,000 patient days and outpatient visits exceed 250,000 yearly.

In the Summer of 1975, OSU Hospitals began construction on a major building program. The primary objectives of the program are to increase the clinical facilities to match the increased medical class size in the College of Medicine, to increase and improve the number of specialized and ancillary treatment services available and to replace some obsolete inpatient facilities. An integral part of the building program is installation of an automated Materials Handling System (MHS) which will transport nearly all of the commodities utilized in patient care for the inpatient medical and surgical facility. The Materials Handling System is designed to reduce costs of material handling, to improve the availability of needed supplies and to enhance the operation of currently decentralized functions which will be consolidated in the ground floor of the new facility. Basically, these functions are receiving and break out of supplies, storage of bulk and processed goods, linen storage and distribution and processing of central sterile supplies and operating room instruments.

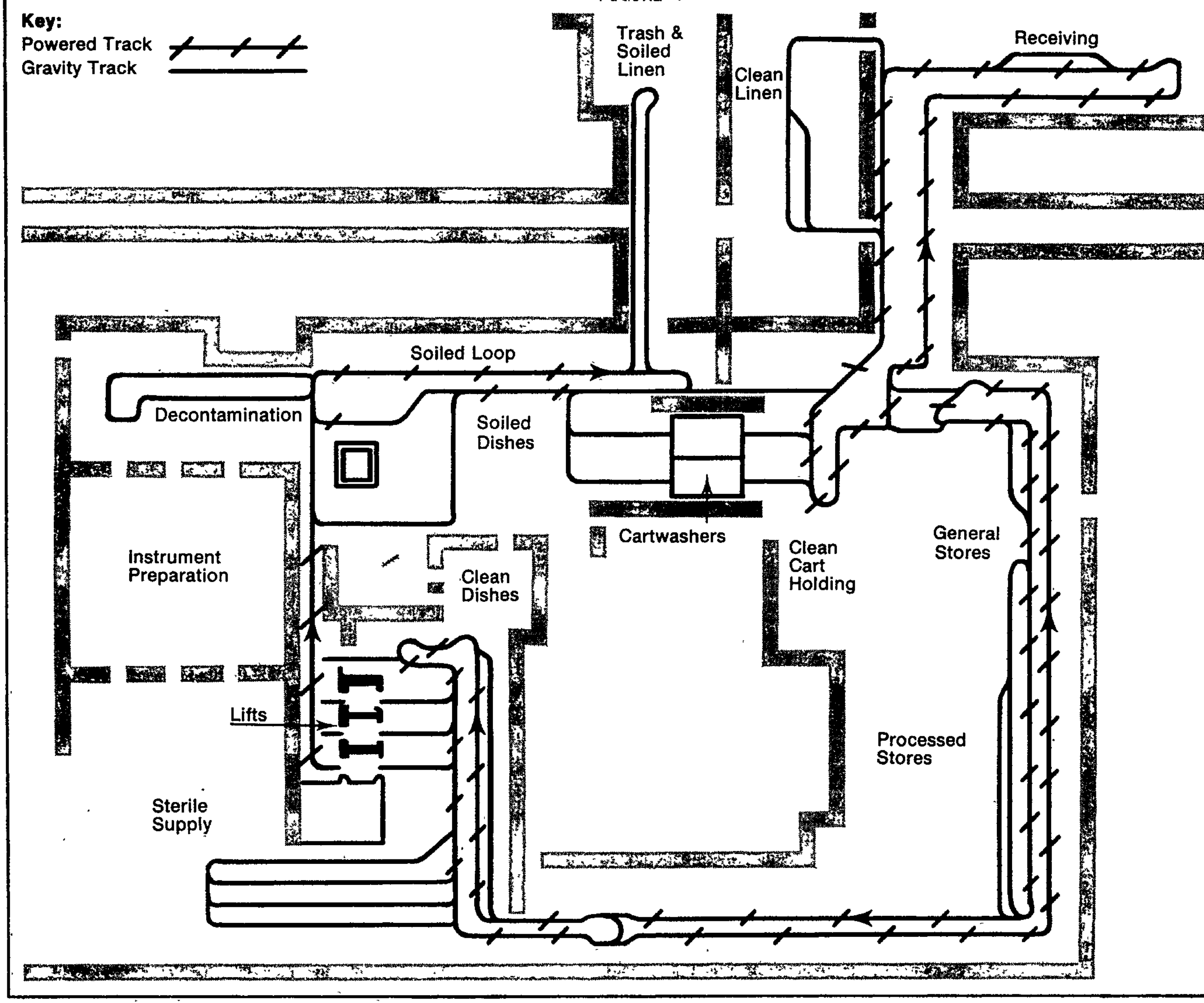
MATERIALS HANDLING SYSTEM DESCRIPTION

The MHS is totally automated in the sense that it will transport commodities in carts from the ground floor to all user levels, floors 2 through 11, utilizing both horizontal and vertical transport components. Horizontal transportation of the carts is accomplished on a monorail system which will exist throughout the ground floor of the new and old facility. Figure 1 is a layout of the ground floor which illustrates the location of the functional areas and the monorail system which will interconnect these functions and the user levels. The ground floor is divided into basically two areas; a soiled area and a clean area. Nearly all of the commodities arriving at the hospital will be received at the loading dock, distributed to the clean storage and processing areas and eventually will be distributed to the user levels. The soiled or "decontamination" area on the ground floor will process all of the trash and soiled linen, the soiled meal trays and all reusable instruments returned from the user levels.

