APPLIED COMPUTING, MATHEMATICS AND STATISTICS GROUP
Division of Applied Management and Computing

SIMMAT: An Aircraft Materials Remanufacturing System Simulation Model

Part II: Implementation and Evaluation

Peter Johnson, Don Kulasiri and Richard Sedcole

Research Report No:99/15
October 1999

ISSN 1174-6696

RESEARCH REPORT

LINCOLN UNIVERSITY
Te Whare Wānaka O Aoraki

Applied Computing, Mathematics and Statistics

The Applied Computing, Mathematics and Statistics Group (ACMS) comprises staff of the Applied Management and Computing Division at Lincoln University whose research and teaching interests are in computing and quantitative disciplines. Previously this group was the academic section of the Centre for Computing and Biometrics at Lincoln University.

The group teaches subjects leading to a Bachelor of Applied Computing degree and a computing major in the Bachelor of Commerce and Management. In addition, it contributes computing, statistics and mathematics subjects to a wide range of other Lincoln University degrees. In particular students can take a computing and mathematics major in the BSc.

The ACMS group is strongly involved in postgraduate teaching leading to honours, masters and PhD degrees. Research interests are in modelling and simulation, applied statistics, end user computing, computer assisted learning, aspects of computer networking, geometric modelling and visualisation.

Research Reports

Every paper appearing in this series has undergone editorial review within the ACMS group. The editorial panel is selected by an editor who is appointed by the Chair of the Applied Management and Computing Division Research Committee.

The views expressed in this paper are not necessarily the same as those held by members of the editorial panel. The accuracy of the information presented in this paper is the sole responsibility of the authors.

This series is a continuation of the series "Centre for Computing and Biometrics Research Report" ISSN 1173-8405.

Copyright

Copyright remains with the authors. Unless otherwise stated permission to copy for research or teaching purposes is granted on the condition that the authors and the series are given due acknowledgement. Reproduction in any form for purposes other than research or teaching is forbidden unless prior written permission has been obtained from the authors.

Correspondence

This paper represents work to date and may not necessarily form the basis for the authors' final conclusions relating to this topic. It is likely, however, that the paper will appear in some form in a journal or in conference proceedings in the near future. The authors would be pleased to receive correspondence in connection with any of the issues raised in this paper. Please contact the authors either by email or by writing to the address below.

Any correspondence concerning the series should be sent to:

The Editor
Applied Computing, Mathematics and Statistics Group
Applied Management and Computing Division
PO Box 84
Lincoln University
Canterbury
NEW ZEALAND

Email: computing@lincoln.ac.nz

SIMMAT: An Aircraft Materials Remaunfacturing System Simulation Model

Part II: Implementation and Evaluation

Peter Johnson, Don Kulasiri, Richard Sedcole

Applied Management and Computing Division,
Lincoln University, New Zealand

Following conceptual development a prototype data-driven simulation model was developed, for decision support, with an actual aircraft materials remanufacturing system located in Christchurch, New Zealand. The model consists of structured logic statements based on observations and information supplied by the system's staff. It processes information relating to staffing levels and the work received over time. Processing times are represented using stochastic probability distributions. Outputs include numerical data and animated graphics. For evaluation purposes the model was set to simulate Repair Group operations for a recent period of time. It was found that after an appropriate warm-up period, performance could stabilise at levels consistent with normal operation. Simulated workloads were compared against the expectations of experienced staff. It was felt that the model gave a credible indication of how the actual system had performed. Two 'what-if' scenarios were also investigated that staff should have found reminiscent with their own experiences. The effect and duration of changes under these scenarios were as consistent with staff expectations.

Keywords: remanufacturing; stochastic; data-driven; simulation; face validation; and evaluation.

1. Introduction

In the first part of this paper a conceptual overview was given of a prototype simulation model and the system it was designed to support. Issues such as the provision of data so a decision support system developed from the model can ultimately be implemented were also covered.

With this second part the prototype's implementation is discussed. Also covered is the testing of operational stability and assessment of face validity.

