Proceedings of the 1988 Winter Simulation Conference
M. Abrams, P. Haigh, and J. Comfort (eds.)

Fox river locks SLAM simulation model

D. Brent Bandy
Department of Information Systems and Operations Management
The University of Wisconsin Oshkosh
College of Business Administration
Oshkosh, Wisconsin 54901

ABSTRACT

A computer simulation model of the locks system on the lower Fox River is described. The SLAM simulation language [Pritsker 1984] is used for the model, which includes boats entering and leaving the locks system and operation of the locks. The model simulates boats traveling upstream and downstream through the locks system, for both one-way trips and round trips. Operation of the locks is simulated through the use of resources and gates that control the movement of the boats entering and leaving the locks.

INTRODUCTION

The Fox River locks SLAM simulation model provides a representation of the boat traffic through the lock system on the lower Fox River between Menasha and DePere. The model is based on a SLAM network representation of the operation of the locks and the boat traffic through the locks.

The simulation model represents just one of many aspects of the Fox River system, which is one of the most important natural resources in the state of Wisconsin. Important considerations for the Fox River system include fish, waterfowl, and game management; environmental aspects; land development; historical considerations; industry; recreation; and water supply for many communities in the Fox Valley.

Many governmental agencies are involved in policy decisions concerning various aspects of the Fox River system. In recent years issues of concern include costs and benefits of continued operation of the locks system on the lower Fox River, pollution from the effluent into the Fox River system from paper companies and other sources, and invasion of the Fox River system by the sea lamprey eel. In fact the threat of the sea lamprey eel resulted in the closing of one of the locks (Rapide Croche) permanently in the spring of 1988, along with a proposal to build a boat lift at the Rapide Croche lock.

The Fox River locks SLAM simulation model is currently based on operation of the locks system prior to the closing of the Rapide Croche lock. It is planned to make modifications to the model in the near future to investigate operation of the boat lift at Rapide Croche. The simulation model and other models should be useful in helping to decide the future of the Fox River locks system. The data analysis and development of the simulation model, including assumptions and verification, and potential uses for the model, have been described previously [Bandy 1987].

PREVIOUS WORK

Previous simulation modeling was done in the early 1970's for the Fox River system. However, the focus of that modeling effort was on water quality in the system, rather than boat traffic. At that time the water quality was very poor, especially in the lower Fox River where fish kills were frequent. Two simulation models were developed for the quality of the water in the lower Fox, one for the De Pere-Green Bay area and the other for the upriver system [Paterson 1980]. The use of these models is for monitoring water quality for waste load allocation. After these models were implemented for control of effluent into the Fox River system, water quality improved tremendously. These models simulate dissolved oxygen in the river and are used daily. In fact, successful implementation of these models is one of the main reasons for increased use of the locks (and also for the threat of invasion of the Fox River system by the sea lamprey eel).

Other models have been used previously for river systems, but primarily for water resources planning and management [Cunningham and Amend 1986; Dalphin 1987]. The design approach used by the U.S. Army Corps of Engineers for river locks, in design of waterway navigation systems, involves extensive use of engineering models [McCartney 1986]. On the other hand, operations research models for locks systems are not very common, although use of a simulation model of the Welland Canal, which has eight locks, by the St. Lawrence Seaway Authority has been reported [McLeod 1983].

DESCRIPTION OF THE FOX RIVER SYSTEM AND THE FOX RIVER LOCKS

The Fox River system encompasses several rivers and lakes, including the Wolf River, Lake Poygan, Lake Winneconne, Lake Butte des Morts, Lake Winnebago, and both the upper and lower sections of the Fox River.

The Fox River locks system has been operating continuously since 1853, when the Menasha and De Pere locks were opened. The complete lock, dam and canal system on the lower Fox River was opened in 1856. In 1884 Congress empowered the U.S. Army Corps of Engineers to take over the system. In 1984 the Corps of Engineers released operation of the locks to the State of Wisconsin.

The operation of locks, which have their original gates and valves, is essentially the same as it has been for over 100 years. The locks system, prior to the closing of the Rapide Croche lock, permitted navigation on the lower Fox River between Lake Winnebago and Lake Michigan. The locks have been used in recent years by both recreational and commercial craft, with an average (prior to 1988) of about 12,000 lockages per year.