Vertical transportation of the carts will be accomplished with six dedicated elevators or lifts. Four of these lifts will service all user levels and two lifts will be dedicated to service the Operating Rooms, the Emergency Room and the cafeteria annex. On the user levels, transportation of all carts will be accomplished manually. Therefore, the lift system must be able to make a transition between floors which have a monorail system and the floors which do not have a monorail system. This is accomplished with an inject/eject mechanism, a device which extends from the bottom of the lift to pick up or deposit carts in front of the lift on the user levels. On the ground floor, the cart will be accepted from or placed on the monorail system by the lifts.

A wide variety of commodities will be transported on the Materials Handling System. It is anticipated that on any given day, approximately 2700 cart moves will occur. Figure 2 illustrates a complete cycle, composed of four cart moves, for commodities which will be transported from Central Sterile Supply to the user levels and returned to decontamination. A cart begins in the clean cart holding area and moves to Central Sterile Supply area. At this point, the commodities for the

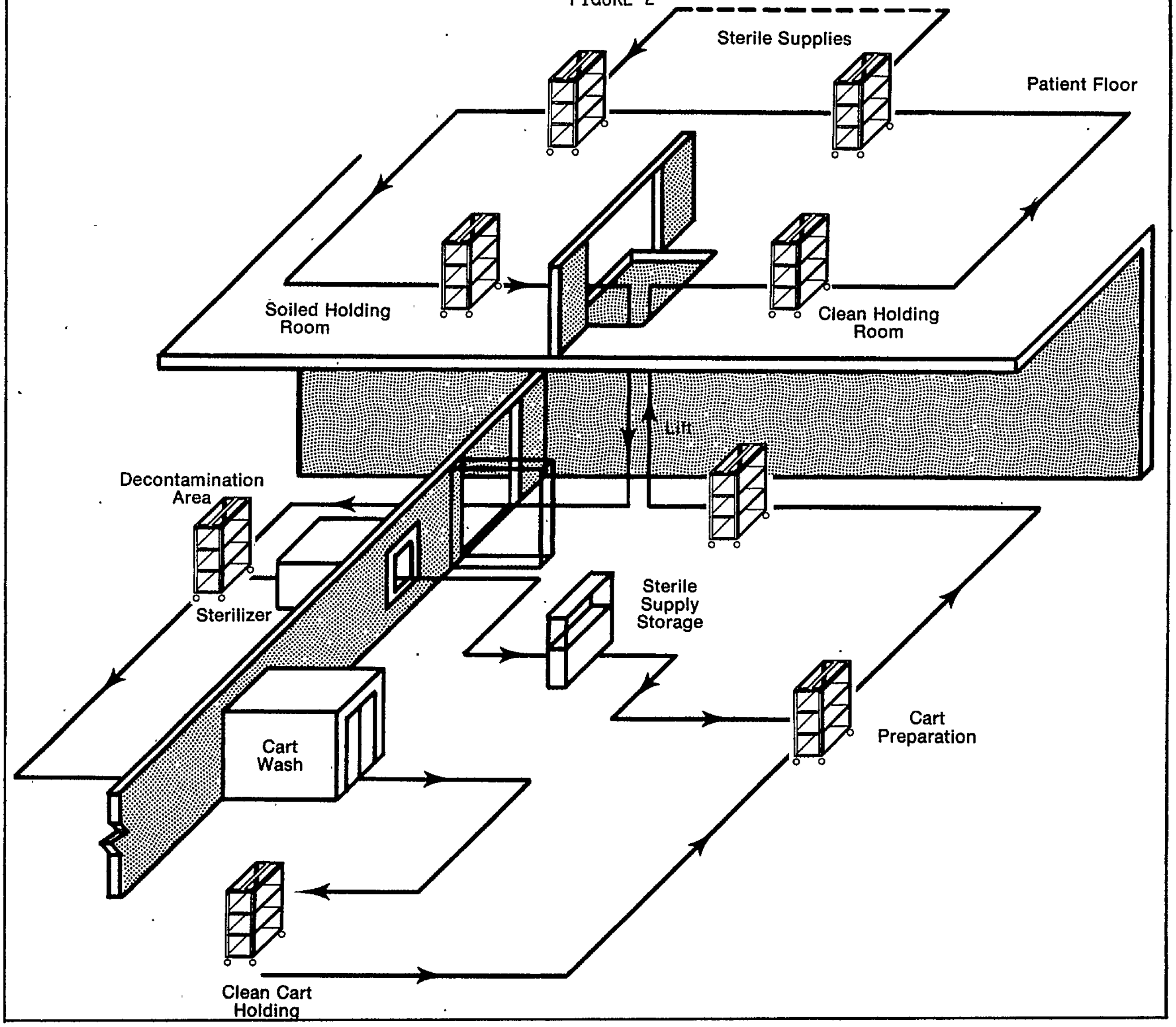
FIGURE 1



user levels are loaded on the cart. The cart is then transported to the user level. At the user level, the cart is unloaded and held to return soiled items at a later time. When the cart returns with soiled items, it is unloaded in the decontamination area. The reprocessible items are placed in the sterilizer system, trash is held for pick up, and the cart is sent to the cart processor to be returned to the clean cart holding area. Similar commodity cycles exist for general stores items, patient meals, pharmaceuticals, linen and miscellaneous other products.

