REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE -	3. REPORT TYPE AND DATES COVERED FINAL 01 Jun 99 - 31 Dec 00

4. TITLE AND SUBTITLE
Use of Simulation-Based Analysis, Prepiction and Control in Remanufacturing Facilities

5. FUNDING NUMBERS
DAAH04-96-1-0223

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 35853.1-RT-AAS

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This ASSERT award focused on investigating the operations in remanufacturing facilities, in particular military remanufacturing facilities such as the Corpus Christi Army Depot (CCAD) helicopter remanufacturing facility. The general area of the project was to investigate remanufacturing and develop tools to help plan, analyze, and operate remanufacturing systems.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION ON THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
scribed by ANSI Std. 239-18
8-102

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This ASSERT award focused on investigating the operations in remanufacturing facilities, in particular military remanufacturing facilities such as the Corpus Christi Army Depot (CCAD) helicopter remanufacturing facility. The general area of the project was to investigate remanufacturing and develop tools to help plan, analyze, and operate remanufacturing systems.

The first step of this task is to understand the complexities involved in remanufacturing and how this environment differs from a traditional environment. The main differences stem from the fact that the work content for a remanufacturing job is not completely known until the operation is started and the disassembly and inspection processes have been completed. Thus, the remanufacturing environment has to deal with more uncertainty and has much more variability in all aspects of the operations, from procurement to individual operation times to overall cycle time.

During the past year and a half, two students have been funded by the ASSERT project. They have been working on two different aspects of the remanufacturing problem. One, Wes Scott, has been looking at the issue of short-term scheduling and shop floor control in remanufacturing environments. His work focuses on developing a methodology and corresponding toolset that uses discrete-event simulation as the basis for shop floor planning and control. This work builds upon previous research at Texas A&M University related to simulation based planning and control. A brief description of Wes's research is contained in Appendix A.

The second student funded by the project during this period is Tim Matis. Tim's research is more theoretical in nature. Tim has been exploring new methods for analyzing queueing systems operating under a WIP limiting strategy. These WIP limiting strategies often provide improvements in cycle time and throughput, which would be desirable in most facilities but particularly in a remanufacturing environment such as CCAD's. However, in order to know how to design such a system, a good estimate of the performance is needed. Current analytical techniques are quite limited in the system structures that they allow and quite extensive in the computational requirements. Tim is working to develop approaches that would be more flexible and more computationally efficient. The resulting methodologies and tools would be of direct benefit in analyzing and improving remanufacturing environments. A brief description of Tim's research is contained in Appendix B.

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Appendix A

Introduction

The goal of this research is to improve short-term scheduling and shop floor control in a manufacturing and remanufacturing environments.

As TAMCAM staff have previously stated, simulation is an "appropriate tool for developing rule based scheduling procedures." The major obstacle in developing these scheduling procedures has been the scarcity of personnel who are trained in both simulation and scheduling/control techniques. The system being developed greatly reduces the knowledge requirements of the personnel using it.

Portions of this research were presented at the 1999 Winter Simulation (WinterSim) conference in the Ph.D. colloquium and poster session. Appendix A contains the presentation slides from WinterSim.

Basic Concepts

To represent a manufacturing/remanufacturing environment three things must be described: the manufacturing system, the products that will be produced and the control system that will determine when the various operations will be performed.

Manufacturing System

The manufacturing system is represented using the following items: a list of equipment in the system, a list of workstations the system contains and the equipment assigned to each workstation, a graph that describes possible movements between workstations, a set of graphs that describes movements inside each workstation.

Messaging Petri nets will be developed based on the description of the factory provided by the user. These nets will be used as the execution portion of the control system.

