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SIMULATION OF CABLE-STAYED BRIDGES USING DISCO

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ABSTRACT

Cable-stayed bridges are ideal for spanning natural barriers such as wide rivers, deep valleys or ravines, and for pedestrian bridges crossing wide interstate highways. The modern construction of cable-stayed bridges makes use of segmental balanced cantilever techniques and involves many repetitive cycles of placing the concrete segments and stay cables. Due to this repetition, it provides a fertile area for the application of computer simulation techniques. This paper employs a graphically-based construction simulation system, DISCO (Dynamic Interface for Simulation of Construction Operations), for the modeling and simulation of the construction of the Pasco-Kennewick Intercity Bridge in the state of Washington. The DISCO system provides a graphical environment in which modeling and simulation of construction operations can be conducted in an interactive fashion. The model developed for the bridge construction and the results of the simulation are presented.

1 INTRODUCTION

The concept and practical application of cable-stayed bridges date back to the 1600's when a Venetian engineer built a bridge with several diagonal stays (Podolny and Scalzi 1986). The concept was attractive to engineers and builders for many centuries. Experimentation and development continued until its modern-day version evolved in 1950. The cable system (figure 1) used in cable-stayed bridges is ideal for spanning natural barriers such as wide rivers, deep valleys or ravines, and for pedestrian bridges crossing wide interstate highways because there are no piers that will form obstructions. For the most part, cable-stayed bridges have been built across navigable rivers where navigation requirements have dictated the dimensions of the spans and clearance above the main water level. Efficient use of materials and speed of erection have made cable-stayed bridges the most advantageous and economical long-span (700-2,000 ft) bridge solution throughout Western Europe since the end of World War II (Rowings and Kaspar 1991).

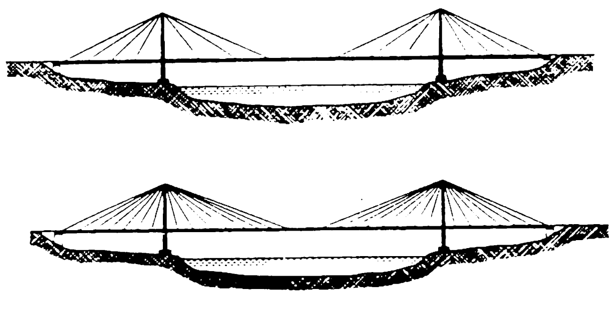


Figure 1: Cable-Stayed Bridges (adapted from Mathivat 1983)

The modern construction of cable-stayed bridges makes use of the segmental balanced cantilever technique to build on both sides of the pylon at the same time (figure 2). Using this method, the bridge structure is made up of concrete segments which are either precast or cast-in-place in their final position in the structure. The segments are post-tensioned to the previous segment and suspended with stay cables from the pylon. The construction of cable-stay bridges involves many repetitive cycles of placing the concrete segments and stay cables, and provides a fertile area for using computer simulation techniques to manage the construction process. This paper employs a graphically-based construction simulation system, DISCO (Dynamic Interface for Simulation of Construction Operations), to study the process dynamics of cable-stayed bridge construction. The model and the results of the simulation are presented.

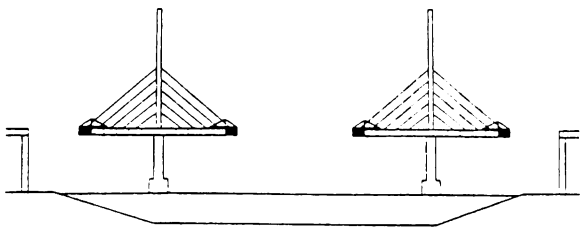


Figure 2: Balanced Cantilever Construction

2 DISCO PROGRAM

DISCO is a prototype program developed for the modeling and simulation of construction operations. It is written in Microsoft^{TM} Visual Basic language and runs under the Windows^{TM} operating environment. The CYCLONE modeling methodology is employed for the abstract model building and its set of standard modeling elements as shown in table 1 constitutes the basic icons in the DISCO graphical menu bar (figure 5). Readers are referred to Halpin and Riggs (1992) for details regarding the CYCLONE modeling methodology.

