STROBOSCOPE Solution to ARGESIM Benchmark C8 'Canal and Lock System'

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Abstract. A STROBOSCOPE simulation model for a canal and lock system illustrates how to model barge traffic logic to estimate the average pooled barge transit time. Investigated are the impact of traffic density and of the number of barges allowed to pass in each cycle. Antithetic sampling and common random numbers illustrate variance reduction techniques.

Introduction

A canal and lock system is described in ARGESIM Comparison C8 [1]. A model of this system was developed in STROBOSCOPE [2], a general-purpose discrete event simulation system, as an example of modelling complex logic. A PROOF Animation model provided verification. Parametric analysis involving the traffic density of arriving barges and the controls for switching traffic direction provides additional insights into system behaviour.

1 Canal and Lock System

A canal and lock system consists of the west canal, the east canal, and the lock, as shown in Figure 1. Water level in the west canal is higher than in the east canal. The times between barge arrivals at the east and west canal entrances are exponential with mean β. The impact of traffic density as measured by β on the average barge transit time is investigated through sensitivity analysis.

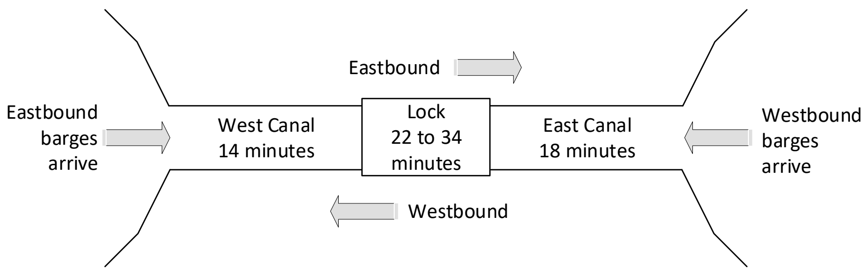

Figure 1: Canal and Lock System Layout.

A barge can go through the west canal in 14 minutes and the east canal in 18 minutes. The time to pass through the lock itself can be anywhere from 22 to 34 minutes. Thus, the total transit time can be from 54 to 66 minutes.

Safety considerations permit only one direction of traffic and only one barge in each canal at the same time. The direction of traffic alternates in cycles between eastbound and westbound barges. Within each cycle, barges enter the system on a first-come, first-served basis.

1.1 Traffic direction

The direction of barge traffic changes in cycles that can be full or partial. A full cycle ends when the number of eastbound barges reaches the limit *Emx* or the limit *Wmx* for westbound barges.

A partial cycle ends when there are not enough barges traveling in the same direction to reach *Emx* or *Wmx*, but there are barges waiting to cross in the opposite direction. In such cases, the following traffic rules apply:

1. If at the end of a cycle, no barges are waiting to cross in either direction, the system remains idle until a barge arrives and starts a new cycle in its direction.
2. If at the end of a full cycle, there are barges queued in the opposite direction, then a new cycle is initiated in the other direction.

3. If no barges are queued in the opposite direction, but there are barges waiting to cross in the current direction, then a new cycle is initiated in the current direction. The barge count for the new cycle is reset to zero and can reach the corresponding limit *Emx* or *Wmx*.

1.2 Lock operations and times

The lock can lower one eastbound barge and raise one westbound barge at a time. Lock operations and times during an eastbound cycle are as follows (lock operations and times for a westbound cycle are the same).

- **Case A**: Lock passage time = 34 min (= maximum).
  Setting: An eastbound barge has just exited the lock into the east canal and another eastbound barge is already waiting at the lock entrance.
  1. Water in lock raised to west canal level, 12 min.
  2. Waiting barge enters lock, 5 min.
  3. Barge lowered to east canal level, 12 min.
  4. Barge exits into the east canal, 5 min.

  Total time = 12+5+12+5 = 34 min.

- **Case B**: Lock passage time = 22 min (= minimum).
  Setting: The next eastbound barge arrives at the lock 12 or more minutes after the previous barge has exited. Only steps 2–4 are needed.
  Total time = 5+12+5 = 22 min.

- **Case C**: Lock passage time = from 22 to 34 min.
  Setting: The next eastbound barge arrives *t* minutes after the lock has started refilling ($0 < t < 12$ min).
  Total time = (12-*t*) min (wait time to refill lock)
  + 22 min (steps 2–4) = (34-*t*) min.