Table 1 shows some of the basic data for the locks system [U.S. Department of Commerce 1981]. There are 19 locks between Lake Winnebago and Lake Michigan, but two of these are guard locks at Little Chute and Kaukauna that involve no change in water elevation. In addition two other locks (Upper and Lower Combined locks) are adjacent, with a common gate. The lower Fox River is 39.0 miles long, with a total change in water elevation of 168.3 feet.

MODEL DEVELOPMENT

Development of the Fox River locks SLAM simulation model involved several steps. The first step was development the SLAM network representation for one of the locks (Menasha). This network representation includes the daily opening and closing of the locks, and the boats approaching, entering, and leaving the locks. Lockages can involve a single boat or several boats, depending on the boat traffic.

The second step was development of the FORTRAN subroutines and associated input data for all sixteen of the locks (the two guard locks are not included and Upper and Lower Combined locks are simulated as a single lock). The subroutines were then tested and "debugged" using the network representation for the Menasha lock. Many of the aspects of the boat traffic are contained in the FORTRAN subroutines, including boat sources and destinations, whether the boats are making one-way or round trips, number of passengers, travel times, boats traveling together, and "interarrival times" at the sources. The FORTRAN subroutines also handle the closing of all the interior locks on Tuesdays and Wednesdays.

The network representation of the Menasha lock was then expanded to that for all sixteen locks. The network representation for each of the other locks is essentially identical to that for the Menasha lock.

MODEL DESCRIPTION

The SLAM network representation of the lock system involves the use of resources, gates, entities, and various network nodes. The types of network nodes that are used are ALTER, ASSIGN, AWAIT, CLOSE, CREATE, FREE, GOON, OPEN, and TERMINATE. Activities are used to control the flow of entities through the network and for the times (in hours) required for entity movements.

A total of four resources and two gates are used to control the operation of each lock. The four resources are for boats entering and leaving the lock going upstream and for boats entering and leaving the lock going downstream. They are defined initially with capacities of 1 and then are altered at the start of the simulation to capacities of 0.

Table 1. Fox River Locks

Name of Lock (or Lake)	Miles above mouth of river at Green Bay	Miles to next lock going upriver	Miles to next lock going downriver	Upriver water elevation (in feet)	Downriver water elevation (in feet)	Lift in feet (at low water datum)
Lake Winnebago	39.0	-	2.0	745.1	745.1	-
Menasha Lock	37.0	-	5.1	745.1	735.4	9.7
Appleton Lock 1	31.9	5.1	0.3	735.4	725.7	9.7
Appleton Lock 2	31.6	0.3	0.3	725.7	716.1	9.6
Appleton Lock 3	31.3	0.3	0.6	716.1	706.3	9.8
Appleton Lock 4	30.7	0.6	3.4	706.3	698.7	7.6
Cedars Lock	27.3	3.4	0.7	698.7	688.9	9.8
Little Chute Guard Lock	26.6	0.7	0.2	688.9	688.9	0.0
Little Chute Lock 2	26.4	0.2	1.0	688.9	675.3	13.6
Upper Combined Lock	25.4	1.0	0.0	675.3	664.7	10.6
Lower Combined Lock	25.4	0.0	1.4	664.7	652.8	11.9
Kaukauna Guard Lock	24.0	1.4	0.4	652.8	652.8	0.0
Kaukauna Lock 1	23.6	0.4	0.2	652.8	642.5	10.3
Kaukauna Lock 2	23.4	0.2	0.1	642.5	632.9	9.6
Kaukauna Lock 3	23.3	0.1	0.2	632.9	622.7	10.2
Kaukauna Lock 4	23.1	0.2	0.3	622.7	612.5	10.2
Kaukauna Lock 5	22.8	0.3	3.6	612.5	602.2	10.3
Rapide Croche Lock	19.2	3.6	6.2	602.2	592.8	9.4
Little Kaukauna Lock	13.0	6.2	5.9	592.8	586.7	6.1
DePere Lock	7.1	5.9	-	586.7	576.8	9.9
Green Bay (Lake Michigan)	0.0	7.1	-	576.8	576.8	-

Minimum width of lock - 35.0 feet

Minimum length of lock - 144.0 feet

Minimum channel depth - Lake Winnebago to DePere - 6 feet
DePere to Green Bay - 18-22 feet

At any time during a simulation run, all four of the resources will have capacities of 0 or one will have a capacity of one and the other three will have capacities of 0. The two gates are for whether or not the lock is busy with one or more boats and for whether or not the lock is closed.

