A GPSS MODEL OF A QUEUEING PROBLEM WITH COMPLEX DECISION MAKING BEHAVIOR

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ABSTRACT

This paper covers in detail the simulation model as well as the associated GPSS computer program of a complex queueing problem. Complexity is manifested in terms of the use of the model as well as the model itself. The former pertains to experimental design aspects. The latter, on the other hand, refers to structural considerations (i.e., parallel queueing systems sharing resources) as well as decision making behavior concerning the allocation of these scarce resources (i.e., a batch arrival and service queue with two different forms of balking and reneging).

Following a general description of the model and program, a detailed presentation of the segment of code which represents decision making is made. Then several significant program highlights are discussed. Finally the technical considerations of the use of the program in a research investigation are described.

The paper is intended for seasoned users of simulation. These may either be research investigators or simulation practitioners who at one time or another have been challenged to bring together the modeling requirements of their problem with the modeling capabilities of GPSS.

INTRODUCTION

Since the introduction of GPSS more than twenty years ago a large number of papers describing simulation models using this language have appeared in the literature. Most of these application articles have attempted to convey to the reader an understanding of the essential features of the problem, be it an engineering, business or other type of system. They have also sought to instill some appreciation for the contribution of simulation to the "solution" of the problem ("solution" of course meaning different things to different people). By and large coverage of GPSS in these papers has been incidental, being limited to a GPSS flowchart and sometimes a small part of the code. Few such articles, a good example being Degen and Schriber(6), have taken up as their main theme the use of GPSS in a particular class of problems. This paper belongs to the latter category of work. Thus, it seeks to demonstrate some of the ways in which the modeling capabilities of GPSS can be "stretched to their limit." By providing a considerable amount of techical detail, it is hoped that this presentation will serve as a case study of the rewards as well as penalties that a problem solver may expect to encounter when using GPSS to study a particularly challenging queueing-type problem.

In this case the problem is generalized in that it represents an abstraction of realistic situations. There is also a considerable amount of complexity. This is because, in addition to being subjected to dynamic and stochastic, environmental inputs, the system exhibits activity interdependence, i.e., the progress of a service activity is directly affected by the progress of another service activity elsewhere in the system. Therefore this problem is an example of a large category of queueing (usually network) problems where

a) in-parallel and/or in-series queueing systems affect one another's demand for and/or supply of service as well as
b) unusual customer behaviour (e.g., balking) or server behaviour (e.g., preemptive priorities) occurs.

Such problems are encountered in production, communications and transportation, to name a few.

THE SIMULATION MODEL

The simulation model includes a number of Customer Queueing Systems (C.Q.S.) that are arranged in parallel. Each serves its own set of customers using a first-come-first-served discipline (see Figure 1). The total number of servers in the group of these C.Q.S.s--otherwise referred to as the Customer Service Echelon (C.S.E.)--is fixed. Inbound and outbound server transfers are initiated at a C.Q.S. independently of the others. Each C.Q.S. uses the same generic, heuristic, event-triggered operating policy. This

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policy is based upon simple feedback control of a performance criterion called the server utilization factor (u.f.). This criterion, calculated separately for each C.Q.S., is as follows:

$$\text{u.f.} = \frac{B + W}{S + T + R}$$

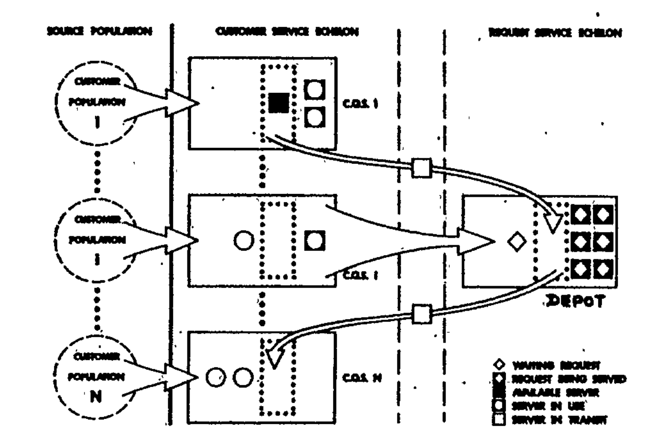
where

B is the number of servers in use at a C.Q.S.,
W is the number of customers waiting to be served at that C.Q.S.,
S is the total number of servers (busy and idle) at the same C.Q.S.,
T is the number of servers in transit to that C.Q.S., and
R is the number of outstanding requests for servers from that C.Q.S. at the Depot (see below).

The policy includes four decision rules that control the timing and extent of the increase or decrease of the number of servers currently assigned to a C.Q.S. These decision rules are of the "stochastic review" type, i.e., the occasions on which the u.f. is computed and compared to the predefined control limits are the three independent events in the operation of the group. These are the events that are a function of the stochastic processes that "drive" the group. They are:

a) the arrival of a customer at a C.Q.S. (generated by the stationary Poisson arrival rate process),
b) the release of a server by a customer (generated by the stationary Erlang-k service time process), and
c) the completion of a requested inbound server transfer at a C.Q.S. (generated by the unknown request waiting and service process).

FIGURE 1
THE SERVICE SYSTEM



On any one of these occasions a C.Q.S. may place an order composed of one or more requests for additional servers (one request per server) with the Depot. The latter is not part of the C.S.E. but of a higher level echelon called the R.S.E., for Request Service Echelon. Thus the Depot acts as a neutral "traffic policeman" of sorts to which unneeded servers are also dispatched from various C.Q.S.s. Consequently, for statistics gathering purposes, there are four different kinds of queues in front of the Depot:

a) the order queue (from the C.S.E.),
b) the request queue (from the C.S.E.),
c) the "segmented" order queue (one from each C.Q.S.), and
d) the "segmented" request queue (one from each C.Q.S.).

It should be stressed that the Depot serves orders, not the requests that make up an order. Furthermore it is postulated that the server transfer times between the R.S.E. and the C.S.E. are deterministic and uniform for all Depot-to-C.Q.S. combinations (in both directions).

Ongoing research with this model (2) has investigated the effects upon C.Q.S. and C.S.E. performance of

a) features of the operating policy and
b) the structural parameters of the C.S.E.

