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PANAMA CANAL SIMULATION MODEL

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ABSTRACT

This paper presents the development process of the Panama Canal Simulation Model (PCSM). The PCSM was developed by The SABRE Group (SABRE) for the Panama Canal Commission (PCC) to be used in assessing pilot working conditions, and as a permanent tool in evaluating canal capacity under different operating conditions.

1 INTRODUCTION

SABRE is a world leader in the electronic distribution of travel-related products and services and is a leading provider of information technology solutions for the travel and transportation industry. The firm employs more than 8000 operations researchers/management science specialists, industrial engineers and computer science professionals. The company specializes in cost reduction, revenue enhancement, quality improvement and strategic decision evaluation for the transportation and related industries. SABRE has been managed as an independent division of AMR Corporation since 1993, when AMR combined the information technology units of American Airlines under the umbrella "The SABRE Group." In June 1996, SABRE became an independent legal entity.

SABRE has extensively applied simulation to transportation problems during the past 14 years. In late 1996 SABRE was contracted by the PCC to provide a report detailing the requirements for developing a simulation model of the major operational components of the Panama Canal. SABRE conducted a two-week site visit which included a thorough tour of the Panama Canal Lock Systems and a full transit of the Canal. SABRE team members also met with various PCC departments to establish the requirements and the objectives of the proposed simulation model. During these meetings model scope and capabilities were discussed and documented. Available data sources and the key variables pertinent to the simulation model were identified. The outcome of the trip was a report detailing the proposed model scope, modeling approach, detailed tasks necessary to build the model, and the plans for PCC personnel training.

The remainder of this paper presents a brief description of the Panama Canal and the issues the PCSM wishes to address. Section 2 briefly discusses the Panama Canal vessel scheduling process. Section 3 addresses the processes and the activities vessels go through while transiting the Panama Canal. Section 4 offers narratives on the development process and the components of the PCSM tool. Finally Section 5 presents a brief summary of our effort in completing this project.

1.1 Panama Canal Principal Components

The Panama Canal (Figure 1) is 50 miles long from deep water in the Atlantic to deep water in the Pacific. It was cut through one of the narrowest and lowest saddles of the long, mountainous Isthmus that joins the North and South American continents. The original elevation was about 300 feet above sea level where it crosses the Continental Divide.

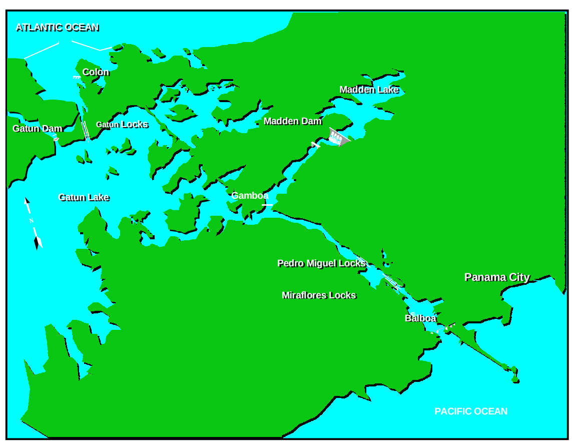

Figure 1: Panama Canal

The Canal runs from northwest to southeast with the Atlantic entrance being 33.5 miles north and 27 miles west of the Pacific entrance. The air distance between the two entrances is 43 miles. It requires about eight to ten hours for an average ship to transit the Canal. The Canal's principal physical features are (see Figure 2):

- Port of Cristobal on the Atlantic side
- Gatun Locks
- Gatun Lake
- Gaillard Cut
- Pedro Miguel Locks
- Miraflores Lake
- Miraflores Locks
- The port of Balboa on the Pacific side