Each entity has five attributes. For entities that represent boats these attributes are: 1) the time the boat enters the lock system, enters the lock, or leaves the lock; 2) the first lock used upon entering the lock system (from 1 for Menasha lock to 16 for DePere); 3) the destination lock for the boat; 4) the number of passengers in the boat; and 5) the number of boats traveling together as a group.

For attribute 3 positive values are used for boats making one-way trips through the locks (from 1 for Menasha lock to 16 for DePere lock) and negative values are used for boats making round trips within the locks system (from -1 for Menasha lock to -16 for DePere lock). Thus for boats making one-way trips, attribute 3 really is the final destination (in terms of locks) for the boat. However, for boats making round trips, attribute 3 is the last lock used by the boat before it turns around and returns; thus the true "final destination" for the boat is the first lock used (attribute 2).

For other entities, including those that create the arrival of boats in the locks system and those that control operation of the locks, the attributes are used as needed for various purposes.

FORTRAN user functions are used for many aspects of the simulation, such as interarrival times for boats, the frequency and number of boats traveling together as groups, final destinations for the boats, number of passengers in the boats, travel times between locks, time spent at the "final destination" before returning to the lock for boats making round trips, and for collecting statistics for the boat traffic through the locks and for the lockages. The user functions allow boats to enter and leave the lock system at any location and are very much "data driven". For example the user functions allow boats to enter and leave the locks system between Appleton lock 2 and Appleton lock 3. In reality this is essentially impossible, and does not happen in the simulation runs due to the data input values for the user functions.

The network representation for the Menasha lock for boats traveling upstream is shown in Figures 1 through 5; the network representation for Menasha lock for boats traveling downstream is essentially identical to that for boats traveling upstream. Furthermore, the network representation for the other fifteen locks is essentially identical to that for the Menasha lock. Therefore Figures 1 through 5 depict only about 3% of the total network for the simulation.

Figure 1 shows the part of the network that creates boats that begin travel upstream with Menasha as the first lock. These boats are quite frequent since the Appleton Yacht Club is between Appleton lock 1 and the Menasha lock. These boats have only two possible values for final destination: 1, which means the boat makes a one-way trip through the Menasha lock and ends up somewhere upstream, such as Neenah, Menasha, Oshkosh, Fond du Lac, somewhere on the Wolf River, etc.; and -1, which means the boat travels through the Menasha lock upstream and subsequently returns through the same lock going downstream, probably after spending some time on Lake Winnebago. For other parts of the network there is a much wider range of possible values for the final destination. For example boats that begin travel downstream with Menasha as the first lock can have values for the final destination ranging from 1 to 16 for one-way trips and from -1 to -16 for round trips. However, the value for the final destination is calculated in one of the user functions and therefore it has no effect on the network representation for the Menasha lock shown in Figure 1.

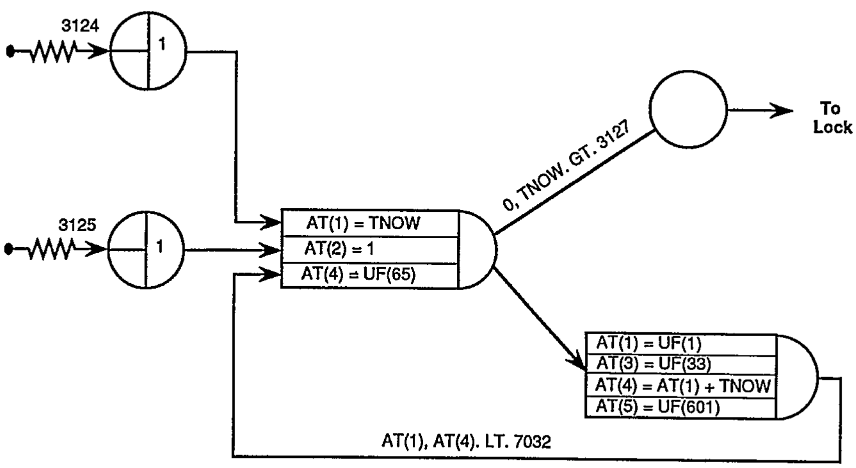

Figure 1. *Creation of boats starting at Menasha Lock going upstream*

As shown in Figure 1, two CREATE nodes are used at the beginning of the season (in May), 3124 and 3125 hours after the beginning of the year, to start creation of boats, and these entities are prevented from going to the lock. Subsequent entities are created by recycling through the ASSIGN nodes and do go to the Menasha lock representing boats travelling upstream. The two entities created initially are for handling (in the user functions) the two types of trips in the simulation model, one-way trips and round trips.