2 Simulation Model

The network for the STROBOSCOPE simulation model of the canal and lock system is shown in Figure 2. The blue nodes (queues and activities) model the movement of eastbound barges. The green nodes model the symmetrical movement of westbound barges.

Three types of resources are defined: *Sequence, Lock*, and *Barge*. Queues *EBSeq*, *WBSeq*, *Set2EBSeq*, and *Set2WBSeq* are initialized with 1 unit of the generic resource *Sequence* to start loops that create serial instances of the succeeding combi activities. Queue *LockWithRsdWL* is initialized with 1 unit of the compound type *LockSystem* to start the loop of activities *LowerWL* and *RaiseWL* that change the lock water level when no barge is in the lock.

Barges are modelled as characterized resources of type *Barge* with two subtypes, *EBBarge* and *WBBarge*. Barges are generated dynamically while the simulation runs. The current direction of travel is stored in savevalue *Direction*, whose values can be *EB* or *WB*.

The time between eastbound arrivals is modelled by combi activity *EBBargesArrive* whose duration is exponential with mean β. When each instance of *EBBargesArrive* ends, a new arriving *EBBarge* is created dynamically by a *GENERATE* statement. The arriving *EBBarge* then enters queue *EBBWait2Enter*, where it waits until the semaphore of activity *EBBEnterSystem* allows it to start.

```
SEMAPHORE EBBEnterSystem 'Direction==EB
  & EBBCount<Emx & !EBBTraverseWC.CurInst
  & !EBWt2EntrLock.CurCount';
BEFOREEND EBBEnterSystem ASSIGN
        EBBCount EBBCount+1;
```

The above semaphore allows *EBBEnterSystem* to start and draw *EBBarge* out of queue *EBBWait2Enter* when

(a) savevalue *Direction* equals *EB*,
(b) the count of eastbound barges allowed to cross in the current cycle is less than *Emx*,
(c) there are no current instances of *EBBTraverseWC* (i.e., the west canal does not contain another eastbound barge), and
(d) there are no barges in queue *EBWt2EntrLock* waiting to enter the lock.

Activity *EBBEnterSystem* has a duration of zero. Before it ends it increments by one the count of eastbound barges *EBBCount* that have crossed in the current cycle. It then releases *EBBarge* to activity *EBBTraverseWC*, where it spends 14 minutes to traverse the west canal. *EBBarge* then enters queue *EBWt2EntrLock* where it waits for the water in the lock to be fully raised (i.e., for queue *LockWithRsdWL* not to be empty) so it can enter the lock. Activity *EBBEnterLock* can then start, draw *EBBarge* and *LockSystem* from the preceding queues, and keep them for the 5 minutes to enter the lock. At its end, both resources are released to activity *LowerWaterLevel* where they remain for 12 minutes for the lock to lower the barge to the east canal. Activity *EBBExitLock* is the 5 minutes it takes for the barge to exit the lock.

At that point, *LockSystem* is released to queue *LockWithLwdWL* and *EBBarge* is released to an instance of activity *EBBTraverseEC* for the 18 minutes needed to traverse the east canal. At the end of *EBBTraverseEC*, the resource *EBBarge* is destroyed, and statistics are kept about its life span, which equals its total transit time.