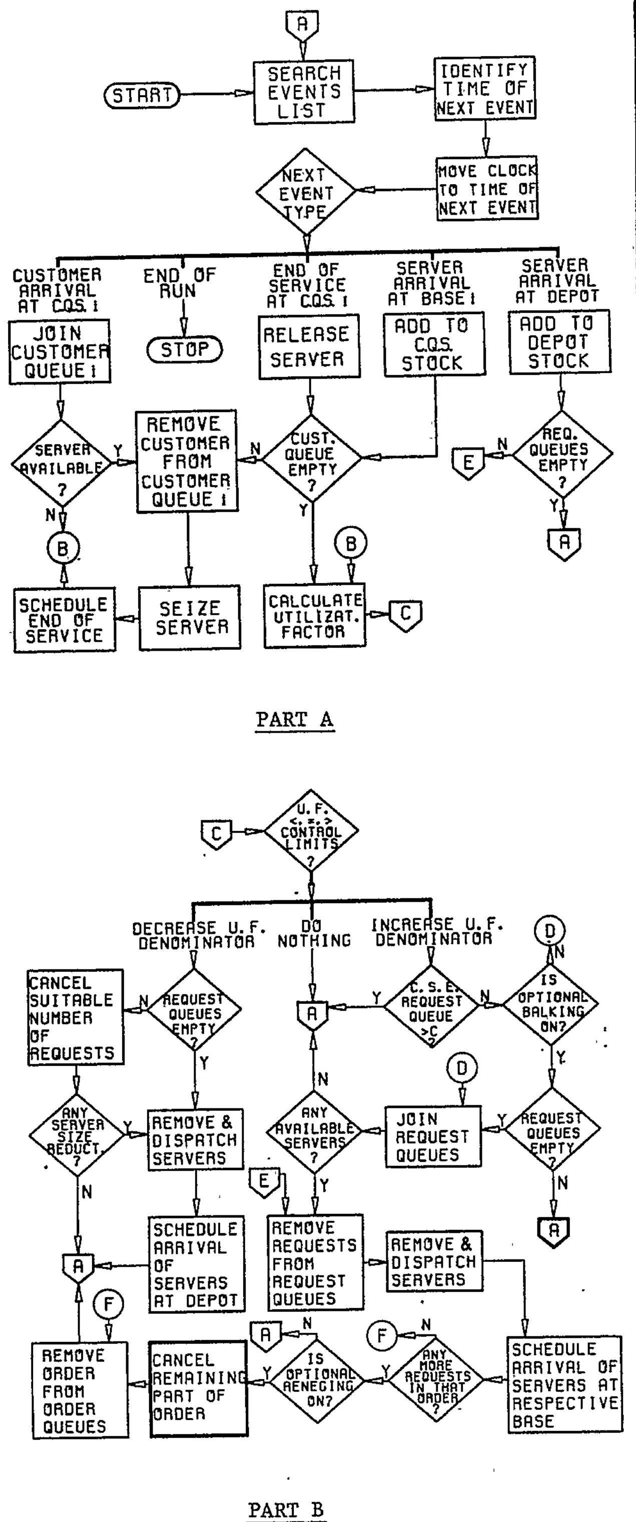
For instance, under the former category, the model has been used to ascertain the control limit sensitivity of the operating policy. Experimental factors in the latter category, on the other hand, have included the size, degree of compactness and homogeneity of the group. Performance has been evaluated by means of criteria that measure various aspects of queuing system behaviour, e.g., quality of service to customers as well as utilization of servers.

Figure 2 is a flowchart of the logic of the simulation model. The first (upper) part shows the typical tasks associated with every discrete simulation model (searching the future events list, identifying the time of the next event, etc.), the three independent events mentioned above plus the two dependent events, i.e., server arrival at the Depot and end of the simulation run. The second part shows the three paths of activity that can be followed after the u.f. has been compared with the control limits. For instance, if a reduction in the u.f. denominator is indicated, the request queue and the segmented request queue associated with that C.Q.S. are checked for any waiting requests. If there are some waiting, a suitable number is cancelled ("mandatory" reneging). On the other hand, if it is desired to increase the u.f. denominator but the request queue contains as many requests as the total number of servers in both echelons, control is transferred to the portion of the program that searches the events list ("mandatory" balking). "Mandatory" balking and reneging should be distinguished from "optional" balking and reneging. The "optional" characterization refers to features that are integral components of the operating policy in that they are under the jurisdiction of the imaginary "C.Q.S. manager."

As such they do not have to be invoked in every simulation run. In Figure 2 "optional" reneging is portrayed by the heavily drawn process box at the lower left hand side of the second part, while "optional" balking is depicted by the heavily drawn off-page connector on the right side of the figure.

FIGURE 2

THE COMPUTER MODEL FLOWCHART



General

The digital simulation literature advocates the choice of a high level simulation language (such as GPSS) over a general purpose programming language (such as FORTRAN) because of the provision of such "built-in" housekeeping chores as maintenance of events lists, data gathering, etc. In this case these were essentially the same reasons behind the elimination of FORTRAN. On the other hand, choosing GPSS over other high level languages was prompted more by availability than anything else. Still, the preference of this investigator for the transaction orientation of GPSS was a strong motivating force. Another was readability. Bobillier et. al. (1) are among the many authors who maintain that the "readability (of GPSS) is a special advantage whenever several people must work on the problem" [p. 384]. It should also be added that this feature is very helpful when one has to "overhaul", i.e., drastically modify, the program--especially after a long period of inactivity! This particular program went through at least three such overhauls. It was originally written and tested in a GPSS V environment (7). However, it subsequently had to be modified to be run under the Xerox version of GPSS which is called GPDS (for General Purpose Discrete Simulator) (9). Conversion would have been completely painless were it not for a strange problem with MACRO expansions, to this date remaining unresolved due to the almost complete lack of vendor support. Nevertheless GPDS itself is a truly outstanding product. As evidence is offered the fact that, even though it was developed in the early seventies, it possesses interactive execution capability. It is the opinion of this author (3) that for anybody with an "unusual" simulation model this feature should more than make up for any drawbacks a particular version of GPSS may have.

Program Structure

Transaction activity in a C.Q.S. is modeled using six distinct operating modules of code (see Table 1). A module is a group of blocks of which the first is a GENERATE block and the last is a TERMINATE block. Transactions of course assume different roles depending upon the function of the module. In the first they are customers, in the second server inventory clerks, in the third C.Q.S. decisionmakers, in the fourth order and requests for servers and in the fifth and sixth servers. Since eight queueing systems are postulated, there are a total of forty eight C.Q.S. operating modules plus a single Depot module which models the imaginary Depot clerk. Each module collects statistics associated with the respective C.Q.S. It also contributes to the updating of the relevant C.S.E. statistics.

The Operating Modules

The first operating module is made up of four segments of code:

a) modeling of the interarrival and service distributions using ASSIGN and LOOP blocks

b) QUEUE & DEPART blocks at C.Q.S. and C.S.E. queues,
c) ENTER, ADVANCE & LEAVE blocks at C.Q.S. and C.S.E. storages to simulate the number of busy servers, and
d) LINK & UNLINK blocks to deactivate and activate respectively customer transactions waiting to be served.