Four user functions are used in the network representation shown in Figure 1 to assign values to the attributes of the entities: UF(65) for the number of passengers on the boat; UF(1) for the interarrival times between boats; UF(33) for the ultimate destination for the boat; and UF(601) for the number of boats traveling together as a group. Of course the interarrival times between boats and the final destinations are impacted by whether the boat is travelling alone or in a group with other boats. For boats travelling alone and for the first boat in a group, the final destinations and interarrival times are calculated in the normal manner. For the second and subsequent boats in a group, the final destination is, of course, the same as that for the first boat in the group and the interarrival time is 0.001 hours. The season ends in October, 7032 hours after the beginning of the year.

Figure 2 shows the part of the network that represents boats approaching the Menasha lock going upstream, starting 0.10 hours before their arrival at the lock. The entities representing these boats can come from the parts of the SLAM network that represent: 1) the creation of boats starting at Menasha lock going upstream (Figure 1); 2) boats from Appleton lock 1 going upstream; and 3) boats from Menasha lock going downstream that are making round trips without going through Appleton lock 1.

What happens at the Menasha lock as the boat approaches depends on whether or not the lock is busy with other boats. If the lock is already busy (NNGAT(MNB).NE.0), it continues with its operation as the boat approaches, and the activity is numbered (1) for use in subsequent decisions concerning the operation of the lock. If the lock is not busy (NNGAT(MNB).EQ.0), a CLOSE node is used for gate MNB immediately to indicate that the lock is now busy and 0.07 hours later an ALTER node is used to alter the capacity of resource MNUE from 0 to 1. Then the boat arrives at the lock 0.03 hours later.

Figure 3 is for boats entering the Menasha lock going upstream. An AWAIT node is used for the boats as they arrive at the lock and wait, if necessary, for use of one unit of the MNUE resource, which has a capacity of either 0 or 1. When the MNUE resource is available, it takes 0.005 hours for the boat to enter the lock. If more than one boat is waiting, they enter one at a time until all are in the lock. User function UF(101) is used to collect statistics on the number of boats and passengers. Once each boat is in the lock, a FREE node is used to free one unit of resource MNUE immediately. Then if other entities are at the AWAIT node for resource MNUE (NNQ(1).GT.0) or another boat is approaching going upstream (NNACT(1).GT.0), the boat waits in the lock. Otherwise (NNQ(1).EQ.0.AND.NNACT(1).EQ.0) 0.10 hours after the boat enters the lock and frees one unit of resource MNUE, ALTER nodes are used to modify the capacity of resource MNUE from 1 to 0 and of MNUL from 0 to 1. Then user function UF(201) is used to collect statistics on lockages.

Figure 4 is the network representation for boats leaving the Menasha lock going upstream. An AWAIT node is used for the boats that are in the lock waiting for the upstream lock door to be opened (one unit of resource MNUL). When resource MNUL is available it will have a capacity of 1 and the boats will leave the lock one at a time. It takes 0.005 hours for each boat to leave the lock, and a FREE node is used to free the unit of capacity for MNUL. After all boats leave the lock (NNQ(2).EQ.0), an additional entity is produced to decide what to do next with the operation of the Menasha lock.

It is then necessary to decide what to do with each boat after it leaves the lock. For boats making one-way trips (AT(3).EQ.1), the Menasha lock is the last lock going upstream, so the entity is terminated. For boats that are making round trips (AT(3).EQ.-1), user function UF(301) is used to calculate how much time they spend upstream of the Menasha lock, and they then return to the Menasha lock going downstream. It should be noted that the network representations for boats leaving most of the locks have an additional option at this point.