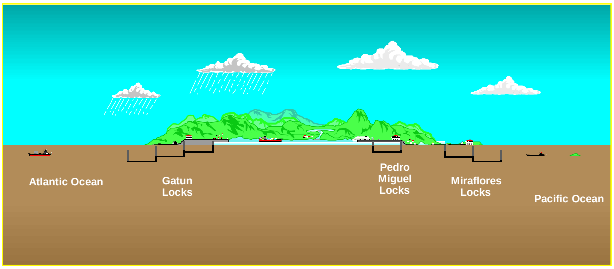

Figure 2: Panama Canal Profile

Gatun Locks: Gatun Locks are situated on the Atlantic side of the Panama Canal. A ship transiting southbound, must first go through the Gatun Locks. At Gatun Locks the southbound vessels are raised 85 feet via three separate chambers laid out in series. While the vessel is in a chamber, water between this chamber and the chamber next in the transit sequence is equalized. The gates separating the two chambers are opened and the vessel moves into the next chamber and eventually completes its transit of the lock system. The entire length of Gatun Locks is approximately 1.2 miles.

Note that each lock system is comprised of two adjacent and parallel lanes (east and west). Vessel lockages are scheduled through either of the two lanes.

Gatun Lake: After a southbound vessel clears the Gatun Locks, it enters the Gatun Lake. Gatun Lake, through which the ship travels for 23.5 miles from Gatun Locks to the north end of Gaillard Cut, covers an area of 163 square miles. Gatun Lake was formed by the construction of Gatun Dam across the Chagres River adjacent to Gatun Locks.

Gaillard Cut: The Gaillard Cut is a narrow channel carved through rocks and gravel for most of its 8.5 miles distance. The Gaillard Cut channel has a minimum width of about 500 feet. This permits unrestricted two-way traffic for about 50% of all ships using the Canal. Presently, the Cut is being widened to accommodate further unrestricted two-way traffic.

Pedro Miguel Locks: Southbound ships enter Pedro Miguel Locks (Figure 3) at the south end of the Gaillard Cut. Here a southbound ship is lowered 31 feet in one step to Miraflores Lake. The length of Pedro Miguel Locks is approximately 0.83 miles.

Miraflores Lake: Miraflores Lake is an artificial body of water one mile wide that separates the Pedro Miguel and the Miraflores Locks Systems. After clearing the Pedro Miguel Locks, southbound vessels transit through the Miraflores Lake on their way to the Miraflores Locks.

Miraflores Locks: Southbound vessels are lowered the remaining 54 feet in two steps to sea level at Miraflores Locks (Figure 3), which is slightly over one mile in length. Due to the extreme tidal variations on the Pacific side the miter gates at Miraflores Locks are the tallest of any in the system. The difference between the low tide and the high tide on the Pacific side can be as much as 21 feet (on the Atlantic side the maximum tidal variation is only about 3 feet). Upon clearing the Miraflores Locks, the vessel enters the Pacific Channel and transits for about 3.5 miles to the Pacific Ocean.

Note that northbound vessels go through a similar process but in the reverse order.

Figure 3: MF and PM Locks

1.2 Pilot Issues

The PCC employs around 240 pilots who are responsible for navigating vessels through the Canal. The working conditions of these pilots are regulated and monitored based on agreements between the PCC and the PC Pilots' Union, and other federal guidelines in effect at the Panama Canal.

The number of pilots required to transit a vessel is dependent on vessel dimensions and other vessel characteristics. In addition, the pilot scheduled workday can not exceed the recommended guidelines in place at the Panama Canal. Some vessel transits will take more than these set limits. Hence, for such vessel transits more than one set of pilots may have to be assigned. Therefore, any change in the operational policy will have an impact on the availability and the working conditions of these pilots. Furthermore, pilot retirement in the next couple of years is a significant factor affecting the required pilot force for effective operation of the Canal. The PCC had expressed the need to evaluate the impact of these changes and events on pilot working conditions and pilot availability. The PCSM has provided the PCC with a tool to analyze Canal operations under various pilot work force and pilot working condition scenarios.

1.3 Capacity Issues

The PCC also believes that by implementing some modifications and operational policy changes it may be able to increase the effective capacity of the Canal. The PCC desires to investigate the impact of implementing Canal improvement measures such as widening the Gaillard Cut and procurement of new equipment on Canal performance. In addition, the PCC feels that the impact of scheduled events such as lane outages, and increases in future traffic through the Panama Canal on the Canal capacity needs to be quantified.