The second operating module contains the following three segments of code:

a) the "initialization" of the appropriate C.Q.S. and C.S.E. storages which model current server capacity as follows:

```
ENTER      RENT1,R$RENT1
LEAVE      RENT1,X$INCR1
```

assuming of course that the following statements have been inserted elsewhere:

```
STORAGE    S$RENT1,50
INITIAL    X$INCR1,6
```

b) the increase of the C.Q.S. server "capacity", upon a "signal" (to be explained below) from the fifth module, using LEAVE blocks as above, and
c) the decrease of the C.Q.S. server "capacity", upon a signal from the sixth module, using ENTER blocks as above.

TABLE 1
CUSTOMER QUEUEING SYSTEM (C.Q.S.)
COMPUTER PROGRAM OPERATING MODULES

Operating Module Number	Function	Number of Blocks
FIRST	Simulation of the processing of customers by a C.Q.S. (arrival, service, exit).	44
SECOND	Stock control of all incoming and outgoing servers to and from a C.Q.S. respectively	32
THIRD	Activation of the decision rules at a C.Q.S. Balking (optional and mandatory) plus mandatory reneging. Management of Depot queue departures due to balking or mandatory reneging.	96
FOURTH	Simulation of the processing at the Depot of orders and requests from a C.Q.S. Optional reneging.	81
FIFTH	Simulation of the transfer of servers from the Depot to a C.Q.S.	19
SIXTH	Simulation of the transfer of servers from a C.Q.S. to the Depot.	26

In the third module a comparison of the u.f. with the appropriate upper and lower control limits takes place first. Then the decision making transaction is routed to one of two HELP blocks which use the same FORTRAN subroutine to determine the size of the intended server capacity change. If an increase is indicated, a message is sent to the fourth module after the current contents of the request queue have been checked, for possible "mandatory" balking. On the other hand, if a decrease is warranted, the length of the appropriate segmented request queue is first checked. If it is zero, a message is sent to the sixth module. Otherwise, first, optional reneging of an order currently in the process of being served is considered, followed by optional reneging of any orders still waiting to be served at the Depot. Obviously partial reneging of an order is possible, i.e., only some of the requests that comprise a particular order (whether waiting or in the process of being served at the Depot) may be cancelled.

The fourth module contains segments which
a) initialize the orders from the C.Q.S.,
b) QUEUE & DEPART from the appropriate order queues and segmented order queues,
c) SEIZE & RELEASE facility SERVE, which represents the Depot clerk,
d) represent the process of being served by SERVE when
   1. there is currently a number of servers at the Depot greater than or equal to the number of requests in the order, and
   2. there are currently not enough servers and consequently some requests have to wait for servers to become available,
e) model optional reneging which is either "ship the requested servers to the C.Q.S. in an unlimited number of batches" or "in only one batch," i.e., don't wait for more servers to become available, and
f) generate the appropriate requests using SPLIT blocks and route them in and out of the appropriate request queues and segmented request queues.

A facility is used to model the Depot because at any one time only one order can be in the process of being served, i.e., occupy the Depot until either all the requests are transformed into servers dispatched to that C.Q.S. or reneging--mandatory or optional--takes place.

The fifth module generates a server and an offspring, "parks" the parent at a user chain, upon a signal from the fourth module moves that transaction through ENTER, ADVANCE and LEAVE blocks to simulate shipment time and finally sends a signal to the second module to notify it that the server has arrived. Obviously the sixth module is similar to the fifth except that the initiating signal is received from the third module and the notification signal is sent to the Depot module. Also, along the way a signal is sent to the second module for records updating.

Table 1 shows that the third and fourth modules make up more than sixty percent of the part of the program that is devoted to the representation of a C.Q.S. To explain balking in the third module, it is necessary that the transaction flow in the fourth module be presented first. A complete description of the fourth and third modules is provided in Appendix 1 and 2 respectively. Both of them refer to C.Q.S. #1. In these and subsequent Appendices the essential blocks are shown sequentially followed immediately by a short explanation of points deemed to be necessary to the understanding of the modeling approach. It is understood of course that some blocks not essential to transaction flow, such as TABULATE for instance, have been omitted. Finally, to facilitate the reference of blocks by other blocks in the same or a different Appendix, a specific block numbering scheme is employed. Thus a two digit number in bold typeface appears on the extreme left hand side of each line of code. The first digit identifies the Appendix number while the second refers to the sequential position of that block within that Appendix.

HIGHLIGHTS OF THE PROGRAM

Intermodule Communications

As is demonstrated in Appendices 1 and 2, one of the challenges to the programming of this simulation model is the need for "communication" between modules. This is achieved by means of logic traps, i.e., strategically placed logic switches which operate in connection with transactions LINKed on and UNLINKed from user chains. That is, when the time comes for a transaction to resume its normal flow, the transaction that instigates the UNLINKing first checks to see if the switch is reset (see line **2-10** for instance). If it is, the simulation stops after the FORTRAN error flagging subroutine EROR1 is called. If it isn't, then the switch is set (line **2-11**) followed by the UNLINK block (line **2-12**). The latter routes the released transaction to a block which resets the switch (line **1-4**) before anything else can take place. Setting and resetting the switches is so important to proper event scheduling that BUFFER blocks are liberally used (see lines **1-31**, **1-37** and **2-38**). As a matter of fact to ensure that the current events chain is scanned in the manner that the investigator desires, many transaction priorities are dynamically modified, e.g.,

```
GENERATE    ,,,1,45
     :
     :
PRIORITY    30,BUFFER

PRIORITY    45
```

Thus these logic traps prevent activity in one module from proceeding without required activity in other modules having been completed.

Error Flagging

The error flagging subroutine does not output the exact location of the error. To do that would require the transaction to "carry" an additional parameter. Then, upon detection of an error condition, the transaction would be routed through an ASSIGN block which would put in that parameter a predetermined code indicating the error location. Subsequently the FORTRAN subroutine would output the contents of that parameter. Naturally an alternative to the use of an error flagging subroutine would be the routing of the offending transaction through a TRACE, UNTRACE and TERMINATE sequence. The advantage of this option is that the address of the previous block is part of the standard full trace output.

HELP Blocks

The limitation upon the maximum number of arguments allowed in HELP blocks (i.e., six) was a serious obstacle to get around. It was done by using two intermediate variables (V17 and V20) to provide input data to the FORTRAN subroutine that calculates the change to the u.f. denominator (see lines **2-7** and **2-17**). The cost of this option is of course the additional storage required by the sixteen--since there are 8 C.Q.S.'s--variables. An alternative would be the use of two, rather than one, subroutines which are called by the GPSS program one after the other. Thus the first would handle half of the calculations and pass the intermediate result back to the GPSS program. This value would then be turned over to the second subroutine to obtain the final result. The disadvantage of this approach is the extra core required by the second subroutine as well as the penalty, in terms of CPU time, associated with an additional subroutine access.