Products

Products are represented by a process plan that contains all of the information required to convert the product from raw material to finished product. This research uses an OR graph (See figure below) to represent the process plan to the system user. The nodes in the graph represent processing steps (with associated instructions and estimated processing times) and the arcs represent processing constraints. Each

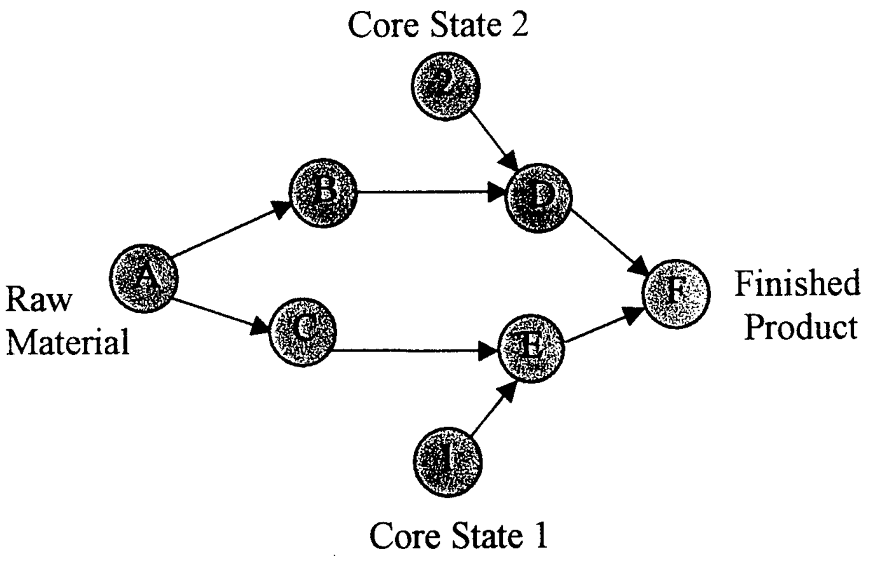

Figure 1 OR graph for a simple product

graph has a final node that represents the finished product (node F in the figure). In a manufacturing system, each graph will have a single entry node representing raw material (node A). In a remanufacturing environment, the graph will have multiple entry nodes (nodes 1 and 2) representing the various conditions of the core that is being remanufactured.

The OR graph is converted to a messaging Petri net for use in the control system.

Control System

The control system being used is a three level hierarchical control system consisting of the following levels: equipment, workstation, and shop/cell. The equipment level provides a standardized interface to the physical equipment (which can include humans) that will perform the work. The workstation level consists of a messaging Petri net and expands commands received from the shop/cell controller and coordinates the activities of equipment. The shop/cell level consists of an artificial neural net and makes all of the decisions for the system.

The equipment level requires a human developed interface specific to the piece of equipment that is to be controlled. The workstation level is automatically generated based on the factory representation provided by the user. The shop/cell level controller is automatically generated in two steps. The first step is generating the basic structure of the controller based on the factory representation that was provided by the user. The second step is to use simulation to train the neural net.

It is possible to simulate the factory performance without the user knowing anything about building a simulation or system control logic. All of the control logic is embedded in the neural net and hidden from the user. The workstation controllers are automatically constructed without user intervention. The equipment controllers use a standardized interface and estimated processing times are provided in the process plans so simulation of the equipment is easily performed.

Messaging Petri Nets

Messaging Petri nets are an extension of Petri nets. Petri nets have been widely used for modeling systems and as a simulation tool. However, their use in control systems has been limited because of the difficulty in linking them to external systems. Messaging Petri nets have two types of places with associated messages. The first type sends messages to the external system when the tokens are removed from them. The second represents a message being received from the external system. The inclusion of these places with a standardized message format allows the messaging Petri net to be easily integrated into a control system.

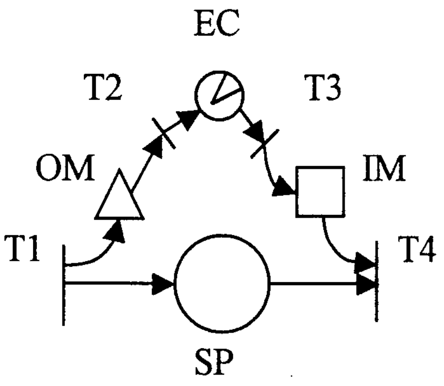

Figure 2 Common Messaging Petri Net Structure

Figure 2 shows a common structure found in the extended Petri nets used in this research. An initial transition (T1) marks the start of an activity. When the transition fires it places tokens in a standard place (SP) which represents the activity occurring and an output place (OM) that represents the message which will be sent to the physical system to actually start the activity. The second transition (T2) then fires removing the token from the output message place and sending the message to the external system and placing a token in the external clock place (EC). The token remains in EC until the appropriate message is received from the external system at which point transition T3 fires placing a token in IM and removing the token from EC. The final transition (T4) then fires indicating the activity is complete.