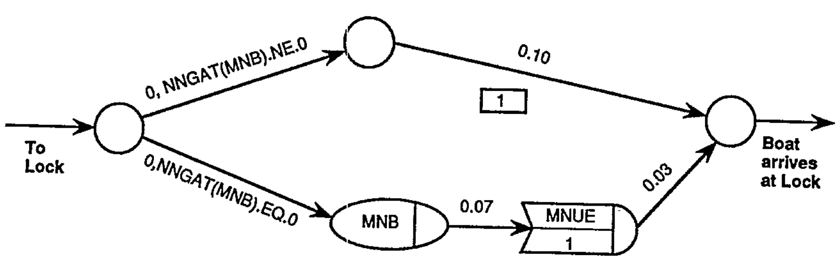

Figure 2. *Boats approaching Menasha Lock going upstream*

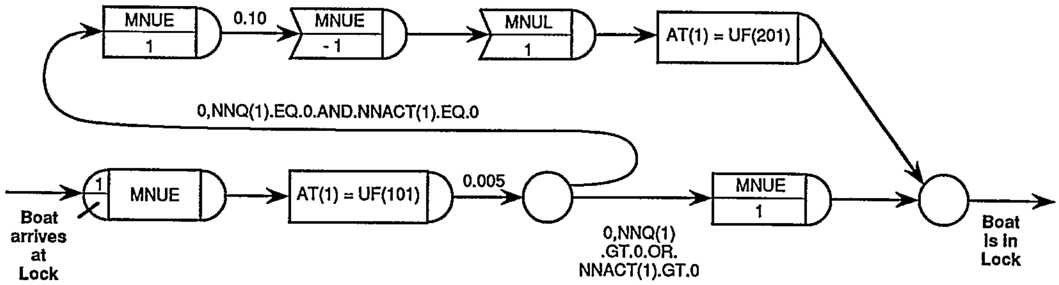

Figure 3. *Boats entering Menasha Lock going upstream*

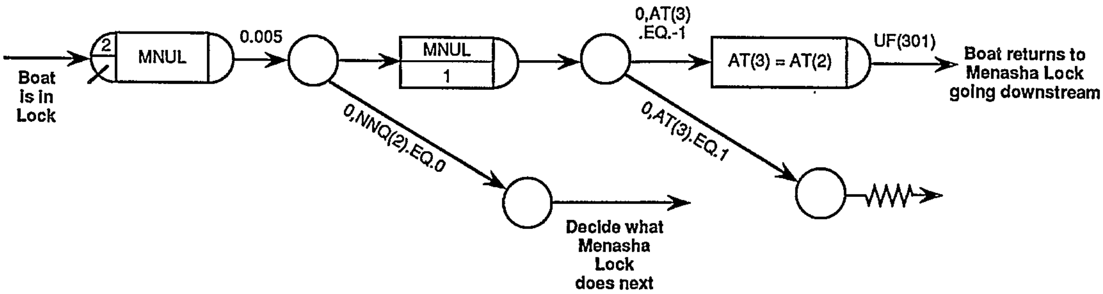

Figure 4. *Boats leaving Menasha Lock going upstream*

For example, for boats leaving the Menasha lock going downstream the three options are: 1) to terminate the entity (AT(3).EQ.1); 2) to have the boat turn around to return through the Menasha lock going upstream (AT(3).EQ.-1); and 3) to have the boat continue on downstream to Appleton lock 1 (any other value for AT(3)).

Figure 5 shows the network representation for deciding what to do next with the Menasha lock after the last boat of a lockage has left the lock going upstream. Immediately (0.01 hours) after the last boat leaves, an ALTER node is used to alter the capacity of resource MNUL from 1 to 0. Then, if a boat is approaching the lock going downstream (NNACT(2).GT.0) or waiting to enter the lock going downstream (NNQ(3).GT.0), resource MNDE's capacity is altered from 0 to 1 and the entity is terminated. Otherwise (NNQ(3).EQ.0.AND.NNACT(2).EQ.0) a check is made for boats traveling upstream. If a boat is waiting to enter the Menasha lock going upstream (NNQ(1).GT.0) or if a boat is approaching the lock going upstream (NNACT(1).GT.0), the capacity for resource MNUE is altered from 0 to 1 after a delay of 0.10 hours, and the entity is terminated. Otherwise (NNQ(1).EQ.0.AND.NNACT(1).EQ.0) an OPEN node is used to open gate MNB, to indicate that the Menasha lock is not busy, and the entity is terminated.

FURTHER WORK

Under normal circumstances there should be several uses for the simulation, including the investigation of the effect of: 1) operating hours for the locks; 2) volume of boat traffic in the lower Fox; and 3) development along the lower Fox. However, the threat of invasion of the Fox River system by the sea lamprey eel has resulted in the permanent closing of the Rapide Croche lock as part of a lamprey barrier. As a result it was decided to operate only three of the locks for the 1988 season, Menasha, Little Kaukauna, and DePere. In addition many decisions need to be made concerning future operation of the Fox River Locks system, including construction of a boat lift at Rapide Croche.