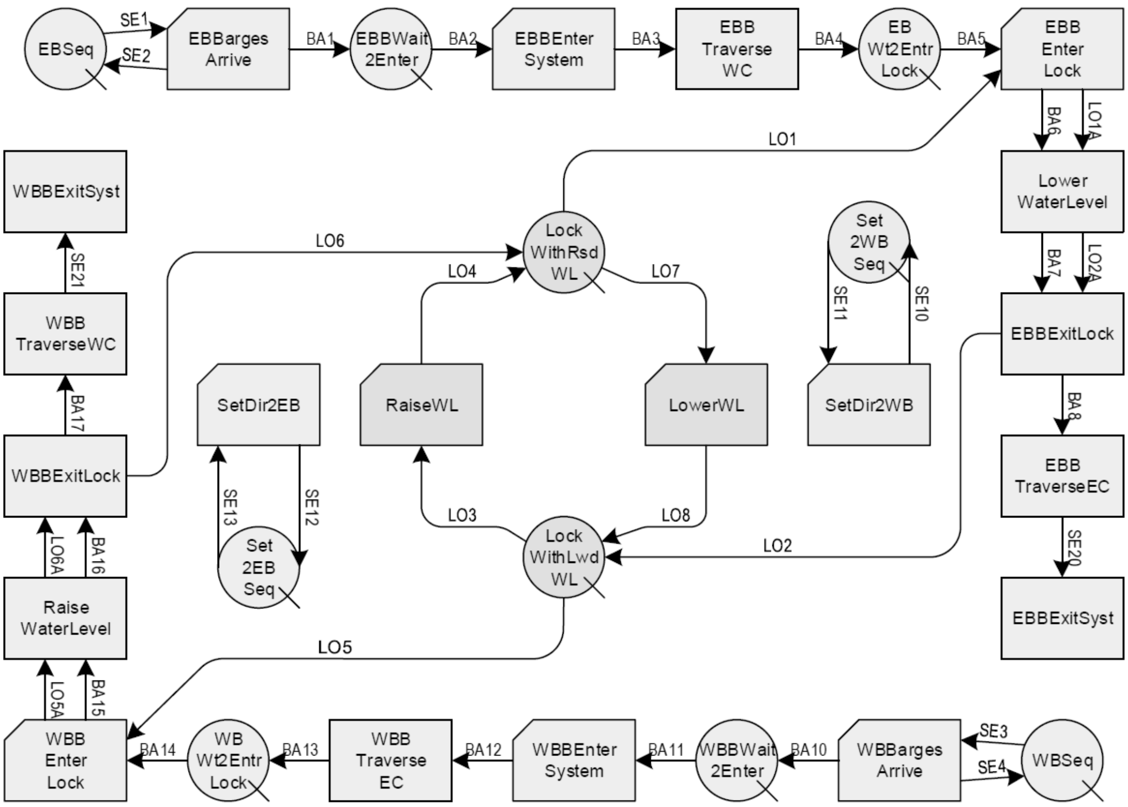

Figure 2: STROBOSCOPE Simulation Network.

The green-shaded queues and activities for the westbound barges are similar to the blue-shaded nodes.

The red activities *RaiseWL* and *LowerWL* model the 12 min to raise or lower the water level in the lock when it does not contain a barge. They start when their semaphores allow as follows.

```
SEMAPHORE RaiseWL 'EBBTraverseWC.CurInst
                  | EBWt2EntrLock.CurCount';
SEMAPHORE LowerWL 'WBBTraverseEC.CurInst
                  | WBWt2EntrLock.CurCount';
```

The semaphore for combi activity *RaiseWL* allows the activity to start when an *EBBarge* is approaching through the west canal (i.e., when there is a current instance of activity *EBBTraverseWC*), or when an *EBBarge* is waiting at the lock for the water to rise (i.e., when queue *EBWt2EntrLock* is not empty). The semaphore for combi activity *LowerWL* is similar.

From the perspective of traffic logic, the key activities are *SetDir2EB* and *SetDir2WB* — they set the direction of barge traffic to *EB* or to *WB* and reset to zero the count of barges that traversed in a cycle.

Both activities have a duration of zero and are preceded by queues that are initialized with 1 unit of *Sequence*. Thus, these two activities are in constant readiness to start and perform actions whenever their semaphores allow. As an example, the following statements illustrate the semaphore logic and actions for combi activity *SetDir2WB*.

```
SEMAPHORE SetDir2WB
'(EBBExitSyst.TotInst==EBBEnterSystem.TotInst)
& ((EBBCount==Emx) |
   (Direction==EB & !EBBWait2Enter.CurCount
                & WBBWait2Enter.CurCount))';
ONEND SetDir2WB ASSIGN EBBCount 0;
ONEND SetDir2WB ASSIGN Direction WB;
```

The above semaphore allows activity *SetDir2WB* to start under one of two logical conditions that correspond to the end of a full cycle or the end of a partial cycle.

- Both cycles require that all eastbound barges that have entered have also exited the system (red code).
- A full cycle ends when, in addition, the number of eastbound barges has reached *Emx* (green code).