The PCSM has provided the PCC with a functional easy-to-use tool that accurately emulates the Canal operations under these various operating scenarios. The PCSM tool allows the PCC to evaluate the impact of time delays encountered during transits and their associated rippling effects, the impact of other critical supporting resources on the operations of the Panama Canal, and provide a wide range of "what-if" analyses flexibility.

2 VESSEL SCHEDULING PROCESS

Through their agents in Panama, vessels transiting the Panama Canal inform the PCC of their Estimated Time of Arrival (ETA) and other information pertinent for transit. The PCC maintains a database of all the vessels that transit the Canal. The information provided by the agent is used to extract other vessel characteristic data from this database. A vessel record is subsequently added to the list of vessels to be scheduled for transit.

The list of vessels scheduled to transit is manually prepared on a daily basis at Marine Traffic Control (MTC). The Transit Scheduler studies the list of vessels that have declared their readiness to transit during a given day. Based on established procedures, he sequences and schedules as many vessels during the day as possible.

After the vessel schedule has been developed, this list is passed on to the Pilot Job Software to create the required number of pilot jobs for the day. A "pilot job" is defined as one contiguous activity in which a pilot engages. Each time a pilot job is created a pilot is assigned to that pilot job. A pilot may perform more than one pilot job during any given day. After the jobs are created, a Transit Operations Officer (TOO) using the list of available pilots for the day matches or "assigns" pilots to these jobs with specified Duty Times. The daily list of available pilots is developed through the Pilot Rotation program maintained by the Pilot's Division of the PCC. This is a Clipper based computer program that tracks and monitors the available pilot work force and updates their records as these pilots complete assignments, return from vacations, sick leave, etc.

3 VESSEL TRANSITING PROCESS

Pilots are scheduled to report for duty at their assigned duty times to one of two Reporting Stations. One station is utilized by the pilots residing on the Pacific side, and the other is utilized by the pilots residing on the Atlantic side.

After a pilot arrives at his Reporting Station, he is transported to his assigned vessel by a watercraft. Once the vessel is determined to be seaworthy, the pilot will get the vessel "Underway" to arrive at the vessel's scheduled arrival time to the first set of locks.

The following narrative describes the events that a northbound vessel will go through in chronological order. The southbound vessels go through similar events but in the reverse order. To better understand the subject discussed in this paper, we present the following definitions :

- Linehandlers - PCC employees that board vessels to assist the vessel in the Locks by tying and untying locomotive wires, tugboat lines, and vessel hawsers. They also assist vessels during tie up operations at Paraiso and Miraflores tie-up stations.
- Locomotives – Are equipment used in the Locks to maintain proper vessel positioning in the center of the Locks' chambers and prevent the vessels from colliding with the chamber walls.
- Tugboats – Are watercraft used to safely guide and properly align vessels into the Locks, at tie-up stations, moorings, and through the Gaillard Cut.
- Miter gates – Are components of the lock systems separating two adjacent chambers. These gates are closed to allow water equalization between adjacent chambers and are opened after water equalization to allow vessel movements between adjacent chambers.
- Launches - Are watercrafts that transport pilots, linehandlers, and other PCC officials to and from vessels.
- Culverts – A culvert is a pipe 18 feet in diameter that allows water to be filled into or spilled out of the Locks chambers.

As a northbound vessel enters the Pacific Channel and crosses under the Bridge of the Americas, linehandlers and additional pilots are transported to the vessel. After the linehandlers board, and before the vessel arrives to the Miraflores Locks, the necessary number of tugboat(s) approach the vessel and the linehandlers secure tugboat lines to the vessel. As soon as the vessel arrives at the Locks, the linehandlers secure locomotive wires to the vessel from both sides. After the tie-up process, the locomotives guide the vessel into the lower chamber.

After the vessel is completely in the lower chamber of the Miraflores Locks, the lower miter gates are closed behind the vessel and the water in the lower and upper chambers is equalized. After water equalization, the center miter gates are opened and the vessel is guided into the upper chamber. Once the vessel is completely in the upper chamber, the center miter gates are closed and the upper chamber is equalized with the Miraflores Lake which is normally about 54 feet above sea level.