Statistics Gathering

The most appealing feature of a special purpose language like GPSS to an investigator with limited time is the availability of standard statistics gathering entities. Sometimes this can obviously be a disadvantage in terms of high computer storage and execution requirements. However, if resource constraints are not severe, use of redundant statistics gathering entities can be a blessing when trying to verify particularly large and complex programs. Thus a model attribute, such as current queue length (Qj), may be recorded by more than one queue. For example, in this program C.Q.S. as well as C.S.E. queues are used at the lower echelon and C.Q.S. as well as R.S.E. queues at the upper echelon. Alternately the average length of a queue may be maintained in attribute QAj as well as in TBj, i.e., using a TABLE entity. Unfortunately, use of these entities may sometimes lead to certain awkward programming problems when the information contained in their attributes must be directly used in the program itself rather than be simply outputted. This is particularly true of TABLES which are the only entities capable of gathering dispersion statistics. Thus weighted means and standard deviations cannot be directly referenced. Furthermore, when unweighted means and standard deviations are referenced, they are truncated. For this investigation accuracy is so important, especially when it comes to u.f. computations, that all the entities are subjected to entry and exit counts with a much larger order of magnitude than shown elsewhere in this paper. Thus

```
QUEUE       LINA,10000
```

is used rather than

```
QUEUE        LINA,1
```

However, this means that additional parameters and variables have to be created to handle the situations, like LOOP control for instance, in which the proper order of magnitude is needed. A good example is parametere #3 which is initialized in 1-6 and used in 1-15.

Data Capturing

The program collects data (experimental observations) of global as well as local performance criteria, i.e., referring to the C.S.E. and C.Q.S. respectively, for a number of simulation subruns. Subsequently the data is analyzed by means of separate linear, additive, regression models. The tabulation of this data is handled by a separate FORTRAN subroutine called at the end of each subrun. This subroutine stores output values on a disk file in binary mode. In this way the preparation of the master data file, upon the completion of all the runs, is a relatively straightforward but nevertheless time consuming process. This is not only due to the size of the data base but also to the fact that the only way to output weighted TABLE means and standard deviations is through the REPORT editor using TEXT cards. The problem is that, for this GPDS implementation, the device (data set reference) number of the binary mode disk file cannot be the same with the device number of the REPORT editor. To make matters worse, the latter can only write to a tape. Thus each simulation run has two output files, one on disk and the other on tape. Not only that, but due to experimental design considerations imposed by the investigator, the data items of the tape files have to be inserted into, rather than added at the end of, the respective disk files to come up with the master data subfile pertaining to a particular run. For a complete discussion of the data gathering module please see Appendix 4.

Simulation Subruns

The subruns of this model are of the "time duration" rather than the "customer arrival count" type. According to Conway (5) the former is appropriate for measuring attributes of permanent entities (utilization of storages for instance) while the latter best suits the measurement of temporary entity attributes (for example mean waiting time of customers). In this case arrival count subruns can be used if, immediately after entering the C.S.E. customer queue,

```
QUEUE        LINAA,1
```

a transaction trips the testing of the number of entries

```
TEST L       QC$LINAA,X$NUM,USE19
```

where USE19 is a block that increments the appropriate arrival counter, adds another 1000 to X$NUM (if that is the size of the arrival count subrun) and then proceeds to output the appropriate statistics. The difficulty comes in when one attempts to reconcile the two schemes in the same GPSS program. This is because of the inability of maintaining two separate sequences of START & RESET cards, where one sequence selectively resets one class of statistics and the other sequence all the rest. That is, GPSS does not provide the capability of "routing" an imaginary transaction through one or the other kind of RESET card.

Macros

Due to the size as well as the repetitive nature of the program (approximately 2600 blocks), MACROs are heavily used. Thus, each operating module, irrespective of C.Q.S., consists of anywhere from two to eleven MACROs. With the use of parallel streams of MACROS, one stream per C.Q.S., proofreading as well as correcting becomes very easy. This is achieved by editing on-line the file that contains the GPSS program and using the command(s) of the computer system editor that search the file and type out all the occurrences of the same <u>kind</u> of MACRO, e.g., the first MACRO in the second module of all the C.Q.S.s. Obviously the existence of a very carefully thought out entity naming convention is invaluable. This applies to tags of such entities as queues, storages and the like as well as the labels of blocks and MACROs. In writing this program particular care was taken with dummy arguments of a MACRO that refer to a block label in another MACRO in the same or another module. A block labeling scheme utilizing a three letter prefix and a two digit suffix was found particularly helpful in tracing areas of unusually heavy transaction flow. The prefix, admittedly not very descriptive, pertains to the type of the operating module, e.g., GET for the fourth module and COR for the third. On the other hand, the first digit of the suffix identifies the C.Q.S. while the second pertains to the location of that specific block relative to all the others in that particular module.

"Good Housekeeping" Practices

Early in the development of the program it was decided to establish and adhere to very strict "housekeeping" practices. It was felt that, for a program of such complexity, a logical physical arrangement of the various categories of code would be invaluable not only to program verification but to subsequent modification as well. As Table 2 shows therefore, definitions of MACROs and such important entities as FUNCTIONS precede SAVEVALUE initializations. Furthermore the operating modules are placed separately from such ancillary modules like the statistics gathering and timer modules. Also the primary (parent) transaction flow at each module is segregated from the secondary (offspring) flow as much as possible. Secondary flow may also refer to transactions which place transactions on (or remove them from) the current events chains. Segments of code which include looping may also be placed at a separate location of a module.

Finally it should be pointed out that a

conscious effort was made to adhere as much as possible to certain simple common sense rules like

a) the placement of such "attention distracting" blocks as TABULATE, MARK or ASSIGN away from such key blocks as GATE LR or TEST, and
b) the placement of QUEUE/DEPART or ENTER/LEAVE blocks for local (C.Q.S.) entities in a consistent manner relative to those of global (C.S.E.) entities (see for instance lines **1-9** and **1-10** as well as **1-64** and **1-65**).

RUNNING THE PROGRAM

Thus far the program has been used in several distinct research phases. A research phase is a set of experiments (simulation runs) carried out for the purpose of testing a specific hypothesis concerning the behavior of the system. To change the configuration of the model from one research phase to the next, the following modifications to the program are required:

- the initial server allocation to the Depot,
- the size of the subrun,
- the duration of the simulation, and
- the target value of the u.f. which is the midpoint between the upper and lower control limit.

Also, in the second operating module, the storage capacity of a C.Q.S. has to be established using an appropriate STORAGE block.