The carts specified for this system will be open carts of four basic types all approximately 2' wide, 4.5' long and 5' high. The first type is the surgical case cart which will be utilized to transport surgical instruments and other products necessary for one complete surgical procedure. The second type of cart is a dietary tray cart, specifically designed to transport 18 individual meal trays for patients. The third type of cart is a general purpose cart which will be used to transport a wide variety of commodities including general and central sterile supply products. The fourth type of cart, which is similar to the general supply cart, is the linen cart which will transport all clean and soiled linens. The dietary and surgical case carts are designed to be one half the length of a general purpose or linen cart and can be transported either in tandem (two carts end to end) or singly on the MHS.

FIGURE 2



PROBLEM ORIENTATION

The Ohio State University Hospitals is faced with several major decisions related to the start up and operation of the Materials Handling System. Given the design constraints of the MHS and the architectural features of the facility, the following are four major areas which need to be addressed:

1) The number of carts to be purchased.

2) Designation of a commodity shipment schedule.

3) Identification of labor resources required to operate the system, and

4) Specification of alternative operating procedures when certain components of the MHS are inoperable.

The cart purchase decision is a capital investment decision. If enough carts are not purchased, the system will not be able to meet commodity shipment schedules and it is expected that an excessive number of personnel will be necessary to keep carts moving rather than sitting idle at some process point in the system. On the other hand, if too many carts are purchased, excessive capital will be tied up in the system, which could be better utilized on other projects. Specification of labor resources required to operate the system is complementary to the cart purchase decision. If not enough personnel are available to operate the system, commodities may not be delivered at their appropriate destination on time, if at all, and if too many personnel are allocated to the system, this too is a misuse of limited funds.

The MHS will be available for a diverse group of ancillary and support services. The hospital management wishes to accommodate these departments by providing them the opportunity to request desired delivery schedules. Once all of the users have specified what they would like to see as their desired utilization of the system, it will be necessary to ascertain whether the system, as a whole, will be able to handle the commodity volume during the hours of operation and if the system will in fact be balanced as far as utilization of personnel.

The final decision which must be evaluated is how the system will operate during periods in which redundant components of the system are inoperable. These components are the parallel lifts to the user levels and the two cart processors which wash and dry soiled carts and return them to the clean holding area. The total system need not shut down if one of these components is unavailable for service. However, shipments may have to be reduced or held depending upon the system demand and commodity priority.

Due to the size and complexity of the Materials Handling System and the volume of commodities which will be transported on this system, the Office of Planning and Development and the Hospital Administration has elected to construct a simulation model to assist in evaluation of the system operation prior to its actual implementation. Such a model would be utilized in the planning phases of the system operation to address the four problems stated above. Once the MHS becomes operational, the simulation model will be used to replicate the actual system and to test alternative operating procedures to fine tune the MHS and reduce operating costs in the long run. The Materials Handling System is a major capital expenditure and an integral part of the new inpatient facility. It is imperative that successful start up and reliable operation of the system occur in order to gain the confidence of the many users and to meet the needs of material distribution throughout the institution.

PROTOTYPE MATERIALS HANDLING SYSTEM

When faced with the problem of developing a simulation model of the Materials Handling System, the management engineering team considered several factors in selecting a project plan or strategy. First of all, it is important to develop a model which will lend itself to the analysis of the four basic issues stated in the previous section. Second, it is important to develop a model which will be used as an educational tool for the various users within the Hospital. Third, the model must be looked upon as a credible source for reliable information in developing implementation plans. Finally, it is necessary to construct a model which could handle the complexity and size of the Materials Handling System, yet be adaptable and easily usable on an IBM model 370/158 which was available in the Hospital Computer Center.

The management engineering team decided to start with a simulation model of a prototype Materials Handling System. It was necessary to develop a prototype system which would retain as many of the characteristics of the actual system as possible, yet be much smaller in scope, such that a variety of alternative modeling techniques could be easily evaluated. It was also hoped that by beginning with a model of a prototype system, it would be possible to transfer results and insights gained at this level, when the model of the actual MHS was constructed. Finally, using this approach would be a convenient method of educating the administrative and department head staff about the new MHS and the methods of simulation analysis. It is very important that this group thoroughly understand the implications of decisions which they make and how they relate to the actual operation of the MHS.