After water equalization is accomplished, the upper miter gates are opened and the vessel is guided out of the chamber and into the Miraflores Lake. As the vessel departs the Miraflores Locks, the linehandlers will release the locomotive wires at the direction of the pilot on board, and the vessel transits through the Miraflores Lake towards the Pedro Miguel Locks.

Assisted by tugboat(s) the vessel enters into the Pedro Miguel Locks. The same process is repeated at the Pedro Miguel Locks as at the Miraflores Locks and the vessel enters the Gaillard Cut. Pedro Miguel Locks contains only one chamber. The elevation at the Gaillard Cut is an additional 31 feet above the Miraflores lake, or 85 feet above sea level. The linehandlers disembark the vessel at Paraiso Landing. Refer to Figure 1 and 2 for the locations referenced in this paper. Assisted by tugboat(s), if needed, the vessel transits the Cut. At Gamboa the tugboat(s) are relieved and may return to Pedro Miguel or stay at Gamboa and the vessel continues toward the Gatun Locks.

Based on its scheduled arrival time at Gatun Locks, the vessel may temporarily anchor at Gatun Lake Anchorage or may approach the Gatun Locks. As the vessel approaches the Gatun Locks, a second linehandler crew boards the vessel. Before the vessel enters the locks, tugboat(s) assist to safely guide and properly align the vessel into the Gatun Locks. The same events are repeated at Gatun Locks as at the Miraflores Locks. There are three chambers at Gatun Locks laid out in series. When the vessel clears the locks, the linehandlers depart. The vessel enters the Atlantic Channel on its way to the Atlantic Ocean where its transit of the Panama Canal is officially complete. All pilots except one disembark the vessel after the vessel clears the Gatun Locks. The last pilot on board disembarks the vessel upon the completion of the vessel transit.

At Miraflores and Gatun Locks Systems, vessels may go through one of two types of lockages, regular, or relay. At Pedro Miguel only regular lockage is performed.

A vessel is said to be engaged in a regular lockage if it is assisted throughout its lockage by only one set of locomotives. In contrast, during a relay lockage, two sets of locomotives share the responsibility of guiding the vessel during its lockage. One set accompanies the vessel from its arrival to the middle of the Locks, and the second set accompanies the vessel during the rest of its lockage. In the meantime, the first set of locomotives returns to assist another incoming vessel.

4 DEVELOPMENT OVERVIEW

During the two week site visit of the Panama Canal and meetings held with the PCC management and operational personnel, the main objectives of the PCSM tool were set to be the following:

1. The model should allow the PCC to evaluate the impact of different pilot working scenarios on pilot availability and pilot working conditions.
2. The model should allow the PCC to evaluate the impact of different operating conditions on Canal capacity or throughput.

Hence the development process was divided into two phases. Phase II.1 would encompass modeling aspects that would satisfy the first objective, while Phase II.2 would include the modeling requirements to address Canal capacity and throughput issues. Phase I referred to the two week on-site effort and the ensuing report. In the next section we discuss the effort expended for Phase II.1 and Phase II.2 model development.

4.1 Phase II.1 Model Development

The list of scenarios submitted by the PCC revealed that the model did not need to be run in the stochastic mode to evaluate the Pilot Working Condition Scenarios (PWCS). This conclusion was reached based on the realization that these scenarios would not impact the actual pilot rotations and the components that introduced stochastic elements in the model did not have to be included for Phase II.1. Therefore, it was possible to run the model in the “Replay Mode”, where the model would use historical vessel schedules, generate pilot rotation list for the day, make assignment, and replicate vessel transits based on historical data. Figure 4 presents the relational diagram between the different components and the I/O of the Replay Mode model.

The following modules were needed for the proper operation of the Replay Mode model.

- The model had to be capable of generating the daily list of available or work-eligible pilots and updating the pilot rotation master file – Pilot Rotation (PR) module.