2. Coding and implementation

The simulation model of a remanufacturing system was implemented via a data-driven collection of interacting program modules or entities. This model, named SIMMAT, is a prototype that takes input details for a particular situation, processes this information using logic and operations based on the actual system, and provides a depiction of how the system would likely react. It was coded using Simscript II.5® (Version 1.9, CACI Products Company Inc., La Jolla, Calif.) processes, routines and data structures. Processes are coded routines that describe the history of an entity, and the systematic logic by which it operates through a sequence of interrelated events in simulated time [L&K]. The non-process routines and data structures are static entities used to initialise model settings, effect actions at particular points in time, and represent aspects of the simulated system's structure like equipment resources. As a program SIMMAT consists of over 8000 lines of source code, in addition to the libraries of Simgraphics graphical objects and external files containing data and settings to drive the model.

The architecture of the model is a set of simulation objects partitioned into competing processes endowed with information that specifies their behaviour subject to the competition they will encounter directly or indirectly from other processes. Simscript processes are created from inputs at specified points in time to represent jobs, and staff entities with values supplied continually from files to create jobs, set shift durations and staff numbers. Details such as parameters for model probability distributions are from computer files. Some settings, although not the probability distributions, are updated as the model advances through simulated time.

2.1 Parameter estimation

When the remanufacturing system was investigated the characteristics were determined of those processes and operations which define it. However inspection of the control and tracking production database indicated processing durations were being recorded to the level of delays within a shop section instead of individual operation durations. This prevented the objective specification of distribution forms and parameters corresponding to the actual system's processes and operations. However following recommendations given by practitioners such as Law and Kelton [L&K] three bounded theoretical distribution types were assumed. By interviewing experienced staff and management, indications were obtained of the duration of operations as well as other forms of delay such as internal handling or data entry. Appropriate parameters were then specified heuristically of scaled uniform, triangular and beta distributions to reflect these operations and delays.

2.2 Form

In part 1 of this paper the concept was introduced of model entities that exist for a temporary duration, whose creation is triggered by external data inputs and which compete against each other to mimic the delays and trade-offs of a remanufacturing system. There is no hierarchy with central or local model components providing a control function. Underlying the model is the principle that external events represented by external information drive the system, but that its constituent entities behave in accordance with standardised procedures and practices. Among the entities that constitute the model there are:

Leadhands accepting work into and signing completed work out of a shop or section.

Jobs that follow specified sequences of steps around the resources in specified shops and sections.

Shop processes to control, on behalf of a job entity, placement in queues for leadhands or processing resources.

External and *specialist* operation processes that represent outsourced processing or processing conducted by specialist service groups.

Processing staff that monitor specified resource queues in assigned shops and simulate the processing of work, which can be newly arrived, queued, or in a state of interrupted processing. Simplified variants of these staff entities are used to effect processing in the support sections.

Miscellaneous processes operate to: monitor staff numbers, processing operation and delay durations, queue-lengths, and workloads; prioritise simulated work; as well as drive animated displays. All processes call upon routines to perform calculations, export data to files or drive graphical devices. Staff entity associations with equipment resources are referenced using pointer variables. Queue structures are incorporated with the resource routines to record waiting job entities.

Inputs from a number of files supply SIMMAT with the details that trigger creation of entities or analogous processes. All input records are chronologically ordered by date and time fields. Information pertinent to the operation of an entity will be supplied as a part of any record. Separate files are used to drive the creation of different entity types, as well entities for different shops and sections within which the same staff entity types operate albeit with different state settings. In all twenty-one different files supply inputs to SIMMAT so it can simulate, with sufficient complexity and detail, the system it approximates.

An example input file *arc_op.dat*, contains sequential records of the following form.

```
ARC.OPERATION   2/26/98  8  0  7.5  8  2  1  1  2
ARC.OPERATION   2/27/98  8  0  7.5  8  2  1  1  2
ARC.OPERATION   2/28/98  8  0  7.5  8  2  1  1  2
```

ARC stands for Airmotive Repair and Control, the name of the support section handling clerical recording of job details, together with certification of serviced parts etc. The model will trigger an *arc.operation* event routine whenever it is scheduled to read a record in simulated time. The first of the above records would trigger the creation of an *arc.operation* instance for 26 February 1998, at 8.00 am. Staff processes created by the routine operate seven hours and thirty minutes for the first shift, and eight hours for the second. Three staff entities will be created for each shift ie, two clerical and one certifying staff for the first shift, one clerical and two certifying staff for the second shift.

Records that trigger creation of job entities are conceptually similar but more complex than those relating to staff entities, occupying multiple lines in the ASCII text format files that supply inputs. In addition to a creation time that equates to a job instance's time of arrival, there is a target date for the completion of processing, and a listing of the sections to be visited and operations performed (processing resources visited).