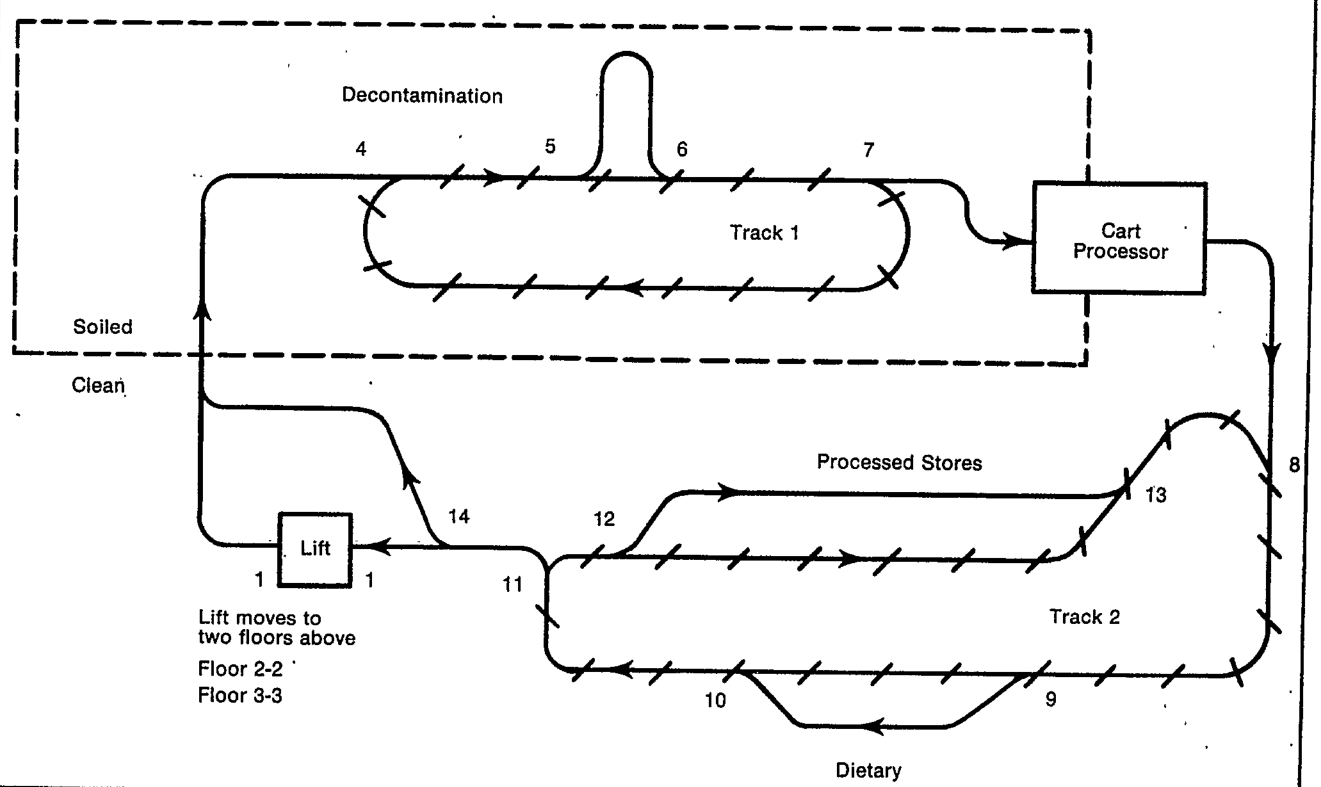
The prototype system is designed to retain as many of the characteristics of the actual MHS as possible yet be much smaller in scope. Figure 3 is a layout of the ground floor of the prototype Materials Handling System. There are three functional areas on the ground floor of this system; a dietary station, a processed stores station, (both on the clean side of the system) and the decontamination area which composes the soiled side of the system. In addition, there is one cart processor, which processes carts from the soiled side to the clean side and one vertical lift which transports carts from the ground floor to the user levels. The prototype system is designed with two user levels. These are patient floors with a variable number of beds (typically 150-200 beds per floor).

The monorail system on the ground floor consists of two powered loops which transports carts from point to point. Physically, carts will transition between the powered monorail tracks, the vertical lift, the cart processor and all process stations via gravity flow tracks. Carts will travel from their origin to their destination by the decision points in the system. These points are numbered one through fourteen. An example sequence of a cart traveling from processed stores to floor 2 would be the decision points 13-9-11-14-1-2. Likewise, carts returning from the user levels would be sent to the soiled side, unloaded and then sent to the clean side through the cart processor.

Each of the process points in the system, i.e. processed stores, dietary, decontamination and the user levels 2 and 3, are characterized by a set of variables. First is the number of servers available by hour of the day to process carts, second is the maximum number of empty carts to be held at that location by hour of the day and third is the minimum number of empty carts to be held at that location by the hour of the day. It is assumed, in this model, that each process point on the ground floor has an infinite entry and exit queue for carts on the track.

The lift must transition between the ground floor which has a monorail system and the user levels which do not. Therefore, the lift is designed to operate with an inject/eject device similar to the actual MHS. On the ground floor, the entry queue to the lift will hold a maximum of three carts and

FIGURE 3



the exit queue will hold six carts. On the user levels where no monorail system exists, the entry queue is restricted to one cart. The exit queue however, is specified to hold a maximum of two carts. When this queue becomes full, the lift will not eject another cart at this location but will stop at this location and go into a holding mode.

Carts that must transition from the soiled to the clean side of the ground floor do so through the cart processor. The entry queue to this processor is four carts long. The cart processor itself consists of two sequential chambers. The first chamber is a wash chamber, the second chamber is a dry chamber. Carts can be processed concurrently in each of these chambers and the cycle time is a variable, assumed to be two minutes in the prototype system design. The exit queue for the cart processor is unlimited.

In the prototype model, two types of carts are specified; a dietary tray cart, which transports patient trays, and a general purpose cart which transports all other commodities. The dietary tray carts are marshalled or held at the dietary processing location when not in use and the general purpose carts are marshalled in the processed stores area when not in use.

At each process point in the system, servers are utilized to load and unload carts and ultimately transport the commodities to their destination. The servers are an important component of the prototype system analysis. For each commodity, a load and unload time is defined. In some situations, the server is responsible for loading the cart as well as placing the cart on the system, in other cases, the server simply gets the cart, already loaded, from an inventory location and places it on the system for transportation. At the unload point or destination, a similar situation occurs. The server may be responsible for delivering the cart to the floor personnel or the server may be responsible for unloading and distributing the commodity.

On the ground floor of the facility, servers are primarily responsible for three activities. The first is the loading of carts, the second is the unloading of carts and the third is placing carts on the system for track entry. At the user level, the server has several more responsibilities. In addition to loading and unloading carts, the server must also load and unload the lift. A disadvantage of the inject/eject device on the lift is the maximum exit queue capacity of two carts. A fundamental responsibility of the servers on the user level is to ensure that the exit queue for the lift remains clear or at most has one cart in queue so the lift is not delayed. Since it is possible to place only one cart at a time in the entry queue for a lift, the servers must return to place each subsequent cart in front of the lift and call the lift by specifying the destination of the cart.