- The model had to be capable of generating jobs and assigning pilots to these jobs – Pilot Assignment (PA) module.
- The model had to include an Engine to replicate the historical vessel transits.
- The model had to include an Output Processor.

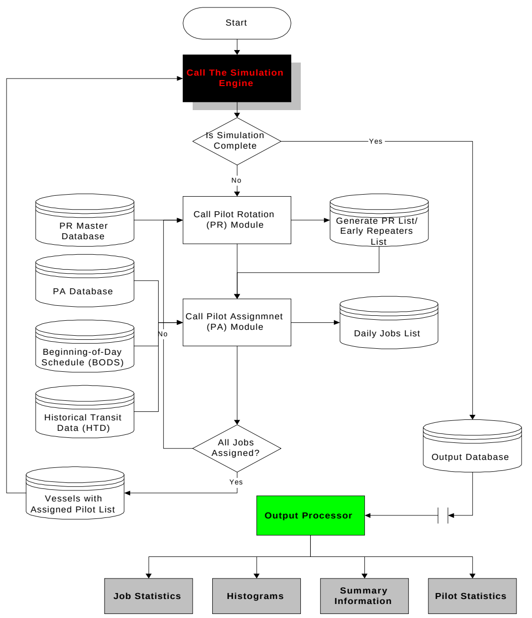

Figure 4: Relational Diagram of the Replay Mode Model Components

4.1.1 Pilot Rotation (PR)

The PR program keeps track of all pilots and their assignment or workload history including latest assignment, vacation, sick leave, and other types of events which impact their availability or their assignment eligibility. At the beginning of each simulated day, the PR module is executed to produce the list of pilots available for duty on that day.

During high traffic days, the list of pilots generated through the PR module may not be sufficient. On these occasions, by invoking other pilot rotation provisions that allow for greater pilot availability, the PR module is executed. The result of the second execution of the PR module is a secondary list of available pilots called the "early repeaters".

Since the PCC had previously developed a PR component, the PCC requested SABRE to translate the existing PR module from its native Clipper and DB2 to C++ and ORACLE database to be used in the PCSM tool.

After the translation process was complete, the model was validated based on the performance of the existing PR module. Initially SABRE's PR module was tested by generating pilot rotations for three randomly selected days and comparing them to the actual rotations for those days. After the appropriate modifications and adjustments were made, the model was tested for consecutive days until there were no discrepancies between the outputs of the two programs for at least three consecutive days. The validation was stopped when there was 100% match between the pilot rotations from SABRE's PR module and PCC's existing Pilot Rotation software for three consecutive days.

4.1.2 Pilot Assignment (PA)

The PA module consists of two components; job creation and pilot assignment. The job creation software had been developed by the PCC and was translated from its native Clipper and DB2 into C++ and ORACLE database. Currently pilot assignments are manually performed based on procedures in place at the Panama Canal. Therefore, this piece needed to be developed. After interviewing several TOOs, assignment procedures were documented and reviewed. When all individuals involved with the process were satisfied with the accuracy of the documented rules and procedures, SABRE developed a pilot assignment algorithm based on the documented rules. This algorithm was subsequently encoded into a pilot assignment component in C++ and ORACLE database. This component was then integrated with the job creation piece into the PA module.

Finally the PR and PA were integrated together to operate as one module. The PA would use the vessel schedule and the output from the PR module to develop the daily assignments.

At the beginning of each simulated day the Vessel Sequencing and Scheduling or the Man-In-Loop (VSS/MIL described later in this section) develops the daily vessel list by sequencing vessels and assigning to these vessels their scheduled arrival times at the Locks. This prepared list is passed onto the PA module. Using the vessel list prepared by the VSS/MIL, the PA module generates the required number of jobs to satisfy the daily vessel schedule. The outputs from the job creation piece and the PR module are read by the pilot assignment piece of the PA module which will attempt to assign pilots to all the vessels in the schedule. If there aren't enough pilots in the list to satisfy the schedule, the PR is triggered once again and the early repeaters list is generated and the process of assignment is repeated. The outcome of this process is the list of "Vessels with Assigned Pilots".