- A partial cycle ends when, in addition, (a) the current *Direction* is *EB*, (b) there are no eastbound barges waiting to enter, and (c) there are westbound barges waiting to enter (blue code).

Whenever one of the above conditions is satisfied, combi activity *SetDir2WB* starts and ends immediately. Before it ends, it performs the following two important actions:

- It resets the barge count *EBBCount* to zero .
- It sets *Direction* to *WB*.

The semaphore and actions for combi activity *SetDir2EB* are similar.

It should be noted that at the end of a full eastbound cycle, activity *SetDir2WB* may switch *Direction* to *WB* only for an instant.

If at that point there are no westbound barges ready to cross, but there are more eastbound barges waiting, then activity *SetDir2EB* will immediately complete a partial cycle and start a new eastbound cycle by setting *Direction* to *EB*. Thus, activities *SetDir2WB* and *SetDir2EB* may start and reset *Direction* at the same simulation time, as needed.

2.1 Model validation

The initial validation of the model was done by using the deterministic datasets described in [1] and produced the required results.

2.2 PROOF Animation

A PROOF Animation model driven by STROBOSCOPE was also developed as an effective way to verify the simulation model logic.

Figure 3 is a snapshot of the animation and shows static data — such as *Emx*=5, *Wmx*=5, and the mean time between barge arrivals, β=75 min—as well as dynamic data—such as *SimTime*=66.7 hrs, the current values of *Te*=292.66 min and *Tw*=216.04 min, the number of barges processed in each cycle (*En*=4, *Wn*=5), and the number of barges waiting to enter the west and the east canals (*Eq*=3, *Wq*=9). The snapshot also shows the lock while lowering an eastbound barge, another eastbound barge currently waiting to enter the lock, three more eastbound barges waiting in line to enter the west canal (red column), and nine westbound barges waiting in line to enter the east canal (blue column).

3 Sensitivity Analysis

The STROBOSCOPE simulation model produces three basic performance metrics as output:

- *Te* = Average Eastbound Barge Transit Time.
- *Tw* = Average Westbound Barge Transit Time.
- *Tp* = Average Pooled Barge Transit Time for all barges irrespective of direction of travel.

Of these, the average pooled barge transit time *Tp* is the most indicative measure of overall system performance and is discussed in the following sections.

The model also includes control statements for performing sensitivity analysis and comparing alternatives:

- The traffic control parameters *Emx* and *Wmx* can vary over a range of values (e.g., 1 to 50).
- The mean time between barge arrivals, β, can also vary over a range (e.g., 70 to 85 min).

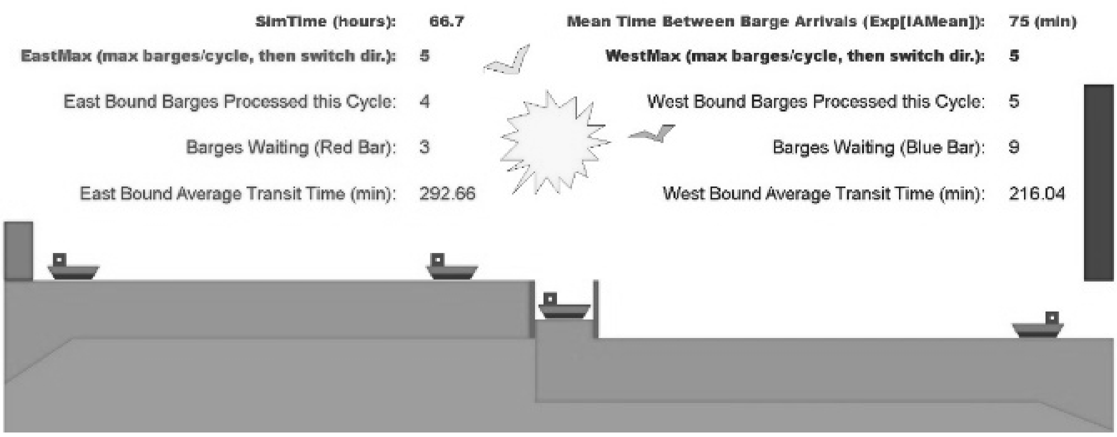

Figure 3: Animation Screen Shot, *Emx* = 5, *Wmx* = 5, and β = 75 min.