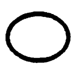
Basically, the DISCO program serves as both a preprocessor and post processor for the MicroCYCLONE program (Halpin 1990), which is a microcomputer-based program that uses CYCLONE methodology. DISCO generates the MicroCYCLONE input file and takes the chronological list file generated by running the MicroCYCLONE program as its input. It then recreates the entire course of simulation dynamically on the computer screen with the schematic model diagram used as the display mechanism.

The DISCO program performs three major functions as follows:

1. It builds a schematic model diagram graphically on the screen and generates the MicroCYCLONE input file.
2. It displays the model dynamics by continuously updating the associated information for each node during the simulation run.
3. It reports node statistics information graphically and tabularly at any simulation event time point.

Readers are referred to the *DISCO User's Guide* (Huang and Halpin 1993) for detailed description of these functions. Figure 3 shows the display format of the run-time information contained in DISCO "watched" nodes. These "watched" nodes are designed to facilitate the monitoring of system dynamics during the simulation run-time. The DISCO program provides a graphical environment in which modeling and simulation of construction operations can be conducted in a more interactive fashion. It is employed in this paper for simulation of the construction of the Pasco-Kennewick Intercity Bridge in the sate of Washington.

Table 1: CYCLONE Modeling Elements

Symbol	Name	Description
	NORMAL	The normal work task modeling element, which is unconstrained in its starting logic and indicates active processing of (or by) resource entities.
	COMBI	The constrained work task modeling element, which is logically constrained in its starting logic, otherwise similar to normal work task modeling element.
	QUEUE	The idle state of a resource entity symbolically represents a queuing up or waiting for use of passive state of resources.
	CONSOLID-ATION	The consolidation is a function used to consolidate flow units at certain points in the system.
	COUNTER	The purpose of a counter is to count the number of times a key unit passes a particular control point in the network model so that production can be measured.
	ARC	An arrow or directed arc is used to model the direction of resource entity flow between the various active-state nodes and the passive-state nodes.