The validation procedure for the PA module was divided into two distinct activities: Job Creation and Pilot Assignment. During the validation process of the Job Creation component, Jobs were created for each day in the validation period. Next, the jobs created by the SABRE's PA module were compared to the jobs created by the

PCC's Job Creation software on a day to day basis for the same period. Finally, the jobs were manually checked to make sure that no job creation rule was violated. The validation was stopped when there was 100% match between jobs created by the SABRE's Job Creation component and jobs created by the PCC's existing Job Creation software.

The same period was also used to validate the Pilot Assignment piece. Initially the assignments were made for each of the days in the validation period using the SABRE's PA module. Next the PCC's experts manually prepared assignments for the same period. The validation was stopped when there was 100% match between the manual assignments made by the PCC experts and the assignments made by the SABRE's PA module.

Once the list of Vessels with Assigned Pilots is prepared, this list is passed on to the simulation engine. The simulation engine reads the list of Vessels with Assigned Pilots as its input and executes the daily schedule.

4.1.3 Replay Mode Model

The outcome of the PR & PA module is the vessel schedule file with pilot assignments. This schedule contains information on vessels and pilots who are assigned to these vessels.

The PCC had decided to run each scenario for three different intervals representing low, medium, and high demand periods. Each period consisted of 28 consecutive days. After generating these schedules, the Replay Mode model reads and simulates these schedules. After pilots working day is over, the pilots are relieved, their status updated in the pilot rotation master file, and their assignment information is recorded in database tables. This information is used by the Output Processor to generate reports, graphs, and charts requested by the PCC.

4.1.4 Output Processor

Historically, the PCC would generate some graphs, charts, and reports after performing manual simulations. It was decided to include in PWCS the capability of automatically generating an expanded list of graphs, charts, and reports through an Output Processor developed in Visual Basic. The output processor generates the standard graphs, charts, and reports in four different categories as indicated in Figure 4.

4.2 Phase II.2 Model Development

The following components were added to the PCSM during the development of Phase II.2:

- Vessel Demand Forecasting (VDF) Module
- Vessel Sequencing and Scheduling/Man-In-Loop (VSS/MIL) Module
- Statistical Elements Module
- The Stochastic Simulation Engine
- Executive Shell

4.2.1 Vessel Demand Forecasting (VDF)

The function of the VDF module is to generate the daily vessel demand when required. Therefore, a VDF module was designed as part of the overall system. The VDF module generates a list of vessels and their ready times (the time vessels indicate their readiness for transit) based on historical or theoretical distributions in the format used by the VSS/MIL module.

The VDF module will determine the number of vessels per day, the type of each vessel, the physical dimensions of each vessel expressed in beam and draft, Precautionary Designate (PD) status, vessel ready time, and direction of transit. The demand will then serve as input to the VSS/MIL module to create the day's vessel schedule.

4.2.2 Vessel Sequencing and Scheduling / Man-In-Loop (VSS/MIL)

Once the daily vessel arrivals are created through the VDF, these vessels will have to be sequenced and scheduled for transit. As part of its ongoing Enhanced Vessel Traffic Management System (EVTMS), the PCC had planned to develop a Vessel Sequencing and Scheduling (VSS) module. Consequently, it was decided to eventually integrate this module into the PCSM when ready.

While the VSS module was under development, it was necessary to include a manual scheduling and sequencing component or Man-In-Loop (MIL). The MIL module allows the user to manually sequence and schedule the daily vessel demand and to pass on this information directly to PR & PA module for pilot assignment.

The MIL is also triggered whenever actual events deviate from their scheduled times by more than pre-specified tolerance levels. In these situations the MIL will study the current conditions of the Canal and may decide to reschedule certain future events. After performing the necessary changes to the schedule the MIL will return the control to the Simulation Engine and the simulation continues with the updated information until the MIL is called again.