Artificial Neural Nets

The artificial neural net will represent the desired scheduling rules. The inputs to the net will be the orders and the position and condition of the parts in the system. The outputs of the net will be command messages that will be sent to the messaging Petri net portion of the shop/cell controller. The weights associated with the links between nodes in the network will represent the scheduling rules. Optimization techniques can be used to change the weights until good system performance is achieved.

Work Completed

A graph based factory representation was developed. This representation was based on the answer to the question "Where can a part be located?" A major limitation of this model was that it did not include a method for dealing with transportation equipment accessories (specifically pallets required to move a part on a conveyor system). A method for converting this graph based representation to a messaging Petri net was developed. Using this conversion process, a simple workstation controller was generated and demonstrated.

A second factory representation has been developed. This factory representation is more equipment oriented in an effort to make it easier for the average factory supervisor to understand. This representation includes the transporter concept to overcome the pallet problem mentioned above. The representation has been implemented as an Access database using data from the TAMCAM FMS.

A set of C++ classes for neural nets was located and acquired.

Work Remaining

Revise the Petri net building tool to use the new factory representation. The earlier representation assumed the workstation level controller was already developed. The new representation does not make this assumption. Workstation controllers will be built based on the workstation movement graphs supplied by the user. A shop/cell controller will be built based on the graph describing the movements between workstations.

Develop a system to automatically build the appropriate neural net given the messaging Petri net controllers. Develop the training system for the neural net including a system for simulating the performance of the factory.

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Appendix B

Working Paper – Year End Report

On the Cumulant Functions of a Tandem Queueing Network with Population Constraints

Tim Matis

Introduction

A major goal of any remanufacturing problem is to find ways to decrease the cycle time of a system for a given level of throughput. There are many ways in which this may be achieved. Some of the obvious methods are through improvement in processing times or enhanced scheduling. Another method, considered in this paper, is the conversion of the manufacturing environment to a pull system instead of a push system. Specifically, the pull system under consideration is similar to that of a CONWIP (CONstant Work In Progress) system. Hopp and Spearman [2] document the advantages of using a CONWIP system as compared to a pure push system. The most notable result, however, is that for a given level of throughput, the cycle time is decreased. Hence in systems that fit the CONWIP assumptions, simply implementing this environment decreases the cycle time.

Traditional CONWIP systems, however, are assumed closed. The queueing model under consideration in this paper, similar to that of CCAD (Corpus Christi Army Depot), is allowed open. One way to analyze the merits of CONWIP type control implementation for an open model is to analyze the population characteristics of the model for all time t. Currently, however, there are no viable tools readily available to perform such a population analysis. Hence, this research investigates an approach for obtaining population characteristics of a tandem queueing network with population constraints, which mimic CONWIP type control, in both the transient and steady state time. It will be assumed that arrivals and services are Markovian, and that these rates are state dependent. The need for models to reflect state dependent service rates, as often encountered in real life and at CCAD, is discussed by Ross [4], and the state dependent arrival rate is due to the population constraint. The population constraint is that as the total number of customers in the system increases, the arrival rate decreases, and at some specified number of customers, the arrival rate drops to zero. With this constraint, the WIP is limited or controlled in the system. Further, if the arrival rate is large relative to the service rates of the latter nodes in the network, the system will approximate that of a traditional CONWIP system. Hence, the queueing network under consideration is an open network, however by adjusting the arrival rate, it may also approximate a closed network.

Model

Initially, the model that is described above will be set up for a two-node tandem network. Expansion of this model to many nodes in tandem is obvious and will clearly follow. A schematic of the two-node network model under consideration is shown below.