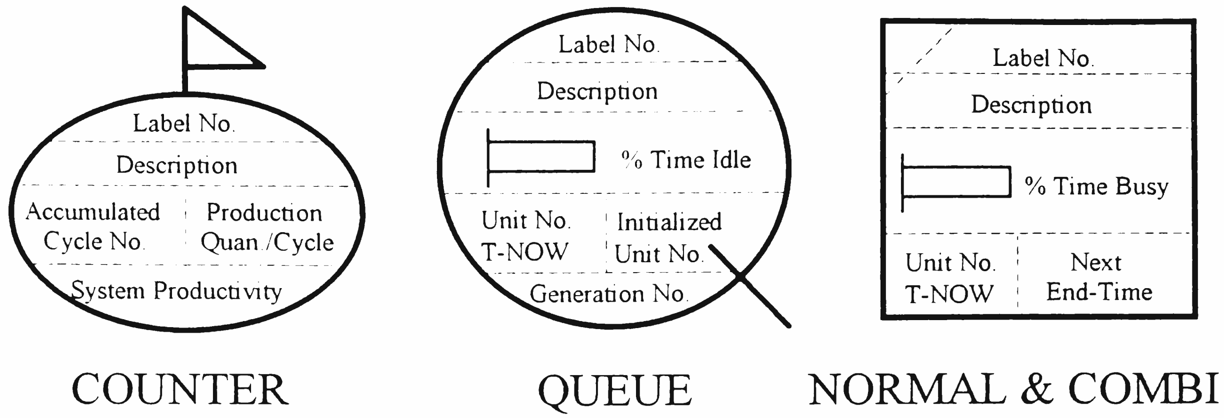


Figure 3: Format of DISCO "watched" Nodes

3 THE PASCO-KENNEWICK INTERCITY BRIDGE CONSTRUCTION

The Pasco-Kennewick Intercity Bridge (figure 4) is the first cable-stayed bridge with a segmental concrete superstructure to be constructed in the United Sates. Spanning the Columbia River and connecting Pasco and Kennewick in the state of Washington, the overall length of this structure is 2,500 ft. Construction began in August 1975 and was completed in May 1978. The center cable-stayed span is 981 ft, and the stayed flanking spans are 406 ft. Deck segments were precast about 2 miles downstream from the bridge site and loaded on a barge to be transported to the structure site for installation in their final position. Each segment weights about 300 tons and is 27-ft long. The bridge has an 8-in thick roadway slab, supported by 9-in thick transverse beams on 9-ft centers. Each segment is joined along the exterior girders by a triangular box that serves the function of cable anchorage stress distribution through the girder body. Readers are referred to Podolny and Scalzi (1986) for a more detailed description of the project.

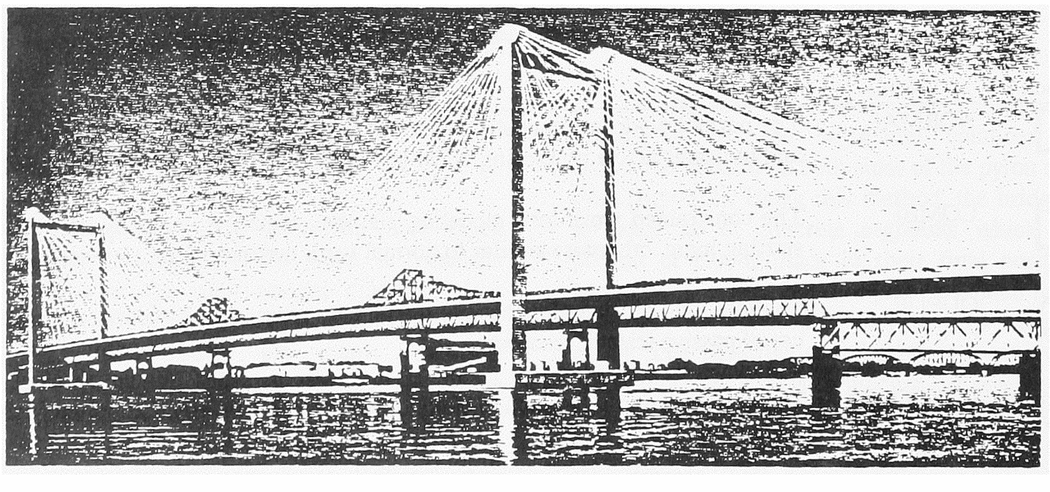


Figure 4: Pasco-Kennewick Intercity Bridge (adapted from Troitsky 1988)

The typical cycle for the installation of one segment and the average duration for each of the tasks in the cycle are described as table 2. These durations are based on the authors' best estimation using information for similar tasks.

Table 2: Typical Segment Installing Sequence and Work Task Durations

Sequences	Description	Duration (hrs)
1	Connect pull rods to the segment	0.25
2	Lift segment to deck elevation	0.67
3	Couple the longitudinal stress bars	0.50
4	Shift the element against the erected superstructure to check the matching of the joints	0.58
5	Pull back the segment	0.25
6	Apply the epoxy glue	1.25
7	Shift the element back to its final position	0.25
8	Stress longitudinal bars for initial joint pressure	2.00
9	Jack load increment on last stays for control of erection bending moments in the structure	2.50
10	Install new stays	6.00
11	Stress stays simultaneously with releasing of the erection cables	3.00
12	Complete the stressing of the longitudinal bars	1.75
13	Grout all stress bars	1.00
14	Weld the top layer of reinforcement and grout the remaining joint	2.00
15	Install rails on new segment	1.25
16	Add length to the erection cables	1.50
17	Push the erection truss forward	1.50
18	Anchor the truss	0.50
19	Stress erection cables until the erection truss is resting on its back support	1.33

4 SIMULATION OF THE OPERATION

Figure 5 shows a CYCLONE model of the cable-stayed bridge operation in DISCO format. The model describes the work tasks required for the construction of two balanced cantilevers of the deck structure. Each cycle represents one segment assembled. The label numbers of the work tasks used in the model are consistent with those described in table 2. Deterministic durations listed in table 2 are employed for the simulation.