Event routines that take job details and create job entities also determine the values of stochastic quantities, such as the duration of processing operations, at the point in simulated time when details are read and an entity created. This feature allows synchronised random number generation, as a variance reduction technique, where the same file listings are processed under differing configurations of the simulated remanufacturing system.

2.3 Initialisation

In addition to supplying SIMMAT with formatted files it is necessary to specify other settings at initialisation. This is done by way of dialog box interaction with users. Among the details to be specified or options selected are: a stream for random number generation; the possible use of antithetic variables for variance reduction; choice of the shop or section for which to display measures of performance; and whether to display animations of aggregate shop-floor operations. Users also have the option of specifying a particular assembly for which extra details of parts processed are to be recorded.

2.4 Outputs

A wide range of outputs are produced by the prototype to enable, in order of importance: verification and validation of operations; evaluation of what-if scenarios; and the making of forecasts about the system's state on the basis of supplied schedules and staffing level details. To this end measures are produced indicating the:

- Time each job instance took to pass through the system, both absolute and relative to the specified target date;
- Time spent by each job instance, off a selected assembly, in each of the sections it was routed to; together with
- Workload, delay and throughput for each section, as well as work volumes and the meeting of target dates for the system overall.

With regard to this last point the measures produced were those staff and management use or could otherwise relate to. In particular the number of jobs and man-hours (labour-hours) of processing on-hand in each shop section, the number of jobs processed each day, and statistical measures of the delay experienced by these jobs in each shop section. The use of measures that staff are familiar with was intended to aid establishment of subjective validity.

Various animated displays of workload and state are produced as an aid to verification, and a means to visualise the model's essence and operation. The displays are dynamically updated as simulated time progresses with time indicated as a calendar date. One animation shows counts of jobs in process, along with counts of the jobs with support groups, other service groups and external service vendors. Icons change colour to show if simulated staff entities are working in a section. The total number of staff in each shop is also indicated. Additional icons indicate if certain areas or equipment resource groupings are in use. Animated graphs are also produced of the proportion of target dates met, together with average delays, volume of work as well as processing on-hand in a selected section. The graphs relate to the period of the model's execution including any warm-up period. Given the model's complexity the displays are necessarily of a aggregate nature, but serve as aids to understanding and using the model. Figures 1 and 2 show example displays from a trial execution of the model.