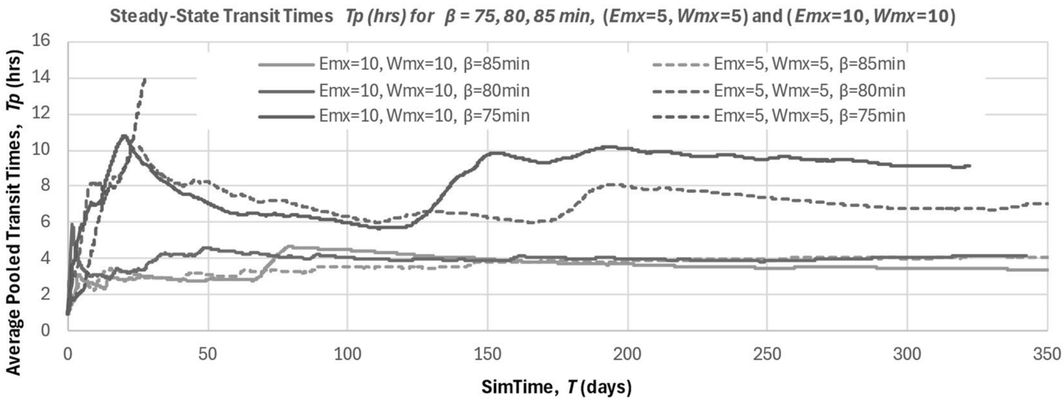

Figure 4: Steady-State Avg Pooled Transit Times, *Tp* (hrs).

- Multiple replications can be performed for all sets of values of the above parameters *Emx*, *Wmx*, and *β*, to increase output statistical accuracy (e.g., 100 reps).

Figure 4 shows the average pooled barge transit times *Tp* for (*Emx*=5, *Wmx*=5), (*Emx*=10, *Wmx*=10), and mean values *β* = 75, 80, 85 min. As shown, when the system is simulated for *T* = 1 year, most transit time curves *Tp* go through a transient phase and then approach steady-state values. Only the dashed red *Tp* curve for *Emx*=5, *Wmx*=5, and *β*=75 min (which unfortunately are the values suggested in [1]) continues to rise to infinity, indicating that the limits *Emx*=5 and *Wmx*=5 are too small for the large traffic volume caused by *β*=75 min. (This is also observed in [3], which switched to *β*=85 min as a better mean value.)

For the same mean *β*=75 min, the solid red *Tp* curve for the larger values *Emx*=10 and *Wmx*=10 does approach steady state values close to 9-10 hours. This shows that larger (but balanced) values of *Emx* and *Wmx* decrease the average pooled transit times *Tp*.

Figure 4 also shows that as *β* increases from 75 to 80 to 85 minutes, demand for the use of the lock decreases, and consequently, the average pooled transit times *Tp* also decrease from about 9 hrs to about 3 hrs.

Figure 5 shows the steady state (*T*=1 yr) average pooled barge transit times *Tp* over 10 replications, for *β*=85 min and for *Emx* and *Wmx* values from 3 to 10. Clearly, the average pooled transit times *Tp* decrease to about 3 hours as both limits *Emx* and *Wmx* increase to 10. Simulations for even larger values of *Emx* and *Wmx* (as high as 50) show that average transit times *Tp* continue to decrease asymptotically (but only by a little) to 2.8 hours.