On the other hand two kinds of programming modification are required to change, within the same research phase, the configuration of the model from one experimental run to another. The first calls for the setting of a number of savevalues using INITIAL blocks. These savevalues represent the experimental factors the values of which specify the experimental levels in effect for a certain run. For example, the values of 0 or 1 in savevalue XFACE indicate that there are four or eight active C.Q.S.s respectively. The values of these savevalues along with the reference numbers of the run and subrun are the first data items to be written out on the binary disk file record which contains all the data for a particular experimental replication. This is because these experimental factors constitute the independent variables of the respective regression equation. There is of course one regression equation for each performance (dependent) variable that is to be analyzed.

The second type of programming alterations consists of the changes to the values of the actual GPSS entities with which a particular experimental factor is associated. All of these entities are savevalues. A description of the experimental factors, the GPSS entities used to model them, along with the maximum number for each, (i.e., equal to the maximum number of C.Q.S.s) is given in Table 3. For instance, Factor E, i.e., size of the C.S.E., is modeled by eight X$BASEj which are used in the initialization interval subfield of the GENERATE blocks in each of the eight customer service C.Q.S. modules.

TABLE 2
SEQUENCE OF PROGRAM SEGMENTS

a. MACRO Definitions
b. Tag Definitions (EQU cards)
c. FUNCTION, VARIABLE, TABLE Definitions
d. SAVEVALUE Initializations
e. Operating Modules
    C.Q.S. #1
        FIRST Module
        SECOND Module
        .
        .
        .
        SIXTH Module
    C.Q.S. #2
        FIRST Module
        .
        .
        .
        SIXTH Module
    C.Q.S. #3
        .
        .
        .
    C.Q.S. #8
    Depot Module
    Auxiliary Module
f. Statistics Gathering Module
g. Timer Module
h. Control Cards
i. Output Editor Cards

The most difficult experimental factor to model is factor G. This refers to the form of the relative frequency distribution of the four or eight (depending upon the value of factor E) C.Q.S. arrival rate means. Thus, there is an experimental requirement that the total, i.e., C.S.E.- wide, "demand for service" has to be the same for all runs of an experimental phase. In other words, the "supply of service", i.e., the total number of servers initially allocated to the C.Q.S.s should be the same for all runs of a research phase. Consequently the initial allocations of servers to the C.Q.S.s will vary from one run to another. For instance, to model a small (four C.Q.S.s) "heterogeneous" C.S.E. with Poisson arrival rate distributions, the interarrival time means of three C.Q.S.s are set at 300 time units while that of the fourth is set at 150. The initial server assignments (X$INCRj) of each of the first three are 48 while that of the fourth is 96. On the other hand, the numbers for a large heterogeneous C.S.E. are 720, 240, 20 and 60 for the first six and the remaining two C.Q.S.s respectively. These figures along with a common service time distribution mean (XH$HOLDj) of 10799 time units ensure that the mean of the C.S.E., not C.Q.S., interarrival rate distribution (XH$BINTj)--which of course is also Poisson--will be 1/60 while the total number of servers will be 240. All these values were determined prior to the execution of the simulation runs using interactively a FORTRAN program of a heuristic numerical search procedure.

Factor H stands for the presence or absence of "interaction " among the C.Q.S.s. That is, whether the C.Q.S.s are to share servers through the Depot or are to operate independently of one another. A simple way of representing this factor

TABLE 3
THE EXPERIMENTAL FACTORS

Factor	Description	GPSS Entity	Maximum Number of Entities
A	Degree of sensitivity of the upper control limit of the operating policy	X$UNOZj	8
B	Degree of sensitivity of the lower control limit of the operating policy	X$LNOZj	8
C	Presence or absence of "optional" balking	XH$LINLj	8
D	Presence or absence of "optional" reneging	XH$NSHPj	8
E	Number of C.Q.S.s	X$BASEj	8
F	Inter-echelon Transportation time	XH$MOVE	1
G	Composition of the Source Population	X$INCRj XH$BINTj XH$HOLDj	8 8 8
H	Presence or absence of operational interaction among the C.Q.S.s	X$STRAj	8
I	Variance of interarrival time distribution	XH$KAPA1	1
J	Variance of service time distribution	XH$KAPA2	1

is to strategically place a TEST block in the third operating module. This block will compare the current absolute clock with savevalue STRAj. Thus, just as with BASEj above, if STRAj contains a very large value, the decision making code will be bypassed and no requests or disposals of servers will be initiated. On the other hand if STRAj contains a very small value, but not zero due to computational complications with the u.f. when the simulation is still "cold", then decision making may take place.

Finally, factors I and J stand for the interarrival and service time distribution variance when both of them are Erlang-k respectively. To model them, all that has to be done is set savevalues KAPA1 and KAPA2 to the appropriate values of k, i.e., a large value of k for small variance and a small value of k for large variance (see Appendix 5).

Simulation run lengths have ranged from 25 to about 42 minutes of CPU time on a Xerox Sigma 9 with 512K bytes of main memory operating under the Control Program Five (CP-V) operating system. As an indication of model complexity, one thousand customers at the C.S.E. take on the average about a second of CPU time to be processed through the model (simulation run duration has been 1,300,000 time units). As a measure of size, there have been peak memory requirements of around 450K bytes. This, despite the fact that the FORTRAN shared library (needed by the FORTRAN data gathering subroutine) was overlayed with the GPDS load modules to obtain the relocatable object module. Table 4 shows that a significant amount of reallocation had to take place to accommodate

a) the large number of tables necessitated by the extraordinary amount of data gathering,
b) the number of blocks (which is a direct function of the number of C.Q.S.s), and
c) the amount of COMMON which is dependent upon the large number of active transactions.

Obviously a lot of "fat" had to be trimmed by employing such well known practices as minimizing the number of parameters per transaction as well as using halfword, instead of fullword, parameters and savevalues whenever possible (see lines **1-30** and **1-32** for instance).

TABLE 4
COMPUTER PROGRAM ENTITY REALLOCATIONS

Entity	Standard Number	Actual Number
Facilities	300	1
Queues	300	55
Functions	200	19
Storages	300	36
User Chains	100	79
Transactions	1200	900
Logic Switches	1000	100
Savevalues (fullword)	1000	118
Savevalues (halfword)	500	90
Groups	25	5
Variables	200	96
Random Number Generators	8	16
Tables	100	150
Blocks	1000	2599
COMMON (in K bytes)	106.5	120

SUMMARY

This paper has provided a detailed description of the GPSS program of a complex queueing problem. Particular emphasis was placed upon the decision making behaviour which generates customers to a bulk arrival queueing system. The process that serves these customers also received considerable attention. Validation and verification topics were not covered inasmuch as they are addressed elsewhere (3).