It can be seen from the model that the labor crew (QUEUE 101) is the major resource in the operation because it is needed by most of the work tasks. One labor crew is initialized originally for the simulation. Other resources used in the simulation includes one barge (QUEUE 102) for transportation of the segments from the precasting yard to the position below the deck, one crane (QUEUE 116) for loading of the segment onto the barge, one command at QUEUE 114 for segment loading, and one command at QUEUE 113 for segment lifting. The COUNTER at node 100 counts one segment assembled in one cycle. The model is then simulated for fifteen cycles.

After the model is simulated in DISCO environment using the MicroCYCLONE program, the user can trigger playback of the simulation. DISCO recreates the entire course of simulation dynamically on the screen. The schematic model diagram is employed as the displaying mechanism. Prior to the simulation, a simulation clock set to 0.00 is shown on the screen to indicate the updated simulation time point T-NOW. Green color is invoked at all the QUEUE nodes with initialized resources (e.g., crew, barge, etc.). This signals the availability of a resource. The % Idle time in these nodes is set to 100 initially. A productivity report window shows up which allows the monitoring of the development of the system cumulative productivity through the simulation run. It is immediately apparent that "load segment to barge" (node 20) will be the only task to be scheduled at simulation clock (T-NOW) 0 due to the availability of all the required resources -- barge, crane and command for segment loading.

As the value of simulation time advances, run-time information for those nodes being "watched" is continuously updated throughout the simulation. The DISCO program attempts to create the impression of "animation" during the simulation run by employing colors. Each type of node is assigned a different color (except NORMAL and COMBI which share the same one.) The color goes on if a unit "enters" an empty node. The entering unit can be a barge returning to an empty queue, or the processing of a task. Similarly, the color goes off when the last unit "exits" a node. Once the simulation starts, the user is able to see colors flashing on and off on the screen, along with continuously updated run-time information. In a way, the user can view the barge as it transports the concrete segment to the position below the deck, the crew starts to connect pull rods to the segment, lifts segment to deck elevation, couples the longitudinal bars, and so on and so forth. This mechanism allows the user to experience system dynamics during the simulation run.