The volume of work at each process point in the system changes by hour of the day. The workload is dependent upon the commodity schedule, cart availability and system congestion at that particular time. There are several alternatives to managing the server workloads at the various locations. First of all, it might be possible to alter the commodity delivery schedules to smooth out the workload at the various locations. Second, it might be possible to move servers from point to point as the workload changes at the various process points. Third, empty carts could be held at the process locations to reduce unavailability of carts when needed. Finally, it might be possible to use a combination of these strategies to reduce the inconvenience or ineffeciency in the operation of the user departments and patient floors.

The prototype MHS is designed to transport nine commodities in a twelve hour operating day. The commodities are similar to the commodities which will be transported on the actual MHS. Table One defines the commodities which will be transported and specifies the periods in which the commodities must be delivered. The volume of commodities delivered daily is a function of the hospital census. Commodity volumes do not change drastically with small changes in the census, however significant variations do occur throughout the weekly cycle of the hospital census.

SIMULATION MODEL

The simulation model developed to evaluate the prototype Materials Handling System is programmed utilizing a Fortran based simulation language, GASP IV. The simulation is run on the University Hospital computer, an IBM 370/158, with an OS/VS2 release 1.7 operating system. The simulation typically executes in a region of 192K and requires approximately 7 1/2 minutes CPU time to simulate 30 days of activity. The model is an event-oriented simulation with 13 system related events and one event for data collection and parameter changes. Table Two is a list of the events and a short description of each.

TABLE 1

COMMODITY	HOURS OF TRANSPORT
PATIENT TRAYS	
Breakfast	8:00 a.m. - 9:30 a.m.
Lunch	11:30 a.m. - 1:00 p.m.
Dinner	4:30 p.m. - 6:00 p.m.
SOILED TRAYS	
Breakfast	9:00 a.m. - 10:30 a.m.
Lunch	1:00 p.m. - 2:30 p.m.
Dinner	6:00 p.m. - 7:30 p.m.
CLEAN LINEN	
AM	9:00 a.m. - 11:00 a.m.
PM	12:30 p.m. - 2:30 p.m.
SOILED LINEN	10:00 a.m. - 4:00 p.m.
CENTRAL STERILE SUPPLIES	
AM	8:00 a.m. - 10:00 a.m.
PM	4:00 p.m. - 6:30 p.m.
As Needed	9:00 a.m. - 5:00 p.m.
TRASH	
AM	8:00 a.m. - 11:00 a.m.
PM	3:00 p.m. - 7:30 p.m.
GENERAL STORES SUPPLIES	9:00 a.m. - 1:00 p.m.
SURGICAL CASE CARTS	8:00 a.m. - 12:00 Noon
SOILED CASE CARTS	10:00 a.m. - 2:00 p.m.
EMPTY CARTS	ALL DAY

Much of the operation of the Materials Handling System is deterministic in nature, that is, the travel time for carts between decision points and the travel time for the lift between floors is determined by the design of the system. Randomness is introduced into the model in five ways.

1) The time of the initial load request for each commodity,

2) The time between subsequent load requests for each commodity,

3) The time required to load or unload each commodity in the system,

4) The census of the hospital for each simulated day, and

5) The time to accomplish a track entry event from a gravity rail to a powered rail (given a known number of carts already on the powered rail and the maximum capacity of the powered rail).

The model utilizes 5 random number streams, one for each of the above methods of introducing variation.

The prototype Materials Handling System is designed to operate 12 hours on any given day. The commodity schedule is specified such that the system begins at rest, executes all of its deliveries within the 12 hour period, and at the end of that time, the system is essentially at rest again. The same distribution of empty carts at the end of a day is assumed to exist the next morning when the system again begins operation. The simulation model simulates consecutive 12 hour periods of materials handling system activity, each 12 hour period corresponding to one work day. For convenience and completeness of statistical information, the simulation must begin at the start of a 12 hour day and must end at the conclusion of a 12 hour day. With this type of design, it is possible to evaluate the MHS operation in two distinct fashions. First, it is possible to simulate a sequence of similar 12 hour MHS days. Secondly, it is possible to simulate one or more sequences of seven consecutive 12 hour MHS days which might represent a weekly cycle of operation in the hospital.

Several parameters are of particular interest in the design of the prototype MHS. It is important to be able to specify the number of servers at the various processing points in the system. It is also important to specify inventory levels of carts at each particular processing point. The simulation model allows the possibility of scheduling servers and inventory levels for all types of carts on an hourly basis at each processing point. Additional

TABLE 2

SIMULATION EVENTS

LODREQ - The event is commodity specific. The subroutine schedules the next LODREQ, and schedules an ENDLOD event if both servers and empty carts are available at the process location. If either a server or cart is not available, the event is queued in an appropriate file.

SERVAV - The event is location specific. When a server becomes available and events are queued for the server, work is selected on a first come, first serve basis. If no work is available, the server becomes idle.

MOVCRT - The event is cart specific. If the cart has arrived at its destination, a CRTREC event is scheduled, otherwise the next decision point is determined and a MOVCRT event is scheduled. If the next decision point is located on a power-free or gravity rail, the appropriate event is scheduled (i.e. call the lift, cart wash, track entry, etc.).

TRKENT - The event is location specific. The next decision point is determined for the cart and a MOVCRT event is scheduled. If the loop is at full capacity, this TRKENT event is rescheduled and no other activity scheduled. If a second cart is waiting for track entry, the time to that event is determined by the current capacity of the power rail loop.