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APPENDIX 1: THE FOURTH OPERATING MODULE

The fourth module is divided into two parts: one which handles order processing at the Depot and another that carries out request processing. These two parts can be visualized as two physically distinct sections of code--i.e., representing separate transaction flow--connected by appropriate TRANSFER blocks.

Part A: Order Processing

```
1-1            GENERATE    ,,X$BASE1,1,65,5,F
```

BASE1 is a fullword savevalue, previously initialized, which is used to activate or deactivate a C.Q.S. #1 depending upon the value of experimental factor E in effect during a particular simulation run, i.e., either all eight C.Q.S.s are "open" or C.Q.S.s #5 through #8 are "closed.".

```
1-2            ASSIGN      2,1
```

Transaction #2 will be used to identify to which C.Q.S. does this order belong (in this case it is the first).

```
1-3   GET10    LINK        SEVE1,FIFO

1-4   GET11    LOGIC R     17
```

Logic switch 17 is set in the third module (line **2-11**). This of course is the way by which modules communicate, i.e., the "signals" that are mentioned in the text.

```
1-5            SPLIT       1,GET10
                           (GET10 is in line 1-3)
```

Create an offspring transaction which will act as an order next time one is dispatched from the third module (i.e., from the C.Q.S. to the Depot, see line **2-12**).

```
1-6            ASSIGN      3,X$INT01
```

INT01 is the size of the current order which is calculated in the third module (line **2-7**).

```
1-7            ASSIGN      4,X$INT01
```

Parameter #3 is used in group operations associated with waiting time only (group LINEG in lines **1-8, 1-18, 2-34, 2-36, 2-43, 2-44**) while parameter #4 is used in group operations associated with time spent being served by the Depot (group WORK in lines **1-19, 1-41, 2-20, 2-23**).

```
1-8            JOIN        LINEG

1-9            QUEUE       LINA,1

1-10           QUEUE       LINA1,1
```

LINA & LINA1 are the order queue and segmented order queue for C.Q.S. #1 respectively.

```
1-11           QUEUE       LINO,1

1-12           QUEUE       LINO1,1
```

LINO & LINO1 are the order queue and segmented order queue which record waiting time plus time to be served at the Depot respectively.

```
1-13  GETK1    SPLIT       1,GETL1,,1
                           (GETL1 is in line 1-53)
```

Generate and route, in the request processing segment described below, a request which will be part of this order. Copy parameter #1 of the parent transaction only.

```
1-14           PRIORITY    65,BUFFER
```

Move that request now!

```
1-15           LOOP        3,GETK1
                           (GETK1 is in line 1-13)
```

Repeat the process as many times as required by the size of the order.

```
1-16           GATE NU     SERVE,IDLE1
                           (IDLE1 is in line 3-1)
```

If the facility is currently tied up, "park" this order transaction at a user chain in the auxiliary

A GPSS Model of a Queueing Problem With Complex Decision-making Behavior (continued)

module (described in Appendix 3).

```
1-17          SEIZE       SERVE
```

If the Depot is free, i.e., if there is no other C.Q.S. in the process of being served, get in!

```
1-18   GETP1  REMOVE      LINEG
1-19          JOIN        WORK
1-20          DEPART      LINA,1
1-21          DEPART      LINA1,1
1-22          UNLINK      WAIT1,GETN1,P3
                          (GETN1 is in line 1-61)
```

WAIT1 is a user chain for requests residing at the request queue or segmented request queue (see line 1-57).

```
1-23   GET12  TEST GE     X$STOKD,P4,GET15
                          (GET15 is in line 1-44)
```

STOKD is a savevalue, previously initialized, which contains the current number of servers at the Depot. An alternative to the use of this savevalue would have been using a storage entity whose capacity would be redefined, everytime a change would take place, using a STORAGE card with a VARIABLE second operand.

```
1-24          SAVEVALUE   STOKD-,P4
1-25          SAVEVALUE   SHIP1,P4
1-26   GET13  ASSIGN      4-,X$SHIP1
```

If there are enough servers at the Depot make the appropriate records changes. SHIP1 is the number of servers to be dispatched to the respective C.Q.S. while STOKD is incremented at the Depot module (not shown).

```
1-27          GATE LR     16,EROR1
```

Before a signal can be sent, a check has to be made. If logic switch 16 is reset, that means that a scheduling conflict exists which is evidence of a program flaw. Therefore the originating transaction is routed to block EROR1 where an error flagging FORTRAN subroutine is called and simulation is terminated (not shown).

```
1-28          LOGIC S     16
1-29          UNLINK      SIX1,MOV12,1
```

MOV12 is a block address in the fifth module which activates the dormant server as previously discussed. The LINK SIX1,FIFO block precedes the MOV12 block in that module.

```
1-30          UNLINK      WATE1,GETO1,X$SHIP1
```

Remove the appropriate number of requests from "parking status" (where they are placed in line 1-60) and direct them to the designated exit from the model (line 1-64).

```
1-31          BUFFER
1-32          TEST E      XH$NSHIP1,1,GET19
```

NSHIP1 is the indicator for the type of optional reneging (see table 3). If the value is 1, then optional reneging is "off", i.e., shipment of servers from the Depot to the C.Q.S. can be in an unlimited number of batches.

```
1-33          TEST E      P4,0,GET17
                          (GET17 is in line 1-48)
1-34          TRANSFER    ,GETQ1
                          (GETQ1 is in line 1-38)
1-35   GET19  TEST NE     P4,0,GETQ1
1-36          UNLINK      WATE1,GETO1,P4
                          (GETO1 is in line 1-64)
```

If optional reneging is "on", destroy the remaining requests. It should be noted that optional reneging may only take place immediately after service begins at the Depot, i.e., for all practical purposes the order which will optionally renege will spend no time at the Depot (it will be serviced "instantaneously"). On the other hand, mandatory reneging--as described in lines 2-26 to 2-33--may very well involve an order which has been already partially filled and is awaiting for more servers to become available.

```
1-37          BUFFER
1-38   GETQ1  RELEASE     SERVE
1-39          DEPART      LINO,1
1-40          DEPART      LINO1,1
1-41          REMOVE      WORK
1-42          UNLINK      WAITD,IDLE2,1
                          (IDLE2 is in line 3-3)
```

User chain WAITD, which is located in the auxiliary module, contains all the order transactions--irrespective of originating C.Q.S.--currently waiting to be served at the Depot. Therefore this UNLINK block "releases" the next order and through block IDLE2 sends it to the fourth module of the respective C.Q.S.

```
1-43          TERMINATE
1-44   GET15  TEST G      X$STOKD,0,GET17
```

This is where an order transaction is routed if there are fewer servers at the Depot than (remaining) requests in the order.

```
1-45          SAVEVALUE   SHIP1,X$STOKD
1-46          SAVEVALUE   STOKD,0
1-47          TRANSFER    ,GET13
                          (GET13 is in line 1-26)
```

1-48 GET17 GATE LS 100,SIT1
(SIT1 is in line 3-5)

If logic switch #100 is not set, that means that no servers have arrived at the Depot yet. Therefore the order transaction should be routed to block SIT1 in the auxiliary module to be placed in a special user chain called BORED.