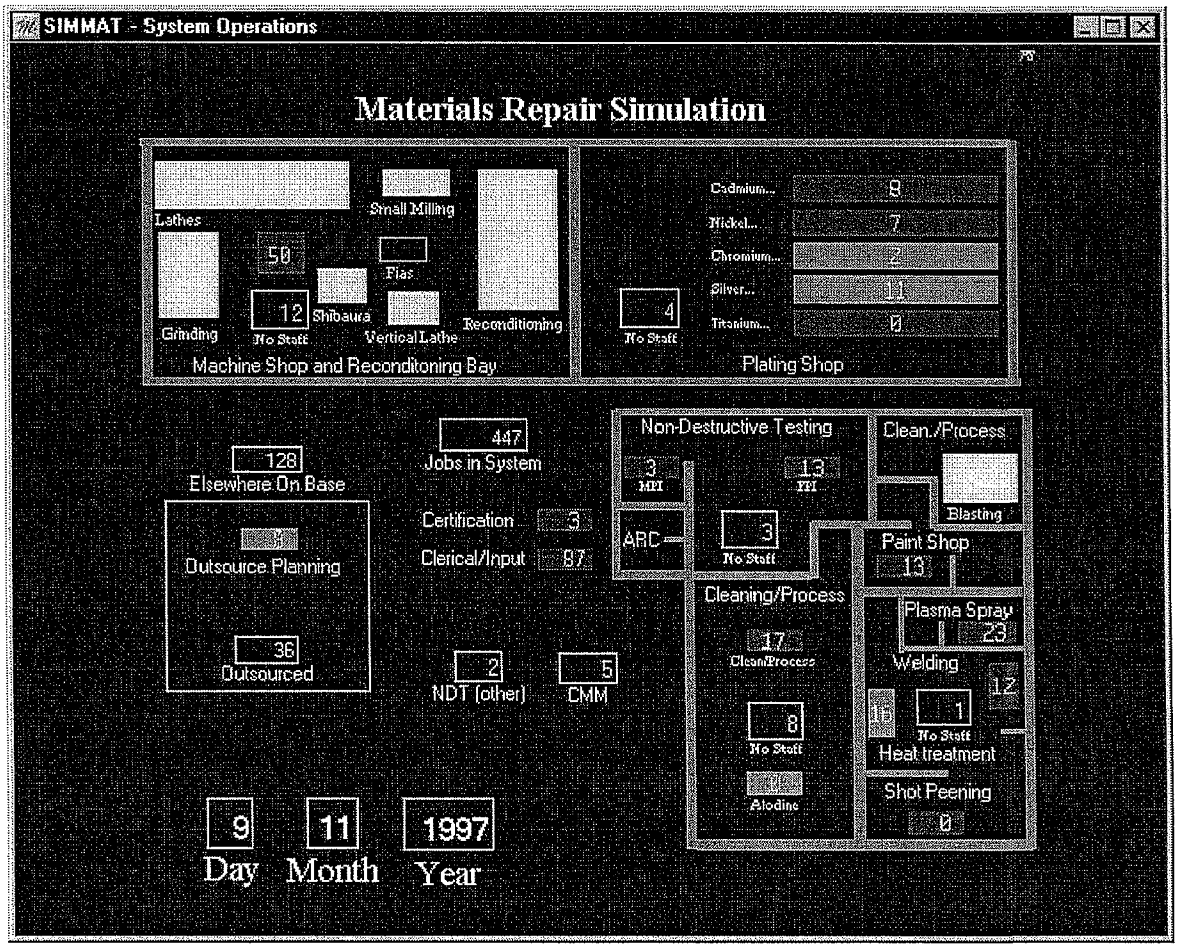

Figure 1: Animation of simulated repair group aggregate operations

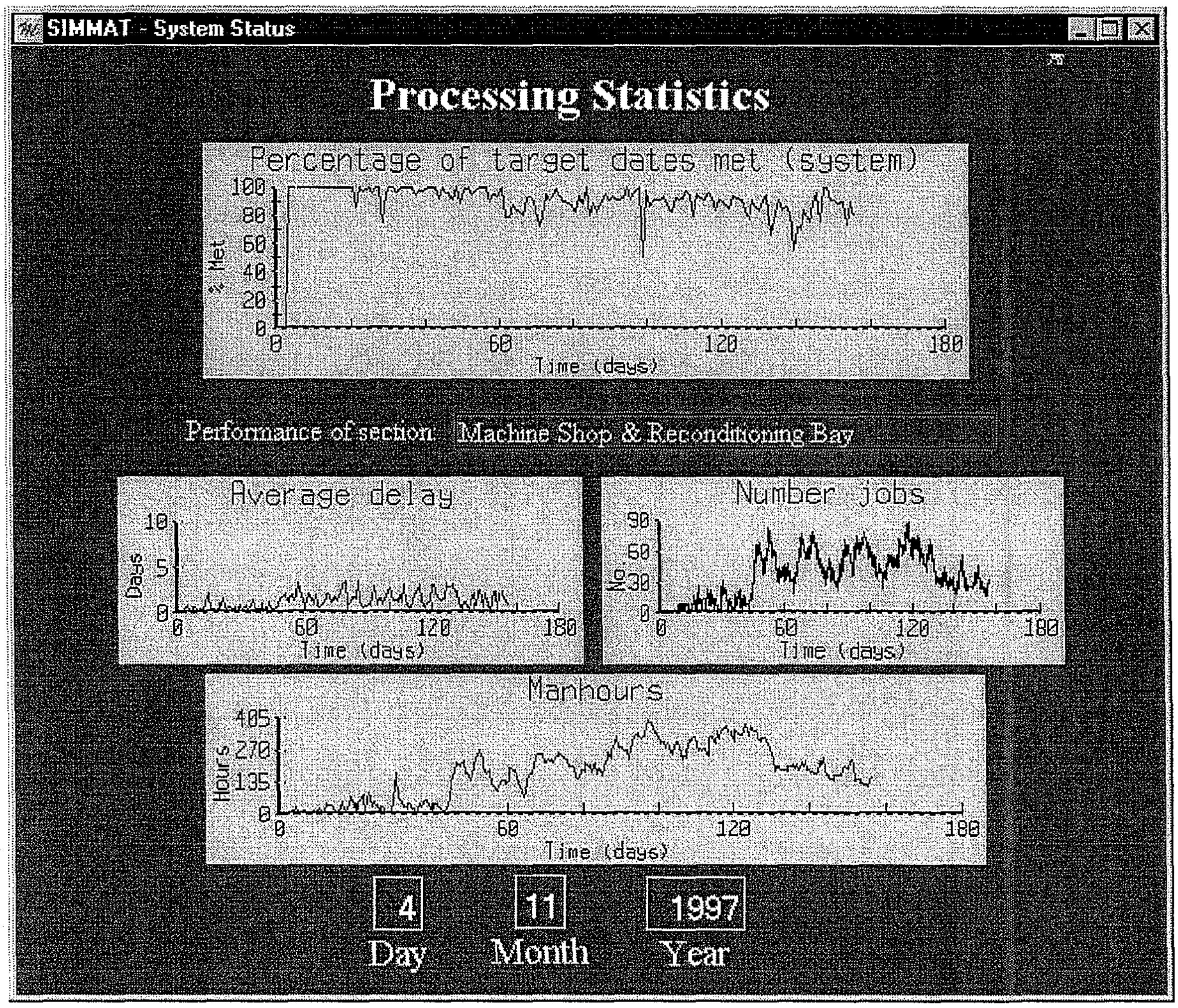

Figure 2: Sample graphic displays of the proportion of target dates met, as well as workload and delay for a selected section of the simulated remanufacturing system.

3. Evaluation and testing

During implementation SIMMAT was subject to some informal testing and review by 'expert' staff and management. This testing was intended primarily to verify the implementation, in accordance with principles laid down or recommended for model development [1,5]. It served to introduce the model to staff and obtain feedback. However the model's unfinished nature during implementation meant any review efforts were limited.

Any evaluation of SIMMAT was bound to be complicated given its stochastic basis and terminating nature, an operation dependent on dynamic inputs, and the usual concerns regarding discrete event simulations and correlated observations with non-stationary outputs. However analytical issues aside, there was also the lack of information to drive the model with, or evaluate it against. The modern enterprise resource planning system discussed in part 1 was not operational and so unable to provide the data required for the model to execute. Further there was limited retention of performance data that model behaviours could be compared against. The available performance data was in the form of processed aggregate tables and graphs, or miscellaneous records kept by individuals. For these reasons, and in view of SIMMAT's prototype status, subjective evaluation was employed to justify the model. A hermeneutic approach was taken where interpretation and understanding was sought through dialog and practice, with knowledge about the model developed through application and participation (4). Hypothetical profiles were produced of staffing and work data together with other settings to configure situations staff and management were familiar with. SIMMAT was then executed using these profiles, with analysed outputs presented back to staff for their critical assessment.

3.1 Validation of warm-up and steady state behaviour