4.2.3 Statistical Elements Module

The purpose of the Statistical Elements module is to maintain, modify, and allow sampling from the statistical distributions representing the activities encountered during vessel transits and lockages. Although the PCC maintains a great deal of data on vessels, there were few data available on transit times and delays. Additionally, the PCC believed the available data was not collected based on acceptable statistical protocol, hence could not be relied upon. Therefore, a data collection and analysis effort was undertaken that lasted for about six months.

Data Collection: A number of students from a local university in Panama were hired to perform the data collection effort. SABRE designed and developed data collection forms and procedures for over 100 activities that take place during a transit. The forms and procedures were tested and modified based on field observations. The PCC engineers and management analysts supervised the data collection effort.

Data Analysis: After the data collection process was completed, SABRE developed data analysis guidelines to be used during data analysis. SABRE also provided on-site guidance and supervision during the data analysis process. Data analysis was performed using the SAS' JMP Data Analysis Tool. The objective of this exercise was to identify distinct subsets within the collected data so that these subsets could be separated into independent samples for distribution development. Finally, statistical distributions were fitted to these subsets. ARENA's Input Processor was used for this activity.

For each subset, an initial number of intervals (usually selected by ARENA's Input Processor) was used and all the appropriate distributions provided within ARENA were tested. Next the number of intervals was altered and the distribution fitting effort was repeated until the best possible fit was reached. The criteria for selecting and comparing between different distributions were based on the results of the following tests and observations:

1) The Goodness-of-Fit test
2) The Kolmogorov-Smirnov test
3) The Error Root Mean Square
4) Visual inspection of the histogram and the theoretical distribution

Empirical distributions were developed whenever the standard statistical distributions did not provide an acceptable fit. The result of this exercise was over 350 statistical distributions that were incorporated into the Statistical Elements Module.

4.2.4 The Simulation Engine

The purpose of the Stochastic Simulation Engine was to simulate vessel transits through the Canal and other critical supporting activities impacting vessel transits.

The simulation component is developed in SIMAN and contains the following operational elements necessary to process vessels through the Panama Canal waters:

Vessel Transit Module: The portion of the model that portrays the vessel movements outside of the locks is called the Vessel Transit module. The Vessel Transit module initializes the lock system status and state variables, reads input data, creates vessel and pilot entities, simulates vessel transit through the Canal, and sets and resets their speed at every station visited during transit. It also checks and maintains transit restrictions, calls different PCSM components such as the VSS/MIL module and PR&PA module. Additionally, the Vessel Transit module begins and terminates pilots duty at the correct locations and time, and passes on data on pilot assignment completion to the PR module.

Locks Operation Module: The Locks Operation module represents the detailed activities that take place within the locks. The Locks module models the water equalization in all the chambers, miter gate operations, all the delays vessels encounter during their transit of the locks and the linehandlers and the locomotive wire tie-up and release times. Additionally, the Locks Operation module maintains the correct timings and relationships between all the activities within the Locks by performing the necessary checks and balances for the proper operations of the Locks. The vessel movements within the locks are also modeled within the Locks Operations module.

Culvert Assignment Module: There are three parallel culverts at each of the three Locks; the east culvert, the center culvert, and the west culvert. The east culvert is exclusively dedicated to the east lane and the west culvert is exclusively dedicated to the west lane. However, the center culvert is switched back and forth between the two lanes depending on availability and lockage type priority (relay lockages have priority over regular lockages) and other procedures and restrictions. The Culvert Assignment module was developed to maximize the utilization of the center culvert.

Tugboats Operation Module: The Tugboats module was developed to portray current and future tugboat fleet operation and the impact of their availability to assist vessels on Canal throughput. There are six tugboat shore facilities throughout the Canal, four on the Pacific side and two on the Atlantic side. Each facility serves a particular area called its area of responsibility. The initial number of tugboats at each facility is set, however, depending on the time of day and tugboat requirements in other parts of the Canal, these tugboats move between areas of responsibilities. Tugboats move between adjacent areas of responsibility by locking with transiting vessels based on operational considerations and restrictions.

Linehandler and Launch Requirements: Although these resources are important to the operations of the Canal, it was decided not to model them in detail at this time. Instead, demands for these resources would be tracked and monitored throughout the simulated day to determine their requirements.