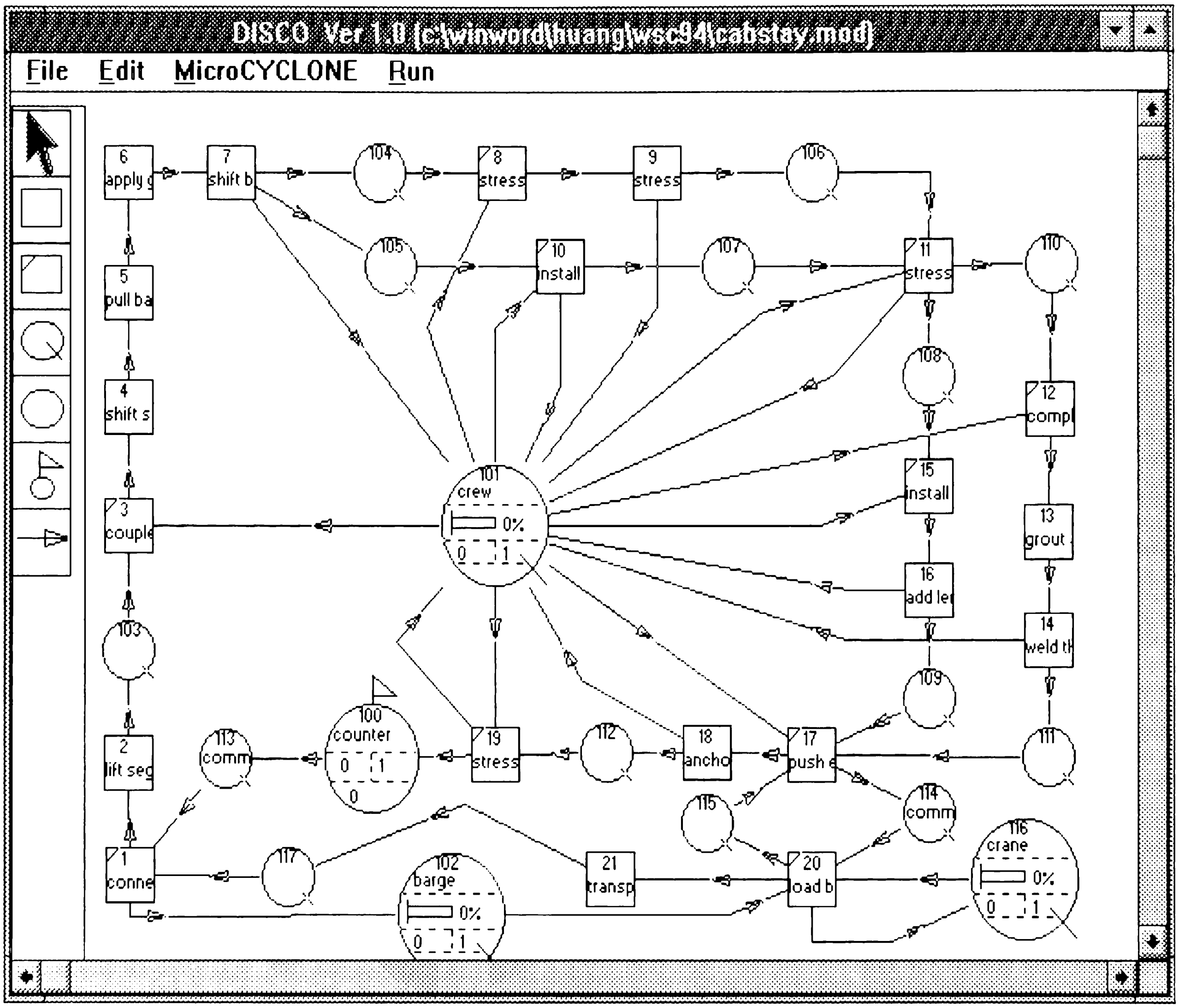


Figure 5: A CYCLONE Model of the Cable-Stayed Bridge Operation in DISCO Format

5 RESULTS OF THE SIMULATION

Figure 6 shows the snapshot of the model at the end of the DISCO simulation run. The operation takes 422.53 hours to finish the placing of fifteen concrete segments and yields a system productivity of 0.04 segments per hour or 0.4 segments per 10-hour shift day. The system productivity is shown in the upper right corner of the productivity report box. The productivity curve in the productivity report box also indicates that the installation of the first segment is finished after approximately 30 hours and the system productivity remained flat thereafter. The system productivity is defined as the rate of production based on cumulative units produced for the total time elapsed since the start of the process.

