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The Development of a Discrete-Event Simulation Model to Aid the Design of Complex Manufacturing Systems

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***Abstract*—The emerging dominance of lean and agile techniques is resulting in a worldwide trend towards shorter product cycles, with smaller lead times and shorter production runs. Discrete-event simulation is a time-consuming process and data collection is such a major part of the time period of such a cycle. This paper introduces the circuit of observation concepts which provide a massively reduced cycle time for data collection; this makes it a much more valuable tool in a manufacturing environment and expands its uses due to its greater flexibility. The case study strongly supports the findings.**

***Index Terms*— Activity Sampling, Manufacturing Systems, Discrete-Event Simulation.**

I. INTRODUCTION

Computer-based simulation [1] is widely used in many disciplines and is becoming an everyday occurrence in the analysis of many fields. Discrete event simulation [2, 3] in a manufacturing environment [4] has been used successfully for several decades with its first uses documented in the 1960s [5, 6]. In the paper written by Foster & Rose [7] they discuss various issues that must be overcome in order to spread process modelling of manufacturing systems into mainstream use.

Simulation software has made great advances recently, with the use of new easy to use graphical interfaces for the use of those with no programming background. [8, 9, 10, 11] However a major handicap remains in using simulations, which is the length of time required to collect necessary data and then prepare a simulation model. Observing processes to form statistical distributions of process times requires a large amount of continuous observation.

Simulation is closely linked with lean/agile manufacturing [12, 13]. The lean and agile methodologies share many attributes, and agility is considered impossible unless a certain element of leanness exists first. Agile development was first fully discussed in a book by Goldman, Nagel & Preiss [14]. In a manufacturing sense, production must be able to operate over short production runs, with small changeover times and a great degree of flexibility. Song and Nagi et al [15] have identified some of the problems with short-run high variety manufacturing in their development of a modelling system for industrial fabrication shops. This is an extreme example, requiring a specialized modelling tool. Some of the issues this model addresses are encountered in a typical simulation study of a short-run manufacturing facility, such as each product having a unique path to define the process sequence. Short run projects also require additional accuracy due to the lack of data available.

As manufacturing cycle times become reduced, there is a reduction in work-in-progress (WIP) and manufacturers seek a faster response, and production runs will operate for less sustained periods of time. The most important aspect of simulation is that it is available for use before it becomes obsolete [16, 17]. In this setting of short production runs and rapid reconstruction, the period of time available to construct accurate simulation models becomes reduced.

II. SIMULATION IN MANUFACTURING SYSTEMS

A. The Need for Faster Cycle Times in Simulation Generation

The goal of '*reducing the period of problem-solving cycles'* is a natural partner of *'greater acceptance of modelling and simulation within industry',* both goals of the simulation community which were identified by Foster & Rose [7]. In reducing the length of a simulation study by improving the method, the time invested in the process results in more overall value for the effort expended. By improving this ratio of effort to the value of the results gained, it becomes a more attractive process in the manufacturing workplace and its adoption becomes more likely.

B. Shorter Lead Times in Manufacturing

The emergence and dominance of Lean/Agile Manufacturing will in the future produce significantly shorter lead times for products, and rapid change in the manufacturing workplace. Lead times will become shorter and shorter, and more flexible factories result in frequent changes in system. As a simulation becomes redundant when the system is changed, the speed of the

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generation of the simulation must be proportional to the time the system is in place.

Generating a simulation can be a slow process, particularly for complex systems. Simulation software has progressed significantly in recent years, with graphic interfaces improving the ease of use substantially. While the process of constructing the simulation from the collected data is shortened every day with new software and additional features, this is only the second half of the process. An immense amount of data is required when modelling simulations using this software. Continuous observation is an extremely inefficient process with a significant amount of observation time, in effect, wasted. When recording the required data using continuous observation to construct a simulation, this 'dead' time becomes a significant source of inefficiency in the process.

A method of quickly collecting the data for the simulation is required so that it can reduce the overall time required to produce a simulation. However, a brief read of much of the published literature reveals a significant problem – almost every text on modelling in manufacturing focuses solely on the actual building of the simulation. There is no mention of techniques that can be employed to collect data for the simulation effectively. 'Discrete Event Simulation: A Practical Approach' by Pooch & Wall [18] is typical of this attitude. The vast majority of the book focuses on software techniques and applying these, while a sole small chapter entitled 'Simulation Data Collection' is written towards the end. The chapter is devoted to collecting data *from* the simulation, rather than for its construction.

Within the simulation community, it appears that the method of the data collection itself is not something to concern themselves with. This is despite it being an integral part of the process [19, 20, 21].

C. *Allowing Managers to Create Their Own Simulations*

Simulations benefit immeasurably from first-hand experience of the situation that is being modelled. For an outside consultant to model the simulation, they must first understand the situation and the crucial points that require modelling. It is easy without complete inside knowledge of the simulation to fail to establish the parts of the system that create unexpected behaviour, and outside consultants have an interest in completing simulations as quickly as possible where this behaviour can be missed.

A manager who is familiar with the system and able to complete the simulation themselves is unlikely to miss factors that create this unusual behaviour, due to their experience of the situation. They will know how best to design the data collection, the simulation itself and interpret the results correctly. Managers that are familiar with the simulation are best able to elect the correct level of detail for the simulation and system, which is a crucial factor in a simulation's success as discussed by Foster & Rose.