Approximate profiles were developed of work received, staffing levels, and other settings, for the period 1 June 1997 to 31 March 1998. These were based on available records and intended to provide a credible picture of staffing levels, work requirements, and other settings. The staffing and shift duration profiles were produced using Microsoft Excel 97® spreadsheets. Sample job details were obtained from a selection of assemblies and analogous sources. These may not have been representative but they were believed typical. Gathered details related to both the assembly and the jobs that arose from each such source. Staffing and shift duration profiles were also produced for the sections and shops that constitute the Repair Process. Other settings were based on what was typical for the period.

Collected job details were entered into an Access 97® database application designed to record the information, manipulate it into an appropriate profile, and configure the profile for input. Forward planning schedules and also staff recollections were used to determine the approximate induction schedule, by date and assembly. Records for the sample assembly or part grouping that most closely matched each instance in the schedule, were repeatedly extracted from the database, and entered into the profile of jobs to be processed. After consultation the developers assumed that although no two assemblies are the same in terms of processing requirements, assemblies of a similar type and history generally make the same demands on the Repair Group.

SIMMAT was run for the period of simulated time 1 June 1997 to 30 June 1998, allowing for a warm-up phase, and also a run-down phase. This accounted for the cessation of simulated work arrivals on 31 March.

There were two main objectives to the evaluation exercise:

1. Assess operational consistency in that the model needed to progress from an empty state to states consistent with normal operation, where dynamic non-stationary operation is the norm; and

2. Assess closeness of the relationship between SIMMAT and the system it approximates. This assessment focused on the following areas or situations:
    - Do the same part types that run late in reality do so in the simulated depiction?
    - Do mean workloads and delays approximate those of the actual system for the evaluated period?