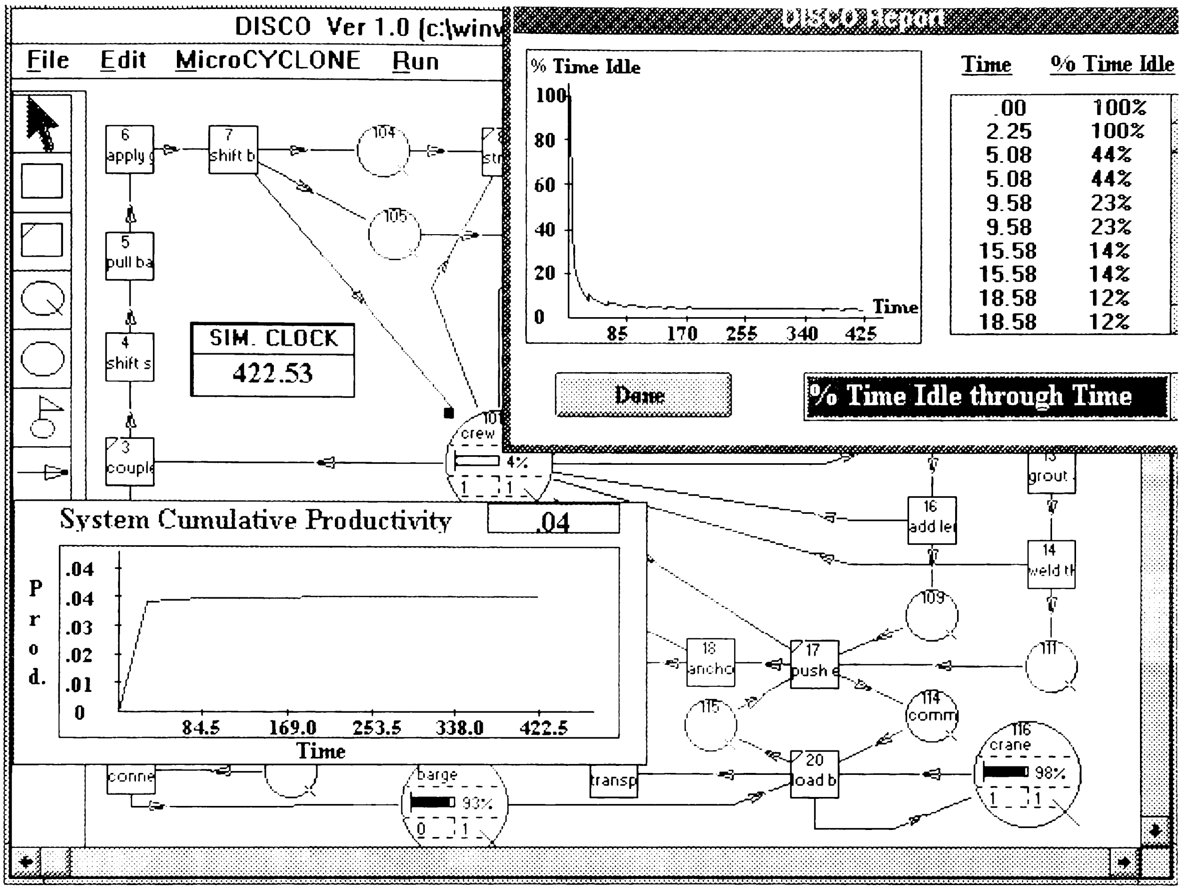


Figure 6: Cable-Stayed Bridge Model at the End of the DISCO Simulation Run

The "% idle time" in QUEUE nodes 101, 102, and 116 reveals that the labor crew, the barge and the crane have an overall percentage idle time of 4%, 93%, and 98% respectively. Apparently the labor crew had a much more intensive work load than the other two resources. This is because the labor crew is needed for almost all the work tasks in the operation. The DISCO program also provides several graphical as well as tabular reports for different types of nodes. The DISCO report shown in figure 6, for instance, shows the % time idle of the labor crew throughout the simulation. It can be seen that the idle time dropped immediately after the simulation began (the initial value is set to 100%) and remained low thereafter. Again, the result indicates that the only labor crew was busy all the time.

6 SENSITIVITY ANALYSIS

Different labor crew sizes (one to four) were tested out in the simulation for the productivity measurement. The results are shown as table 3. The system productivity is improved significantly when the crew size was increased from one to two. However, the productivity remains constant when more than two crews are used. It is obvious that the barge and crane become the constraining resources when there are more than two labor crews in the system. To further improve the productivity, the feasibility of employing more than one barge and/or one crane should be examined.

Table 3: Results of the Sensitivity Analysis

Labor crew size	Concrete segments installed	Simulation length (hours)	System Productivity (seg/hour)
1	15	422.53	0.036
2	15	313.78	0.048
3	15	313.78	0.048
4	15	313.78	0.048

7 CONCLUSIONS

Construction of cable-stay bridges involves many repetitive cycles of placing the concrete segments and stay cables. It provides a fertile area for the application of computer simulation techniques for the planning and analysis of construction processes. The DISCO simulation system has been employed for the modeling and simulation of a concrete segment installation in the Pasco-Kennewick Intercity bridge construction. A CYCLONE model for the operation has been developed in DISCO format and the system productivity as well as resource utilization are analyzed by examining the graphical reports provided by DISCO. Sensitivity analysis of different labor crew sizes is also investigated for improving system productivity.

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