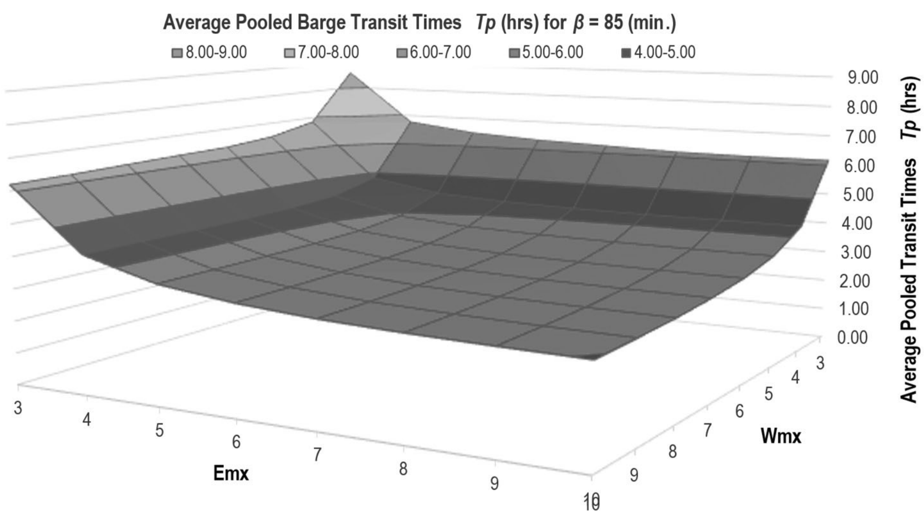

Figure 5: Average Pooled Transit Times *Tp* (hrs) vs. *Emx* and *Wmx* for *β* = 85 min.

4 Variance Reduction

4.1 Antithetic Random Variates (ARV)

An investigation of variance reduction using antithetic variates for the estimation of 90% confidence intervals for the average pooled transit times *Tp* (min) was conducted for the values suggested in [1], *Emx*=5, *Wmx*=5, *β*=75 min, and *T*=10 days (14400 min). The results are shown in Table 1 and are very close to those in [4].

		100 Independent Replications		50 Replications using Antithetic Variates	
Run	**Avg Tp**	**90% CI**	**σ**	**90% CI**	**σ**
1	494.9	37.7	227.10	25.8	108.91
2	520.0	37.1	223.46	24.7	104.23
3	489.5	41.2	247.87	25.2	106.32

Table 1: Antithetic variates-Average pooled transit times *Tp* (min), *Emx*=5, *Wmx*=5, *β*=75 min, T=10 days.

A total of 100 replications were divided into two groups, 50 using independent samples and 50 using the corresponding antithetic variates. The sample for the independent statistics used all 100 average pooled transit time *Tp* values. For antithetic sampling, each pair of *Tp* values (standard and its antithetic) was added and divided by two to give a sample of 50 averages.

Table 1 shows the independent and antithetic statistics for the average pooled transit times *Tp* (min) from three separate runs for comparison.

Clearly, antithetic random variates are an effective variance reduction technique and reduce the half-width of the confidence intervals and the standard deviation σ significantly in all three runs.

4.2 Common Random Numbers (CRN)

Variance reduction using common random numbers was used to compare the pooled transit times *Tp* between two alternative policies: policy *Mx*5 = (*Emx*=5, *Wmx*=5) and *Mx*6 = (*Emx*=6, *Wmx*=6). The null hypothesis was that "*Tp*5 is less than *Tp*6" (i.e., that the *Tp* for *Mx*5 is less than the *Tp* for *Mx*6).

Table 2 shows the results from 50 replications for *β*=75 min and *T*=10 days (14400 min). For comparison, three separate runs are shown. The confidence intervals for the difference *Tp*5-*Tp*6 from *independent* simulations contain negative values, and thus the null hypothesis cannot be rejected. When using CRN, however, the confidence intervals for the difference *Tp*5-*Tp*6 contain only positive values and thus the null hypothesis can be rejected at the 10% level of significance.

	Average	**Ind: *Tp*5-*Tp*6**		**CRN: *Tp*5-*Tp*6**	
Run	***Tp*5-*Tp*6**	**90%CI**	**σ**	**90%CI**	**σ**
1	57.3	79.1	333.6	9.0	37.9
2	69.8	78.2	330.0	8.2	34.6
3	59.6	63.6	268.4	7.5	31.6

Table 2: CRN- *Tp*5-*Tp*6 (min) for *Mx*5=(*Emx*=5,*Wmx*=5) vs. *Mx*6=(*Emx*=6,*Wmx*=6), for *β*=75 min, *T*=10 days