CALIFT - The event is location specific. If the lift is busy, the event is queued for the lift. If the lift is idle, the time is determined to deliver the cart based upon the cart's location and destination and the lift's current location. An UNLDLF event is scheduled, given the time required to deliver the cart.

UNLDLF - The event is location specific. If the exit queue at the lift destination is full, the lift is placed in a holding mode at the location. If the cart can be ejected, a CRTREC or TRKENT event is scheduled and the lift will look for other CALIFT events.

CRTREC - The event is location specific. If a server is available, the time to unload the cart is determined and an EMPTY and SERVAV event scheduled. If no server is available, the event is queued.

EMPTY - The event is location and cart specific. If there is an outstanding request for an empty car (of this type) at this location, the cart is made available for the outstanding request. If no outstanding requests exist, the cart is placed in inventory at this location, or sent to the marshalling area on the ground floor.

EODAY - This is an end of day event. It is utilized to schedule the first LODREQ for each commodity for the next day, and the maximum number of each commodity to be sent. Various statistics are also collected at this time.

EOWSH - This event is specific to the cart processor. If the dry chamber of the processor is empty, an EODRY event is scheduled, otherwise the cart is held for a few seconds until the current EODRY event occurs.

TABLE 2 (Contd.)

EODRY - This event is specific to the cart processor. The cart in the dry chamber is ejected and a TRKENT event is scheduled or the cart is queued for track entry. If a cart is queued for the dry chamber, an EODRY event is scheduled. If a cart is queued for the wash chamber, an EOWSH is also scheduled.

ENDLOD - This event is location specific. If the location is a user level, either the cart is scheduled for a LFTLOD or CALIFT event depending on the lift entry queue. If the location is on the ground floor, the cart is either queued for a track entry event or a TRKENT event is scheduled if the queue is empty.

LFTLOD - This event is specific to the user levels. If a server is available, a CALIFT event is scheduled, otherwise the LFTLOD event is queued, pending server availability.

HRCHG - This event is utilized to change server and specified cart inventory levels at each location by hour of the day. Statistics are also collected to measure system performance for the previous hour's activity.

parameters which the simulation model requires are an origin/destination matrix (14 x 14) which defines the next location for the cart given the current location and ultimate destination, and a matrix (14 x 14) which specifies the time to travel from a given point in the system to the next decision point. Each of the nine commodities to be transported on the system have six associated parameters. Two of the parameters, alpha and beta, are parameters of the Erlang distribution used to determine the time between load requests for that commodity. Two other parameters are the start and stop times for each commodity as defined in the commodity shipment schedule, Table One. Finally, it is necessary to provide an estimate of the load and unload times as an average for each commodity as it will be handled by the MHS personnel. The load or unload times are not necessarily the time to load or unload the cart, but simply the time required of the server to handle the commodity either at the origin or destination on the Materials Handling System. Finally, it is necessary to provide an estimate of the expected hospital census as a percent of the total beds available for a seven day period. The simulation will repeat the occupancy sequence until reaching the time specified to terminate the simulation.

ANALYSIS OF SIMULATION RESULTS

As noted at the start of this paper, a primary objective of the MHS simulation is to assist in determining the levels of equipment and personnel required for efficient, balanced operation of the system. In working with the prototype simulation, our objective has been to gain information about the general operating characteristics of the system and to begin an investigation of the alternatives in cart supply, personnel requirements, and commodity flow schedules that will help to limit the range of alternatives that must be ultimately evaluated with the use of the more expensive simulation of the actual system. In addition, we have used the prototype simulation to evaluate the performance of the simulation model and to aid in our understanding of the amount of detail that must be included in the larger simulation in order to adequately indicate the performance of the actual system.

In this section, we discuss our initial investigation of the cart and personnel allocation problems as performed with the prototype model. Each of the prototype simulation runs spans a period of 12 hours for 30 simulated days. The average number of commodity moves during a simulated day is 263 (roughly 20% of the anticipated moves in the actual full-scale system), utilization of the cart processor is approximately 6.5 hours per day (53%), and the lift is utilized about 7.0 hours per simulated day (58%) in all of the simulation trials.

CART ALLOCATION

In order to maintain the level of delay in shipments at a reasonable level, it appears that some system of allocating carts to the various load generating stations is necessary. Use of a cart allocation policy to anticipate future demands for shipment from a point also tend to reduce the number of empty cart moves through the system. In the prototype system, cart allocation rules are applicable only on the user levels, floors 2 and 3, and only for the general purpose carts. (Dietary carts are transported on an exchange basis. Each meal is transported to the user level and back on the same carts, thus the flow up and back is equal.) For all commodities, on the average per day, 6.91 more carts are sent than received on floor 2 and 6.32 more carts are sent than received on floor 3 due primarily to expansion in the volume of trash and soiled linens. Overall this is not a very large imbalance, but on an hour by hour basis the relative imbalance is much greater. Table 3 summarizes the simulated cart flows to and from each floor, assuming that a large number of servers and carts are available each hour of the day.

Specification of a cart allocation plan consists of determining a maximum and a minimum number of empty carts to be held at each location for each hour of the day. The primary performance measure is the average total delay time. For example, if five shipments are delayed, each for 6 minutes (.10 hours) because of the unavailability of carts, then the total delay for that hour is .50 hours. Given a sample of 30 simulated days, the average total delay time is determined for each of the 12 hours of the day and each user level.