- Did selected sections behave in a credible manner when simulated?
- Does the absence of staff from a critical section have the expected effect on workload and delay?
- How does aircraft servicing affect operations both overall and in selected sections?

While there is a virtually infinite range of profiles and situations SIMMAT could have been tested with, those specified were felt to match the study objectives and encompass a reasonable range of operating conditions. Operational consistency was judged in terms of three criteria:

- Measures of system performance or state stabilising within limits appropriate to normal operation;
- Variation about these measures stabilising between bounds linked to a controlled non-stationary state; and
- Further increases in warm-up period duration having negligible effect on job processing times.

The latter criteria was intended to assess sensitivity of job processing times to warm-up period, and validate the warm-up period determined from assessment of the other criteria. Ensemble averages were calculated, together with measures of variance, for the performance measures output by the model for each day of simulated operation from independent runs (2). Standard deviations were plotted over simulated time to test whether values were stabilised in an acceptable band between control limits, which is the same approach taken in industry with statistical process control charts. 'Normal' operation was equated achieving states of statistical control. Plotted ensemble average values indicated when the simulated performance measures were of reasonable magnitude and whether the model's operating state was controlled albeit dynamic. Figure 3 is an example plot of the number of jobs in process over simulated time.

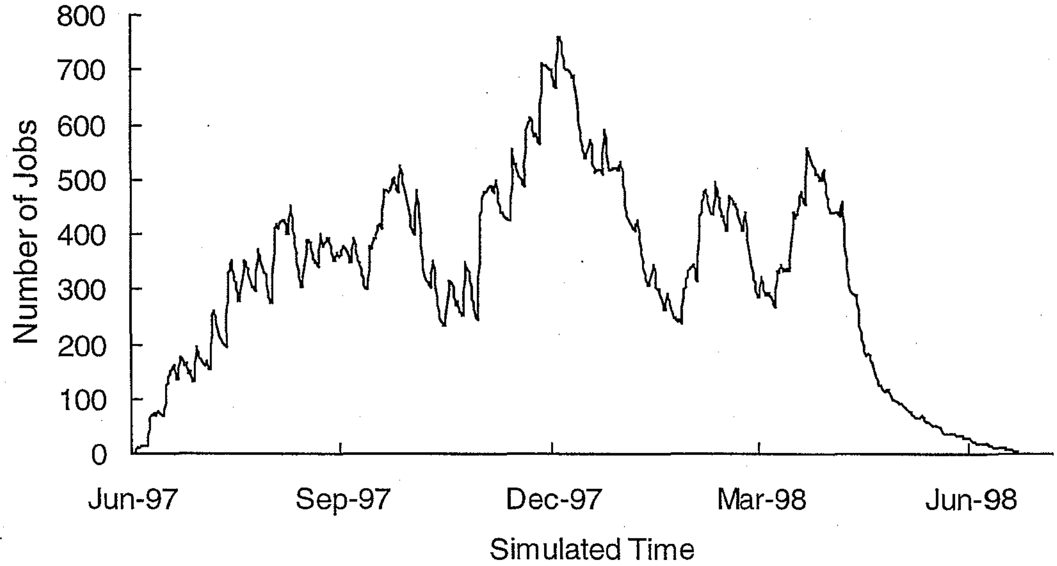

Figure 3: Ensemble average number of jobs in process over simulated time. Minor troughs and peaks on the plot are attributable to a greatly reduced volume of work arriving at weekends, followed by a surge in arrivals at the start of the working week.

After assessing a number of measures, and using the developed profiles, it was determined fourteen-weeks simulated operation was more than adequate to achieve normal consistent states of operation. As a check on warm-up period duration, processing times were investigated for a sample of parts received into the simulated system at a particular point in simulated time. The profile of jobs to be processed prior to these parts arrival was repeatedly truncated in order that the preceding volume of work, and therefore potential level of competition for resources would be reduced. One-way analysis of variance indicated processing times for the sampled parts did not vary significantly, whether the preceding warm-up period was four or fourteen weeks in duration. Stable resource queue lengths appeared to have been achieved in a reasonably short period of simulated operation.

Once operational consistency was assured, SIMMAT's operation was investigated using the prepared profiles, together with variants modified to effect a change in situation. The frequency with which each generic part type tended to run late was determined, with results presented to staff for comment in light of their experience and expectations. Ensemble averaged measures of workload and delay were plotted in raw and smoothed form over simulated time. These were compared against staff expectations, together with recollections and retained records for the period being simulated. This was done for measures of overall system performance, as well as performance in selected sections. An example trace is given as figure 4.