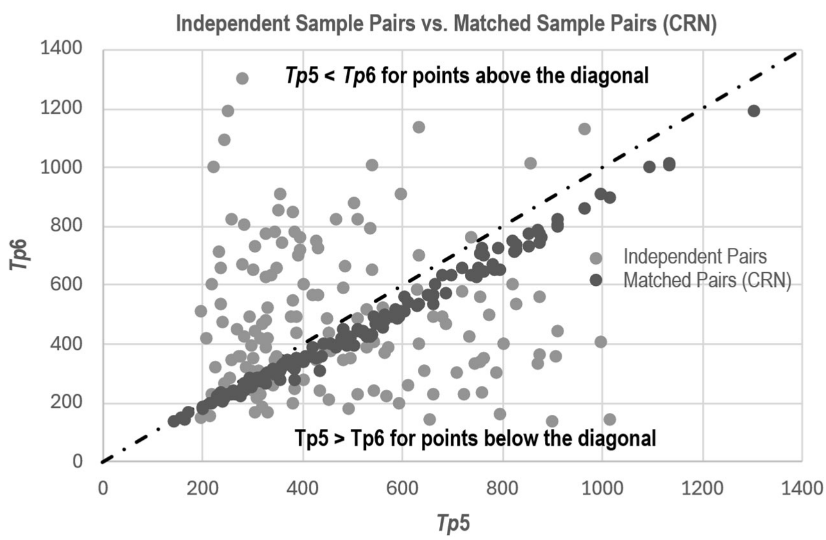

Figure 6: Average Pooled Transit Times *Tp* (hrs) vs *β* for (*Emx*=5, *Wmx*=5) vs. (*Emx*=6, *Wmx*=6).

The 150 pairs of values (*Tp5*, *Tp*6) from successive independent and matched pairs (CRN) for all three runs are shown in Figure 6. The 150 orange pairs of independent values (*Tp5*, *Tp*6) are scattered and cannot be used to discern whether "*Tp*5 is less than *Tp*6" or vice versa.

In contrast, the 150 blue matched pairs (*Tp5*, *Tp*6) produced by CRN lie below the diagonal and show a strong positive correlation. This indicates clearly that the null hypothesis that "*Tp*5 is less than *Tp*6" can safely be rejected. For the same stream of barge arrivals, the operating policy *Mx*6 produces shorter and thus better average pooled barge transit times *Tp*6<*Tp*5 and should be preferred.

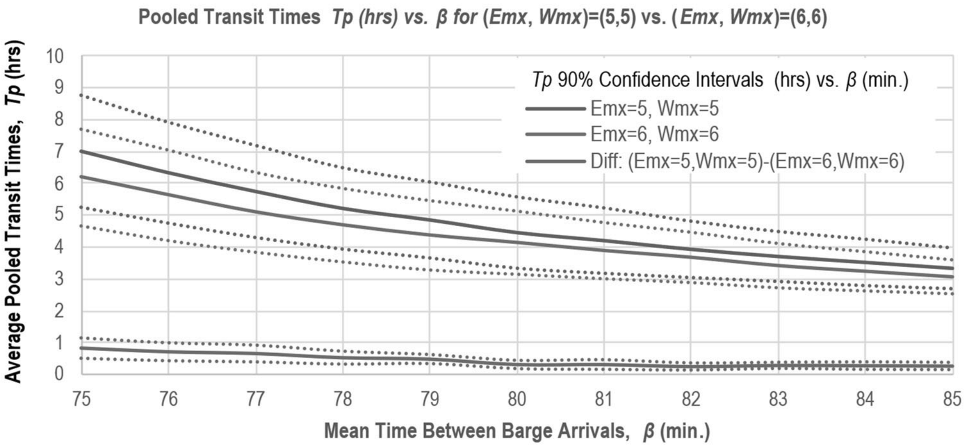

Figure 7: Average Pooled Transit Times *Tp* (hrs) vs β for (*Emx*=5, *Wmx*=5) vs. (*Emx*=6, *Wmx*=6).

Figure 7 shows a comparison of *Tp*5 vs *Tp*6 for values of the mean barge interarrival time β from 75 to 85 min. The solid red curve shows the average *Tp*5 from 10 replications and the dotted red curves show the 90% confidence intervals around the average for the true mean barge transit time for *Mx*5. The solid and dotted green curves are similar but for *Tp*6 and *Mx*6.