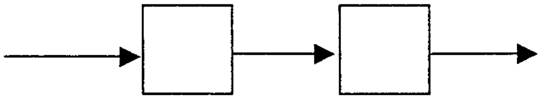

Figure 1: Tandem Queueing Model

The possible changes within this system in the time interval $(t, t+\Delta t)$ are given by

Pr{increase in X_1 of one unit $|$ X_1, X_2} = $\lambda(1-e^{-c_1(u-(X_1+X_2))})\Delta t + o(\Delta t)$

Pr{decrease in X_1 of one unit and increase in X_2 of one unit $|$ X_1, X_2} =

$\mu_1(1-e^{-c_2 X_1})\Delta t + o(\Delta t)$

Pr{decrease in X_2 of one unit $|$ X_1, X_2} = $\mu_2(1-e^{-c_3 X_2})\Delta t + o(\Delta t)$

where X_i, for i=1,2, is a random variable that describes the population in the i^{th} node; c_j, for j=1,..,3, is a constant; and u is the upper WIP level.

Hence, the intensity functions are

$$
\begin{aligned}
f_{1,0} &= \lambda(1-e^{-c_1(u-(X_1+X_2))}) \\
f_{-1,1} &= \mu_1(1-e^{-c_2X_1}) \\
f_{0,-1} &= \mu_2(1-e^{-c_3X_2})
\end{aligned}
$$

Notice that as c_j is varied, these intensity functions take on many different shapes with the function approaching λ(1-I(•)) or μI(•), where I(•) is an indicator function, as $c_j \to \infty$. The flexibility of these intensity, or rate, functions facilitates modeling many different real life state dependent phenomena both in population constraining and in service. A schematic with labeled intensities for a traditional CONWIP model and a population constrained open tandem queueing model is given below.

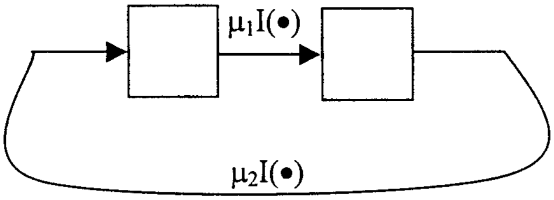

Figure 2: Traditional CONWIP Model

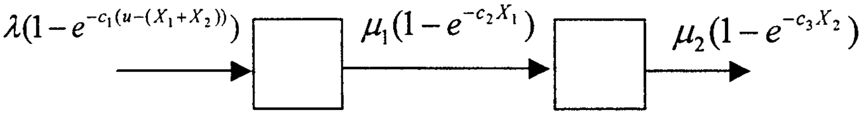

Figure 3: Tandem Model with State Dependencies

A few more characteristics of the model under consideration are that there are no internal buffers and the transfer time between nodes is negligible. In the future research section of this paper, an extension of this model in which internal buffers and blocking are allowed will be discussed.

Analysis

As was mentioned earlier, previous methods used for solving this type of model in the transient and steady state time are often not viable. The traditional approach to obtain such characteristics would be to set up a system of differential equations describing each individual population probability, corresponding to the Kolmogorov equations, which would then be solved simultaneously. While this is possible for small prototype (or demonstrated) systems, the number of these differential equations would make finding a solution intractable if the upper WIP limit is large or if there are many nodes in tandem. Hence, the Kolmogorov approach is often not viable. The purpose of this research is to propose a robust method that obtains population characteristics, i.e. mean, variance, and covariance, for this model for all time t. Specifically, this method obtains the first and second order joint cumulants for all time t. A full description of cumulants and their relationship to moments is given in Johnson and Kotz [3].

The method proposed in this paper is as follows. First, Taylor series expansions are utilized to get the intensity functions in a polynomial form. Once this is done, the techniques developed by Bailey [1] are employed to obtain a partial differential equation for the moment generating function. This moment generating function is converted to a cumulant generating function using techniques given by Zheng [5]. Then, taking partials and performing expansions once again, coefficients of the dummy variables will be equated to form a set of differential cumulant equations. Cumulants above a certain, as of yet undetermined, order will be truncated to make this set finite. These differential equations will then be solved resulting in approximate cumulant functions. Notice that these differential equations describe the cumulants and not the individual population probabilities, as do the Kolmogorov equations. Hence, it is reasonable that even if the truncation level is at the fourth or fifth order cumulants, the number of differential cumulant equations for any large system will be many orders of magnitude less than the number differential equations resulting from the Kolmogorov equations.