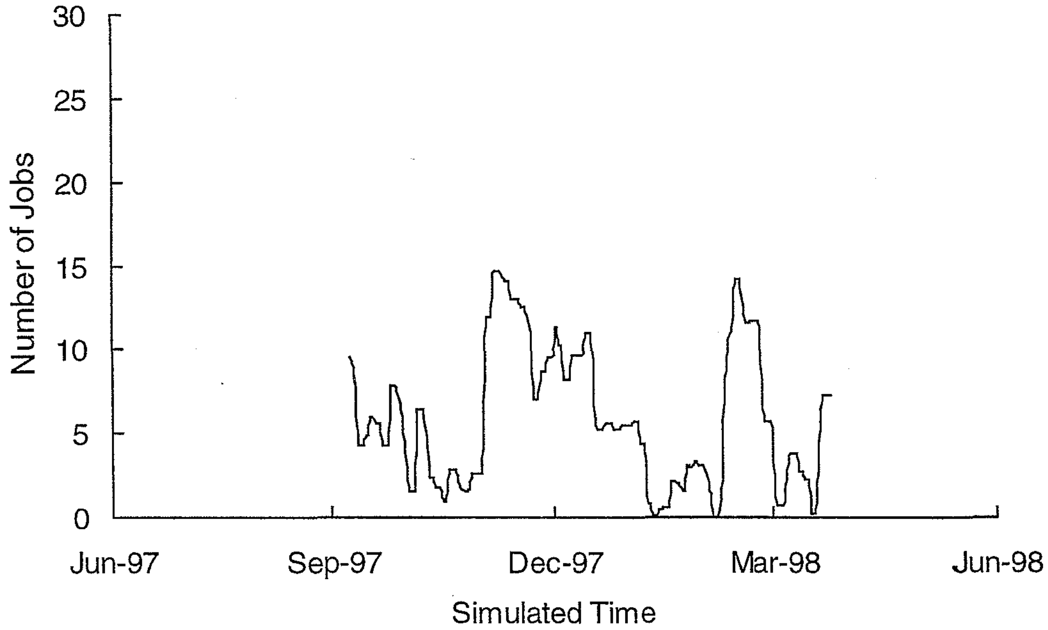

Figure 4: Smoothed plot of number of jobs on hand in the nickel plating section of the Plating Shop.

3.3 What-if scenarios

Experiments were also conducted where staffing and work profiles were modified to assess the effect: where the dye penetrant inspection section in the Non-Destructive Testing Shop was not staffed for one shift over three days; and also where additional aircraft are accepted for servicing elsewhere on the base. With each evaluated case, performance measures for the alternate scenarios were generated, and compared using forms of multivariate profile analysis (6,3). The analyses were used to test for differences between the profiled measures, and also to test when over simulated time the differences arose or otherwise ceased. Analysis results together with the plots of ensemble average performance measures for the alternate scenarios were presented to staff for comment. Figure 5 is an example plot of the man-hours of work on-hand in the dye penetrant inspection section.

Overall the subjective evaluation of SIMMAT's performance subject to hypothetical but realistic work and staff detail profiles found the prototype's behaviours to be credible. The employed measures were commented on as been meaningful. Performance measures were recognisable to staff in terms of both their magnitudes for particular situations, and also their responsiveness to changes in situation. Furthermore, SIMMAT was judged by staff and management to have good potential as a tool to support operational planning together with strategic decision-making.

4. Summary and future work

Development was reviewed of a model representing the material flows of a remanufacturing system. The model, SIMMAT, consists of entities and structures that relate to those present in the actual system. It is data-driven allowing simulated staffing levels, work arrival characteristics, and also the processing requirements of individual jobs to be changed over time as would happen in reality. Sufficient detail was built into SIMMAT for the system's