The simulation model currently represents the operation of the Fox River locks system prior to the 1988 season. Several modifications should be made to investigate the consequences of possible future actions. For example the model could be altered to analyze the impact on boat traffic of construction of a boat lift at Rapide Croche and reopening all of the other locks for the 1989 season.

In addition there are several areas where other models and further data analysis should be useful. There are many difficult, important decisions facing

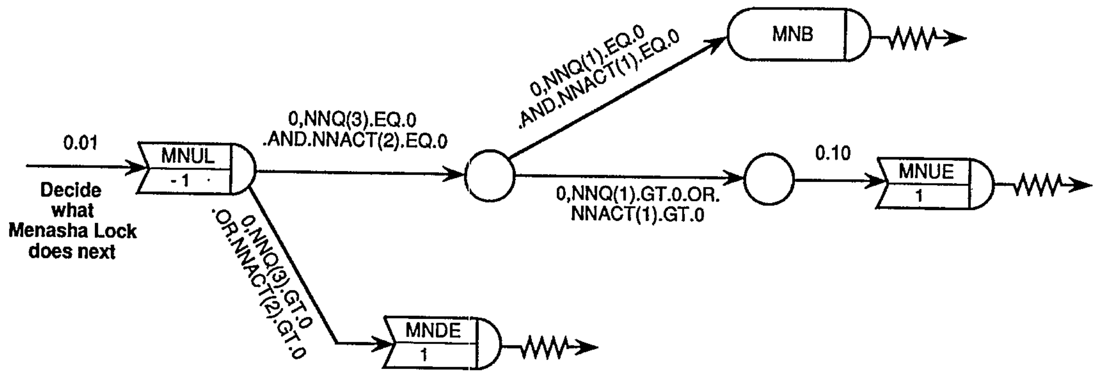

Figure 5. *Decide what to do next with Menasha Lock*

the Fox River system. Furthermore these decisions are complicated by the number and diversity of governmental units that are involved. The many, varied aspects of importance to the Fox River system mentioned earlier are another complication. It is hoped that the Fox River locks SLAM simulation model and other models can be useful in carrying out "what if" types of analysis to help with the difficult decisions that need to be made.

REFERENCES

Bandy, D.B.(1987). Simulation of Fox River Locks Boat Traffic. Presented at St. Louis ORSA/TIMS Joint National Meeting.

Cunningham, A.B. and Amend J.R.(1986). Interactive Simulation of Water Resource Systems. Journal of Water Resources Planning and Management 112, 326-338.

Dalphin, R.J.(1987). Markov-Weibull Model of Monthly Streamflow. Journal of Water Resources Planning and Management 113, 53-69.

McCartney, B.L.(1986). Inland Waterway Navigation Project Design. Journal of Waterway, Port, Coastal and Ocean Engineering 112, 645-657.

McLeod, J.B.(1983). Reducing a Bottleneck in the St. Lawrence Seaway. Successful Operational Research in Canada. Canadian Operational Research Society Publication.

Patterson, D.(1980). Water Quality Monitoring of the Lower Fox River for Waste Load Allocation Development. State of Wisconsin Department of Natural Resource Publication.

Pritsker, A.A.B.(1984). Introduction to Simulation and SLAM II. Second Edition. Halsted Press, New York.

U. S. Department of Commerce (1981). United States - Great Lakes, Wisconsin, Lake Winnebago and Lower Fox River. Sixth Edition. National Oceanic & Atmospheric Administration, National Ocean Survey, Recreational Chart No. 14916.

AUTHOR'S BIOGRAPHY

D. BRENT BANDY is a professor of Information Systems and Operations Management at the University of Wisconsin Oshkosh. Prior to coming to UW Oshkosh in 1984 he worked for sixteen years for Amoco as a systems analyst and operations research consultant. He received his BS (1964) in chemical engineering from the University of Illinois, his MS (1966) and PhD (1968) in chemical engineering from Northwestern University, and his MBA (1977) from the University of Chicago. He is a member of AIChE and TIMS. He has published extensively in the fields of computer simulation and optimization. His current research interests include the application of optimization, simulation, and decision support systems.

College of Business Administration
The University of Wisconsin Oshkosh
Oshkosh, Wisconsin 54901
(414) 424-3152