There are some issues relating to the procedure outlined above which still remain under investigation. The level of truncation that is necessary to ensure sufficient accuracy for the first, second, and higher order cumulants must be determined. It is initially hypothesized that only one order higher than the order desired is sufficient for reasonable accuracy. This hypothesis, however, needs sufficient testing. Another issue is to determine how well this procedure works in high vs. low traffic. Still, yet another pertains to the required expansion length of the Taylor series expansions in the intensity functions.

Numerical Example

A simple numerical example, with a low upper WIP limit, is presented here for the two-node network depicted in the model section. First we will assume that $c_j = 1$ for all j, the upper WIP limit u=3, and the parameter $\lambda=10$ and $\mu_1=\mu_2=15$. We will further assume, for computational ease and to focus error on the population constraint, that the service at each node is proportional to the number of customers at the node. Hence, the intensity functions for this example are as follows.

$$f_{1,0} = 10(1 - e^{-(u-(X_1+X_2))})$$
$$f_{-1,1} = 15X_1$$
$$f_{0,-1} = 15X_2$$

Now as hypothesized, we will keep cumulants one order higher than the order that we desire. Since we would like to obtain the means, variances, and covariance for this model (up to second order), we will truncate all cumulants with an order greater than 3.

Numerical results were calculated using the method proposed in this paper and the exact Kolmogorov equations for the example given above. The first and second order cumulants, for various times t are given below as well as a calculation of the relative error.

Arrival Rate = 10, Service Rates = 15, Upper WIP Limit = 3

Time	0.1	0.3	0.5	1	2
Exact					
E[x1]	0.459	0.525	0.522	0.522	0.522
E[x2]	0.268	0.51	0.522	0.522	0.522
var[x1]	0.422	0.462	0.46	0.46	0.46
var[x2]	0.256	0.452	0.46	0.46	0.46
Approx.					
E[x1]	0.458	0.516	0.513	0.513	0.513
E[x2]	0.267	0.503	0.513	0.513	0.513
var[x1]	0.414	0.431	0.428	0.428	0.428
var[x2]	0.255	0.424	0.428	0.428	0.428
Rel Diff (Ex-App/Ex)					
E[x1]	0.003	0.016	0.017	0.017	0.017
E[x2]	0.001	0.014	0.017	0.017	0.017
var[x1]	0.018	0.067	0.068	0.068	0.068
var[x2]	0.005	0.062	0.068	0.068	0.068

Future Research

The proposed method demonstrated above is not yet fully verified for the reasons mentioned in the analysis section. Exhaustive testing of this procedure against exact answers, obtained through Kolmogorov equations, and simulated results, for larger models, needs to be performed. Initial tests, however, prove to be promising. If only the first and second order cumulants are desired and if the error from hypothesized truncation is reasonable, only 9 differential equations are needed, despite the size of the upper WIP level, for a two-node model. This is in contrast to the use of Kolmogorov equations that will result in approximately u^2 simultaneous differential equations. For example, if the upper WIP level of this two-node network were set to 10 customers, the Kolmogorov equations would produce on the order of 100 differential equations, while the method proposed in this paper would only require 9 differential equations. In practice, upper WIP limits are often much higher than 10, sometime ranging into the hundreds of customers, which even further exemplifies the usefulness of this procedure. These results are even more striking for a m-node tandem network, for $m \geq 3$, where the approximate number of Kolmogorov equations is on the order of u^m.

There are many extensions to this model that may serve as the basis for future research. It was previously mentioned that one extension would be to consider a network with finite internal buffers and blocking. In the case of CCAD, this would facilitate possible stoppage of manufacturing at upstream stations due to extensive delays at a downstream station. It is hypothesized that this extension would be almost immediate. An extra expression describing this phenomenon would simply be added to the intensity functions for the service rate of each node. Hence, the service rate at a node would be governed by the availability of a job at the node and the availability of space at following nodes. Another extension would be to consider non-homogeneous rates with respect to time. Hence, arrival and service rates would not only depend on the state of the system, but on the time of the day. In the case of CCAD, this would also be very useful in modeling worker productivity during the day and allowing for time dependent arrival rates of helicopters for repair.

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