Two cart allocation plans have been tested to find an acceptable plan for operation. The first cart allocation plan is based on the following decision rule:

$$X_{ij} = \text{Round}\left[a\, S_{ij} + \text{MAX}\left(b(S_{i+1,j} - R_{i+1,j})\ ,\ 0\right)\right]$$

$$Y_{ij} = 0$$

where:

X_{ij} is the maximum number of carts in inventory for hour i at location j

Y_{ij} is the minimum number of carts in inventory for hour i at location j

S_{ij} is the expected number of carts sent in hour i from location j

R_{ij} is the expected number of carts received in hour i at location j.

$a,b \quad 0; \quad i = 1,\ldots,n; \quad j = 2,3$

The intent is to save a portion of the carts received for the commodities to be transported each hour, and to save extra carts if a deficit of carts will occur in the next hour. There is no attempt to maintain a minimum inventory of carts by specifying $Y_{ij} = 0$ for all i and j. The decision rule is applied in the following manner. If the inventory at location j for hour i is equal to X_{ij} and another empty cart is generated at the location, it is sent to the marshalling area on the ground floor when a server is available to do so. If the inventory is less than X_{ij} for hour i and an empty cart is generated, it is placed in inventory on the user level.

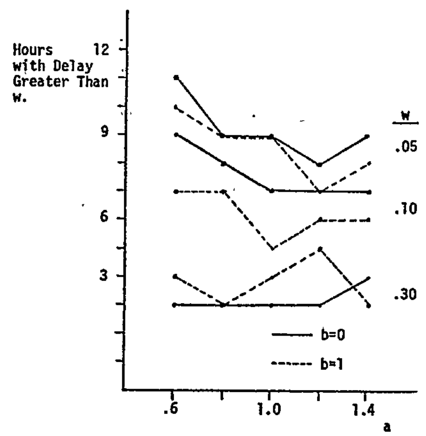
The simulation shows that this is not a particularly good strategy. If a deficit of carts occurs (more

TABLE 3

	Floor 2			Floor 3		
	Average Carts/Hr.			Average Carts/Hr.		
Hour	Sent	Rec.	(Sent-Rec.)	Sent	Rec.	(Sent-Rec.)
1	6.90	11.32	-4.42	7.78	15.25	-7.47
2	10.22	13.42	-3.20	10.92	15.13	-4.21
3	7.45	3.80	3.65	10.70	10.07	.63
4	7.75	6.10	1.65	10.30	6.98	3.32
5	2.90	7.40	-4.50	5.83	5.10	.73
6	6.03	3.70	2.33	8.15	4.10	4.05
7	0.0	0.0	0.0	2.63	0.0	2.63
8	5.95	0.0	5.95	7.88	0.0	7.88
9	5.23	3.08	2.15	6.18	11.17	-4.99
10	0.25	2.78	-2.53	1.20	5.63	-4.43
11	5.80	0.0	5.80	7.05	0.0	7.05
12	0.03	0.0	0.03	1.08	0.0	1.08

carts are sent than received) the inventory at the end of the hour will be zero. Therefore, it is not possible to maintain an inventory any larger than the excess of carts received for any hour, and for many hours the ending inventory would be zero. Figure 4 is a summary of the experimental results for the first cart allocation plan for levels of a equal to 0.6, 0.8, 1.0, 1.2, and 1.4 and levels of b equal to 0.0 and 1.0. The vertical axis is the <u>number of hours during the simulated day for which the average total delay exceeds the specified value</u>. The horizontal axis is the different levels of a. The benchmark values of the average total wait selected are 0.05 hours, 0.10 hours and 0.30 hours. The simulation experiment was run assuming a large number of servers available at each location and assuming a large number of carts (both types) in the system. This was done to minimize the possibility of inadvertently introducing the effects of other constraints on the system operation.

FIGURE 4



The results indicate that the inclusion of the preview factor (b) does improve the system operation, but only marginally. On floor 2 over half of the 12 hours, on the average, have a total delay of more than 6 minutes (0.10 hours), and for 3 or more hours the total delay time exceeds 18 minutes (0.30 hours). The final determination as to the acceptability of these results rests with the system manager, however by changing the cart allocation plan to include a <u>minimum</u> cart rule, as well as a maximum cart rule, the results can be greatly improved.

The addition of a decision rule which specifies a minimum cart inventory, by hour of the day, provides a method of requesting empty carts without an associated delay for loading and transporting the commodity. The minimum cart rule would function in the following manner. Each time the inventory level of empty carts goes below the minimum specified level, a cart is requested from the ground floor marshalling area to replenish the inventory. The maximum cart inventory rule, of course, would still be applicable. This cart allocation plan is specified by the following rule:

$$Y_{ij} = \begin{cases} \text{Round}\left[\text{MAX}\left(d(S_{ij}-R_{ij})\ ,\ 0\right)\right] & \text{for } R_{ij} \quad 0 \\ \text{Round}\left[\text{Max}\left(d\ S_{ij}\ ,\ 2\right)\right] & \text{for } R_{ij} = 0 \end{cases}$$

$$X_{ij} = \text{Max}\left[\text{Round}\left[a\ S_{ij} + \left[\text{Max}\left(b(S_{i+1,j}-R_{i+1,j}),0\right)\right]\right]\ Y_{ij}\right]$$

The experimental results using this decision rule are presented for levels of a equal to 0.6, 0.8, 1.0, 1.2, 1.4, b equal to 0.0 and d equal to 0.5 and 1.0. (Table 4 is an example of the cart allocation plan for the second floor for d=0.5, a=0.8, and b=0.0.) Figure 5 is a summary of the results similar to those in Figure 4 for floor 2 or the prototype MHS. The benchmark values of the average total wait presented are 0.05 hours and 0.20 hours. The cart allocation plan for d equal to 0.0 and b equal to 0.0 (the first plan) is also presented for comparative purposes.