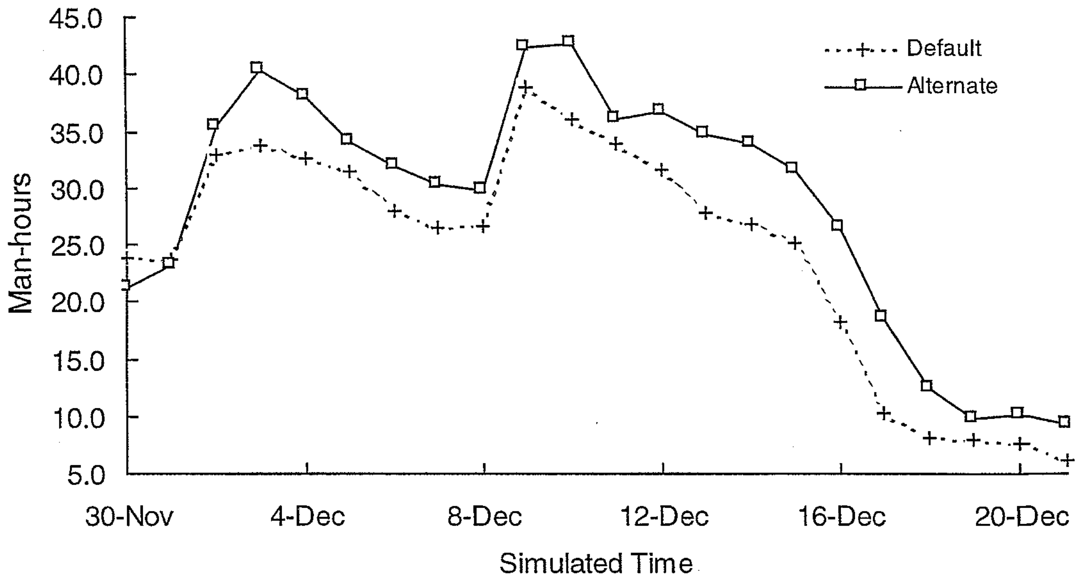

Figure 5: Man-hours of work on-hand on the dye penetrant inspection section. The staffing change occurred for the simulated day-shifts on December 1,2 and 3. No overtime was worked after these dates in simulated time to clear any backlog. A comparable situation to the alternate scenario in reality would be day shift operators attending a training course with no substitute staff been available. The duration of effect is realistic as staff in the Non-Destructive Testing section generally don't work overtime.

main processing resources ie, staff entities and major items of equipment, to be represented. The model was evaluated subjectively under hypothetical simulated conditions related to the actual system's state over a recent period of time. Expert staff who evaluated SIMMAT under the defined scenarios thought its performance to be credible.

Potentially, with further development and testing the simulation model could be utilised as a decision support tool. Ostensibly it should also be possible to develop useful simulation models of other dynamic remanufacturing systems. Empirical testing and calibration, would be a necessary aspect of any further development and require accurate detailed information to be available from production databases. Extending production databases to record a more detailed level of information, along with adaptation of this information to forecast future workloads is an issue to be addressed. It would also be desirable to revisit some of the assumptions and limitations that underlie the model. Since SIMMAT was developed changes have been made to the Materials Repair Group, for example the location of certain equipment resources. Modifications will be required to reflect these changes. Performance measures produced by SIMMAT are those that Air New Zealand staff could recognise and evaluate. However other measures should also be considered, such as levels of equipment resource utilisation. Modifications so additional or alternative measures of performance are recorded is an area for further consideration. Modifications using technologies such as heuristic rules and artificial intelligence could also be used to extend SIMMAT's capabilities in terms of the provision and processing of information, as well as the analysis of outputs.

5. Acknowledgments

Research described in this article was undertaken in conjunction with the Airmotive Group, and the Materials Repair Group, on Air New Zealand's Christchurch Base. The New Zealand Government, under its Graduate Research in Industry Scheme, provided financial support. This scheme is administered by the Foundation for Research, Science and Technology.

6. References

[1] O. Balci. Principles of simulation model validation, verification and testing. *Transactions of The Society for Computer Simulation International*, 14(1), 3-12, 1997.

[2] J. Banks, J.S.Carson, and B.L.Nelson. *Discrete-Event system simulation (2nd edition).* Prentice-Hill, 1996.

[3] M.G. Kenward. A method for comparing profiles of repeated measures. *Applied Statistics*, 36(3), 296-308, 1987.

[4] G.B. Kleindorfer, L. O'Neill, and R. Geneshan. Validation in simulation: various positions in the philosophy of science. *Management Science*, 44(8), 1087-1099, 1998.

[5] A.M. Law, and D.W. Kelton. *Simulation Modelling and Analysis (2nd edition).* McGraw-Hill, 1991.

[6] D.F. Morrison. *Multivariate Statistical Methods (3rd edition).* McGraw-Hill, 1991.