Locomotives Operation Module: The Locomotives module models the detailed activities that the locomotives engage in while assisting vessels in the locks. Up to eight locomotives fasten up to 16 wires to a vessel in order to hold the vessel in the center of the Locks chambers. As the vessel nears the Locks center wall, the required number of locomotives will be waiting to receive the vessel. One by one, at the direction of the pilot(s) on board, the locomotive lines are secured and fastened to the vessel by the linehandlers. At the request of pilot(s) on board, the locomotive operators tighten or loosen the wires under their control to maintain the vessel in the center of the chamber and to guide the vessel through the Locks. During relay lockages, in the middle of the Locks, the vessel is tied up to the side and center walls. These locomotives are released and return to the beginning of the Locks to assist the next incoming vessel. A second locomotive team assumes the responsibility of guiding this vessel through the rest of its lockage. The exchange occurs in the middle chamber at Gatun Locks and in the upper chamber at the Miraflores Locks. The vessel is untied from the side and center walls and transit continues.

The Tide Module: The high and low tides on the Pacific side of the Canal vary by as much as 21 feet. These tidal variations have significant impact on the operations of the Miraflores Locks. The Tide Module accounts for the existing tide and adjusts the amount of water that needs to be spilled, filled, by-passed, and the water equalization level at the Miraflores Locks. Tidal information is read on an hourly basis. As vessels arrive at the Miraflores Locks, the necessary adjustments are made to the water level equalization, by-pass level, and filling or spilling amount.

The Fog Module: Usually between April and December, the Pedro Miguel Locks and the Gaillard Cut may be covered in fog. Fog usually occurs between midnight and 7:00am the next morning. When the Cut is under fog, vessel transits is curtailed in the Cut. The Fog Module samples from the monthly fog occurance and fog duration distributions. In the case there is fog in the Cut, the Fog module sets the appropriate variable and prevents vessel movements in the Cut.

The Executive Shell: The framework of the PCSM tool is an interface that aids the user in running the simulation, maintaining the previously run scenarios, and presenting the simulation output. These tasks are accomplished through the Run Manager, the Scenario Manager, and the Output Processor components of the Executive Shell.

Through the Run Manager the user is able to select a scenario (a scenario is referred to a complete set of directives needed for the successful execution of the PCSM), choose the mode in which to run the scenario (batch run or animation) and run the model.

The scenario manager provides the user with the ability to develop new scenarios, to modify existing scenarios, and to maintain previously defined scenarios for future use.

When the simulation execution is complete, the output data is stored in a database for further use and presentation through the Output Processor. Figure 5 presents a relational diagram for the completed PCSM tool.

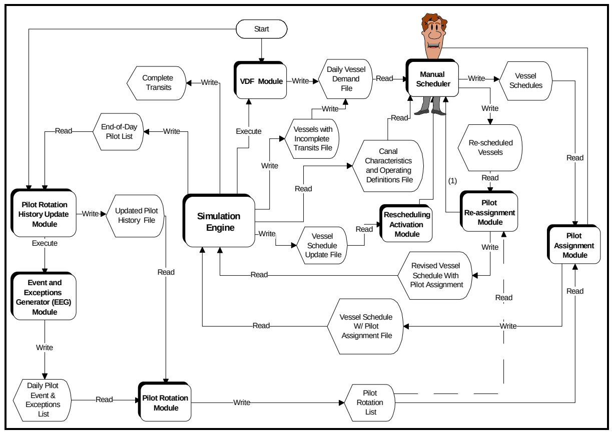

Figure 5: Relational Diagram of the PCSM Tool

5 SUMMARY

The work presented in this paper suggests that useful and important simulation projects can in fact incorporate more than just simulation analysis. In over 10 years of experience in simulation, this is probably one of the most challenging projects in which we have been involved, both in terms of complexity and magnitude. Through this project, we have demonstrated that it is possible to successfully design, develop, and integrate modeling components in different native languages. We hope that our approach and experience can be viewed as a stepping stone in propelling simulation modeling and analysis beyond its present day boundaries.

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