The results indicate that the decision rules for d equal to 0.5 and 1.0 are <u>both</u> similar in system performance and <u>both</u> superior to the previous allocation plan. In most cases, six or more of the 12 hours have an average total wait of less than 3 minutes (0.05 hours) which is very good compared to 2 or 3 hours of such performance under the previous maximum cart rule plan. It is also important to note that only 1 or 2 hours have more than a 12 minutes (0.20 hours) average total wait as opposed to 5 or 6 hours under the previous plan. This simulation experiment was also conducted assuming a large number of carts in the system and a large number of servers at each location to minimize unwanted constraints.

SERVER ALLOCATION

The allocation of servers to the system processing stations is less amenable to specification with the use of a decision rule. This is due to the diversity in the types and sequences of tasks that must be performed by the servers and due to some uncertainty about the actual role of the servers in system operation. In the prototype simulation, a server allocation plan is proposed for each of the process points in the model, and the performance of the system is evaluated on the basis of 1) server

FIGURE 5

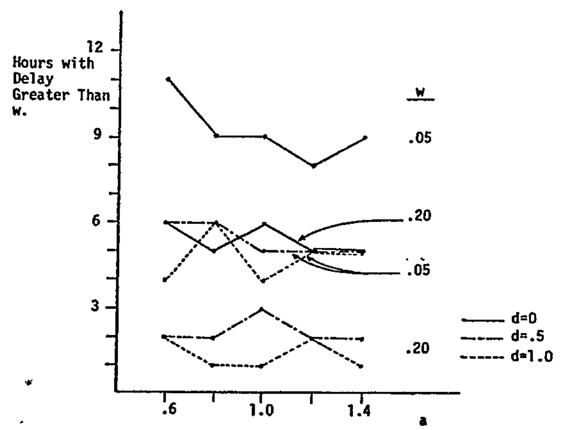


TABLE 4

HOUR	1	2	3	4	5	6	7	8	9	10	11	12
MAX CARTS	6	8	6	6	2	5	2	5	4	0	5	2
MIN CARTS	0	0	2	1	0	1	2	3	1	0	3	2

utilization, 2) the average processing delay due to server unavailability, 3) the average number of delays per day, and 4) the average duration of delays due to all causes (both server and cart unavailability). These measures aid in identifying the tradeoff between the level of server utilization achieved and the average amount of delay in system operation that can be attributed to server unavailability. The latter measures are also useful in evaluating the interactions between the supply of servers and the supply of carts provided in the system.

As an example of this type of investigation, Table 5 shows two plans for server allocation at the decontamination station of the prototype system. The number of servers provided has been specified to achieve a relatively even level of utilization throughout the day according to the anticipated demand for decontamination services. In the first plan, an attempt has been made to keep the utilization level near 65%, while in the second plan an approximate limit of 80% utilization has been used. For the decontamination station, there are no originated commodity moves, so there is no contribution to movement delay from the unavailability of carts, and all delay at the decontamination station is due to the server being occupied. The results indicate that the amount of delay at the decontamination area is quite sensitive to the level of utilization demanded from the servers. In the first plan, the overall utilization averages 57% for all 12 hours of the day, and the average delay over all simulated hours is .39 hours (that is, a total of .39 hours delay in processing occurred during each hour of the average day). In the second plan, reducing the number of servers increased the average utilization to 75% and the average amount of delay during an hour increased to 2.42 hours. In addition, the number of carts remaining to be emptied at the end of the simulated day increased from .39 to 2.42. This last problem could be avoided by adding one server during either of the last two hours of the day, since there is little decontamination activity during the tenth hour of the simulated day. The rapid increase in average delay during the eleventh hour of the simulation is a result of the rapid return of dietary trays after dinner combined with the relatively long period of time required to empty a dietary tray at the decontamination station.

CONCLUSIONS

In this paper we have examined the simulation of a relatively complex hospital system and made use of a prototype approach to obtain an initial understanding of both modeling methods and basic system operating characteristics. The complexity of the actual MHS dictates the use of a simulation approach to the problem, and it appears that the use of the prototype is beneficial in reducing both the amount of professional time and the amount of computing time from the levels that would be required to debug and execute a simulation model of the entire system from the beginning. Many of the results obtained relative to the general policy for allocating carts and servers to the processing points in the system will apply to the full-scale simulation with only minor changes due to the higher utilization of some of the system resources such as the lifts and the cart processor. Results obtained relative to the impact of reducing the cart inventory should also extend to the full-scale system although the effects of the greater distances in the full-scale system may be somewhat more significant.

TABLE 5

Hour	1	2	3	4	5	6	7	8	9	10	11	12
# Servers	2	5	2	2	1	3	3	3	3	1	2	1
% Utilized	40.2	64.7	62.0	47.6	70.5	65.5	49.6	58.6	55.9	23.4	62.4	82.5
Total Delay	.12	.10	.34	.13	.51	.43	.43	.27	.28	.09	1.22	.79
# Servers	1	3	1	1	1	2	2	2	2	1	1	1
% Utilized	88.8	94.7	90.5	88.7	88.3	79.9	92.0	74.7	90.0	35.8	67.1	100.0
Total Delay	1.68	3.47	1.75	2.12	2.02	1.52	3.88	1.20	3.10	.22	2.61	5.46