1-49 GET18 LOGIC R 100

When servers do become available, the Depot module sets logic switch #100, UNLINKs the transaction from BORED and sends it to block GET18.

1-50 GATE LS 13,GET12
(GET12 is in line 1-23)

Inasmuch as logic switch #100 can also be "tripped" from the third module (line 2-27), i.e., to simulate mandatory reneging of an order in the process of being served, logic switch #13 is inserted here to find out the origin of the transaction that set switch #100. Therefore logic switch #100 is a global entity (associated with the order queue) while logic switch #13 is a local entity (asociated with the segmented order queue belonging to C.Q.S. #1).

1-51 LOGIC R 13

1-52 TRANSFER ,GETQ1
(GETQ1 is in line 1-38)

If switch #100 were set in the third module, then there is only need to remove the order transaction from the model through the appropriate order queues.

Part B: Request Processing

1-53 GETL1 PRIORITY 70

1-54 QUEUE LINED,1

1-55 QUEUE LINB1,1

Request queues LINED & LINB1 correspond to order queues LINA & LINA1 respectively (see lines 1-9 and 1-10).

1-56 SPLIT 1,GETM1,,1

Generate an "offspring of the offspring transaction".

1-57 LINK WAIT1,FIFO

1-58 GETM1 QUEUE SERV,1

1-59 QUEUE SERV1,1

Request queues SERV & SERV1 correspond to order queues LINO & LINO1 respectively (see lines 1-11 and 1-12).

1-60 LINK WATE1,FIFO

1-61 GETN1 DEPART LINED,1

1-62 DEPART LINB1,1

1-63 TERMINATE

1-64 GETO1 DEPART SERV,1

1-65 DEPART SERV1,1

1-66 TERMINATE

APPENDIX 2: THE THIRD OPERATING MODULE

The third operating module starts off the same way as the fourth:

2-1 GENERATE ,,X$BASE1,1,45,2,F

2-2 COR10 LINK ONE1,FIFO

2-3 COR11 LOGIC R 11

Logic switch #11 is tripped by the three independent events that were identified in the section that describes the simulation model. Two of these, i.e., customer arrival and departure, take place in the first module while server arrival at the C.Q.S. is recorded in the second module.

2-4 SPLIT 1,COR10

2-5 TEST G V16,X$UNOZ1,COR14
(COR14 is in line 2-16)

Variable #16 has been previously defined as the u.f. of C.Q.S. #1 while UNOZ1 is a savevalue which has been initialized to the appropriate level of the upper control limit (see Table 3).

2-6 TRANSFER FN,17

Through the use of function #17 control is transferred either to block COR12 or block COR13. In the former no optional balking may take place while in the latter optional balking is allowed. The X-coordinate values of this function are the current contents of XH$LINLj (see Table 3).

2-7 COR12 HELPF GPDF1,X$TARG1,S$USE1,V17,
X$INTO1,0,V20

Five of the arguments of FORTRAN subroutine GPDF1 are used for input purposes. The only output argument is X$INTO1 which contains the intended order size.

2-8 TEST NE X$INTO1,0,CORY1
(CORY1 is in line 2-47)

If the intended order size is zero, remove the transaction from the module.

2-9 TEST L Q$LINED,X$INCR,BALKT

INCR is a savevalue which contains the number of total servers in the C.S.E. Therefore if the size of the request queue is equal to that number, the transaction is removed from the program through block BALKT (mandatory balking). The latter is in a SAVEVALUE block which accumulates the total number of mandatory balking occasions (for the C.S.E.).

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```
2-10            GATE LR     17,EROR1

2-11            LOGIC S     17

2-12            UNLINK      SEVE1,GET11,1
                            (GET11 is in line 1-4)
```

Activate the dormant order transaction in the fourth module.

```
2-13            TRANSFER    ,CORY1
                            (CORY1 is in line 2-47)

2-14    COR13   TEST E      Q$SERV,0,CORA1
```

According to the form of "optional" balking used in this program, the order will not join the order queue if there happens to be any other order either waiting to be served or actually being served at the Depot. CORA1 is a TERMINATE block (not shown) which is used to record the number of optional balking occurrences, i.e., N$CORA1.

```
2-15            TRANSFER    ,COR12
                            (COR12 is in line 2-7)

2-16    COR14   TEST L      V16,X$LNOZ1,CORY1
```

LNOZ1 is a savevalue which contains the lower control limit for the particular simulation run.

```
2-17    COR15   HELPF       GPDF1,X$TARG1,S$USE1,V17,
                            X$OUT1,R$RENT1,V20

2-18            TEST NE     X$OUT1,0,CORY1
```

OUT1 is the size of the intended reduction to the u.f. denominator at the C.Q.S.

```
2-19            TEST G      Q$SERV1,0,CORX1
                            (CORX1 is in line 2-55)
```

If there are no requests from this C.Q.S. at the Depot, waiting or being served, there is no possibility for "optional" reneging. Therefore the transaction is routed to a segment (see below) which sends a signal to the sixth module.

```
2-20            SCAN        WORK,2,1,4,1,COR17
```

If there are requests at the Depot, the first thing to do is to check and see if there are some currently being served, i.e., if there is an outstanding order from that C.Q.S. Thus group WORK is scanned for the first transaction from C.Q.S. #1, i.e., a transaction that has the value of 1 in parameter #2. If such a transaction is found, the contents of its parameter #4 (the current size of the order) are placed in parameter #1 of the scanning transaction. Block COR17 (in line 2-34) is the alternate exit in case such a transaction is not located.

```
2-21            TEST L      X$OUT1,P1,COR16
```

If there are fewer requests being served than X$OUT1, go to block COR16 (in line 2-26).

```
2-22            ASSIGN      1-,X$OUT1

2-23            ALTER       WORK,1,4,P1,2,1
```

Modify the current size of the order at the Depot by passing the contents of parameter #1 of the scanning transaction to parameter #4 of the first transaction encountered in group WORK which happens to have the value 1 in parameter #2.

```
2-24            UNLINK      WATE1,GET01,P1
                            (GET01 is in line 1-64)
```

Remove the requests that are being cancelled from the program.