For each value of β, 10 replications were performed using CRN (i.e., the same stream of random barge arrivals) to produce one matched pair (*Tp*5, *Tp*6). These 10 pairs were then averaged to produce the red and green pairs (*Tp*5, *Tp*6) for that value of β. However, because the number of replications, 10, is small, the 90% confidence intervals for *Tp*5 and *Tp*6 shown in Figure 7 overlap, and thus it is not possible to discern whether the mean *Tp*5 is strictly greater and thus worse than the mean *Tp*6. To make this determination, each of the 10 replications also calculated one sample for the difference *Tp*5-*Tp*6 from the matched pair (*Tp*5, *Tp*6) for that value of β. These 10 samples of the difference *Tp*5-*Tp*6 gave the average and the 90% confidence intervals for the difference *Tp*5-*Tp*6, shown by the solid and dotted blue curves.

The important point is that the blue curve values for *Tp*5-*Tp*6 are due mainly to differences in performance between policy *Mx*5 and *Mx*6 and are not due to chance. The blue curves for the 90% confidence intervals for *Tp*5-*Tp*6 in Figure 7 are positive for all β. Thus, the null hypothesis that the mean *Tp*5 is less than the mean *Tp*6 can be rejected at the 10% level of significance for all values of the mean interarrival time β. As a result, policy *Mx*6 results in shorter average transit times than *Mx*5 for all β.

The remarkable reductions in the width of the 90% confidence intervals and the standard deviation σ shown in Table 2 and Figure 7 illustrate the effectiveness of matched pairs and common random numbers as a variance reduction technique for the comparison of alternative policies.

5 Comments

The canal and lock system is an interesting transportation problem that is similar to an earthmoving project for the construction of a dam in California that used heavy trucks to haul fill material [5]. In that project, most of the rural road from the borrow area to the dam could handle two-way traffic (similar to the east and west waterways) except for a narrow segment at the side of a cliff, which could accommodate only one-way traffic (similar to the canal and lock system). The narrow segment was divided into two parts of about the same length (similar to the east and west canals) by a temporary bridge (similar to the lock) that could support only one heavy truck at a time.

A STROBOSCOPE simulation model for this earthmoving project for the construction of a dam used engineering calculations to determine the optimum mix of trucks, to evaluate traffic policies, and to investigate the construction of two bridges to streamline traffic to save time [5].

As also noted in [3], the original assumptions of a mean time of β=75 min for the exponentially distributed barge interarrival times, together with the limits of *Emx*=5 and *Wmx*=5 barges, result in queues at the canal entrances that grow to infinity. A better choice would have been β=85 min as was assumed in [3].

The complete data for Figure 5 for a long simulation run, *T*=1 year, that reaches steady state, show that the average pooled barge transit times *Tp* for a system with a mean time of *β*=85 min continue to decrease as the values of *Emx* and *Wmx* increase from 1 to 50. Values of *Emx*=*Wmx*=14 give *Tp*=173 min. Values as high as *Emx*=*Wmx*=50 continue to decrease *Tp*, but only by a little to 169.3 min.

The corresponding figure for *β*=75 min and values of *Emx* and *Wmx* from 1 to 50 is similar in shape to Figure 5 but has higher *Tp* values. For a simulation run *T*=10 days, the minimum value is *Tp*=255 min, while for *T*=1 year, the minimum value is *Tp*=317 min. Both occur at large values of *Emx* and *Wmx* ≥ 40.

The fact that higher values for *Emx* and *Wmx* result in lower average pooled barge transit times *Tp* indicates that the best traffic policy for the canal and lock system might be to abolish the *Emx* and *Wmx* limits and allow all queued barges that travel in the same direction to cross without an upper limit. The direction of traffic would then switch whenever there are no more barges that travel in the current direction (i.e., similar to the end of a partial cycle with infinite limits). For *β*=85 min, this would give a minimum average pooled transit time of *Tp*≈169.3 min.

The canal and lock system described in [1] (with minor changes) is well suited to education and the teaching of simulation. The authors have used it as an assignment in a graduate course on simulation with success.

STROBOSCOPE [2] (an acronym for State and Resource-Based Simulation of Construction Processes) is a general-purpose discrete-event simulation system and language co-developed by the first author. Its simulation models use a graphical network-based representation similar to activity cycle diagrams. Its design is based on three-phase activity scanning that can model the complex resource interactions that characterize cyclic operations without the need to make a distinction between the resources that serve (servers or scarce resources) and those served (customers or moving entities). The late Thomas J. Schriber [1] was a member of the doctoral committee that oversaw the development of STROBOSCOPE.

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