```
2-25            TRANSFER    ,CORY1

2-26    COR16   GATE LR     100,EROR1

2-27            LOGIC S     100

2-28            GATE LR     13,EROR1

2-29            LOGIC S     13
```

If the size of the order currently being served is smaller than X$OUT1, the entire order must be cancelled. Therefore the proper set of signals must be prepared to be sent to the fourth module (see lines 1-49 to 1-51).

```
2-30            UNLINK      WATE1,GET01,P1
                            (GET01 is in line 1-64)

2-31            SAVEVALUE   OUT1-,P1

2-32            UNLINK      BORED,SIT2,1
                            (SIT2 is in line 3-6)
```

The signal will be conveyed by the order transaction which will be removed from user chain BORED and, through block SIT2 in the auxiliary module, sent to block GET18 in the fourth module (line 1-49).

```
2-33            TEST G      X$OUT1,0,CORB1
```

If there is no need for any further request cancellations, remove the transaction through CORB1 which is a TERMINATE block (not shown).

```
2-34    COR17   SCAN        LINEG,2,1,3,1,CORX1
```

If there is a need for further request cancellations, see if there is an order in group LINEG from C.Q.S. #1, i.e., an order that has yet to receive service. It should be noted that parameter #3, rather than #4 as in scanning WORK above, is used because the value of parameter #3 does not change every time a batch of servers arrives at the Depot to satisfy the remainder of an order, as of course parameter #4 does.

```
2-35            TEST LE     P1,X$OUT1,COR18
                            (COR18 is in line 2-42)

2-36            REMOVE      LINEG,1,,2,1
```

If the size of this order is smaller than the current (remaining) size of the reduction to the u.f. denominator, terminate that order transaction from membership in group LINEG.

2-37 UNLINK WAITD,COR19,1,2,1

Also remove that order transaction from user chain WAITD (which it entered through line **1-16**) and route it to block COR19 (line **2-48**).

2-38 BUFFER

2-39 SAVEVALUE OUT1-,P1

2-40 TEST G X$OUT1,0,CORC1

2-41 TRANSFER ,COR17
(COR17 is in line **2-34**)

If there is no need for more request cancellations, TERMINATE the transaction through block CORC1 (not shown); otherwise go back to see if there are more orders from C.Q.S. #1 waiting in line.

2-42 COR18 ASSIGN 1-,X$OUT1

2-43 ALTER LINEG,1,3,P1,2,1,EROR1

2-44 ALTER LINEG,1,4,P1,2,1,EROR1

If the remaining size of the u.f. denominator reduction is smaller than the current size of the order, modify the order accordingly, i.e., change parameters #3 and #4.

2-45 UNLINK WAIT1,GETN1,X$OUT1

2-46 UNLINK WATE1,GETO1,X$OUT1

Destroy the appropriate number of requests (GETN1 is in line **1-61** while GETO1 is in line **1-64**).

2-47 CORY1 TERMINATE

2-48 COR19 DEPART LINA,1

2-49 DEPART LINA1,1

2-50 DEPART LINO,1

2-51 DEPART LINO1,1

2-52 UNLINK WAIT1,GETN1,P4

2-53 UNLINK WATE1,GETO1,P4

2-54 TERMINATE

Block COR19 is entered by an order transaction from the fourth module, not a decision making transaction from the third. Consequently this is a segment that in a way "belongs" to the fourth module.

2-55 CORX1 GATE LR 12,EROR1

2-56 LOGIC S 12

2-57 UNLINK TWO1,GIV12,1

2-58 TERMINATE

Logic switch #12 is reset by a server transaction going through block GIV12 in the sixth module.

APPENDIX 3: THE AUXILIARY MODULE

The auxiliary module is a segment of the program where code which is common to all the members of the C.S.E is segregated. The blocks which are relevant to the third and fourth operating modules are the following:

3-1 IDLE1 PRIORITY 69

3-2 LINK WAITD,FIFO

3-3 IDLE2 SEIZE SERVE

3-4 TRANSFER FN,25

3-5 SIT1 LINK BORED,FIFO

3-6 SIT2 TRANSFER FN,26

The function selection mode (FN) of the TRANSFER block is used to direct the order transaction that is being UNLINKed back to the C.Q.S. to which it belongs. Discrete numerical value functions have to be used. For instance function #25 is defined as follows:

```
25      FUNCTION    P2,D8
1,GETP1/2,GETP2/3,GETP3/4,GETP4/......
8,GETP8/
```

where GETP1 returns the order transaction to C.Q.S. #1 (line **1-18**), GETP2 to C.Q.S. #2, GETP3 to C.Q.S. #3 etc.

APPENDIX 4: THE DATA GATHERING MODULE

The outputting of data onto the binary disk file takes place in a separate module, the first block of which is naturally a GENERATE block, i.e.,

GENERATE X$STAT,,,1,19,0

STAT contains either the value of zero, for the option of recording statistics, or a very large value for the option of not recording, as in test runs for instance.

ADVANCE 100000

This block simulates the duration of the transient period.

SPLIT 1,STAT1

TERMINATE 1

The termination count is of course linked to a sequence of START and RESET blocks.

STAT1 SAVEVALUE COUNT+,1

COUNT is the subrun counter.

ADVANCE X$BLOCT

BLOCT is the duration of the subrun. Next to follow are the HELP blocks which call FORTRAN subroutine GPDF2 so that they can pass to the output file:

a) the settings of the seven binary experimental factors that are represented by SAVEVALUES, i.e., either "high" or "low" values,
b) the identity of the simulation run and subrun, and
c) the statistics, six per HELP block, starting with customer waiting status statistics at the C.Q.S.s and the C.S.E. and ending with statistics that describe the process of the matching of requests with servers at the Depot.

During the first research phase, approximately 800 statistics were collected.

```
        SPLIT       1,STAT1
```

This block generates an offspring transaction to take care of the next subrun.

```
        TERMINATE   1
```

APPENDIX 5: MODELING THE LOOPING OF TRANSACTION FLOW

To model the generation of C.Q.S. customer transactions according to the Erlang-k distribution in the first operating module, the following blocks may be placed after the GENERATE ,,X$BASE1,1,35,4,F block:

```
USE10   SPLIT       1,USE16

        PRIORITY    34,BUFFER
```

USE16 is a block tag in the following segment of code placed at the end of the first module:

```
USE16   ASSIGN      3,0

        ASSIGN      4,XH$KAPA1
```

where KAPA1 is the type of the Erlang-k distribution and

```
USE17   ASSIGN      3+,V97,1
```

where V97 contains the ratio of the mean customer interarrival time over KAPA1.

```
        LOOP        4,USE17

        ADVANCE     *3

        TRANSFER    ,USE10
```