Assuming training is provided in simulation software, the most important aspect of achieving this goal is to ensure that data for the simulation can be collected and building the simulation itself can be completed as efficiently as possible. A manager will only want to invest precious time in the process of the simulation if it requires as little effort as possible for maximum returns.

III. CIRCUIT OF OBSERVATION

A. *Activity Sampling*

'Work Study' by R.M. Currie [22] discusses a technique which can be used to observe a number of simultaneous processes over a period of time. The method of 'activity sampling' considers a continuous process as being comprised of "*a number of individual moments during which a particular state of activity or inactivity prevails*" [23]. This forms the basis of a technique where a number of individual moments selected at random or fixed intervals can form an estimation of the overall time spent on each activity.

'Activity Sampling' is a technique that is "aimed at providing a record of what is actually taking place at the instant the job is observed; it is not a record of what the observer thinks should be happening, nor what has just happened nor is about to happen"[23]. This is an important feature of the technique, as it attempts to provide an objective method of providing a scientific estimation of the percentage of time spent on a given activity, rather than a subjective estimate. Estimations can be formed over a period of time by making observations, to build up a picture of the overall pattern of work.

The technique can be best explained with an example - a single machine, with only two states: active and inactive. Figure 1 shows what would have been observed with continuous observation.

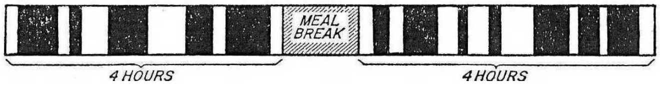


Figure 1 Single machine with continuous observation (picture courtesy Work Study, R. M. Currie)

Total period of continuous observation = 8.0 hours
Total non-working time = 3.7 hours
Non-working time (% of total time) = 46.3%

Supposing random activity sampling was carried out independently, with thirty random observations over the period, the situation would be shown in Figure 2:

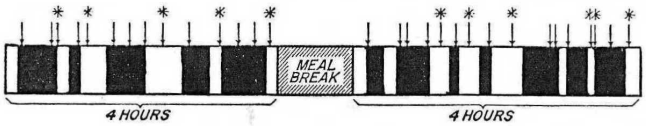


Figure 2 Single machines with random activity sampling (picture courtesy Work Study, R. M. Currie)

Number of random observations = 30
Number of non-work observations (*) = 11
Percentage of observations that are non-working = 36.7%

Random interval sampling is preferred over fixed interval sampling. This is because it is possible with a fixed interval that the fixed time duration may coincide with regular work patterns. For example if works occurs every five minutes and a sample is taken every ten, it is likely the samples will show a disproportionate amount of work that is occurring. However, as long as it can be ensured that a sampling interval is not an exact interval of a work cycle this problem can be avoided easily.

B. Accuracy

In any sampling activity the estimated value will inevitably differ from the real answer value. With more observations, a more detailed profile would be built up and the accuracy of the estimate would be improved. The accuracy of the figure obtained can be guaranteed to within ± L nineteen times out of twenty (95%), L representing the limits of the permitted variation stated as a percentage of total time. The number of observations (N) required for 95% accuracy to be within the percentage limits, L%, is expressed as the given formula:

$$N = \frac{4p(100-p)}{L^2} \qquad (1)$$

This can be rewritten as:

$$L = 2\sqrt{\frac{p(100-p)}{N}} \qquad (2)$$

where p is the (approximate) occurrence of the specified activity as a percentage of N. As the number of samples increases, p can be reassessed to give a more accurate value of the 95% variation, L.

C. Circuit of Observation

Activity sampling is used to provide large quantities of data for a relatively low proportion of observation time. It is possible to combine the studies of many different processes into a circuit of observation. A circuit of observation comprises of a set pattern that can be replicated precisely with fixed intervals between each circuit (typically 10 to 15 minutes, depending on the circumstances in each individual case). It can be used to provide data quickly on a number of locations requiring study. Activity sampling is ideal for studying many different operations that occur simultaneously.

A circuit of observation involves making a sample at each location on a circular tour, over a fixed period. Each measurement is made on a circular route that is designed to reduce the time needed to complete the circuit. This allows the maximum amount of data to be made. The observer must establish the locations for which observations are required and adjust the route accordingly.

It is also important to decide the type of measurement to be taken, which is very flexible depending on the information required. Many types of measurements seemingly requiring continuous observation for the purpose of simulation construction can be approximated using this circuit method.

IV. ADVANTAGES OF ACTIVITY SAMPLING IN SIMULATION

A. Rapid Data Collection

It may appear advantageous to have many precise durations gathered using continuous study, it is in fact a demonstration of the significant time that has been inefficiently wasted by the observer. All that required is an observation of the start time and finish time to form the duration. Any observation in between these times is essentially valueless. For example, just twenty observations of a single process that takes on average 5 minutes long would result in over an hour and forty minutes of observation time.

B. Study of Multiple Processes Simultaneously

As already discussed, activity sampling is ideal in collecting data from the study of multiple processes simultaneously, and provides estimates in a systematic way much more effectively than continuous observation. It enables the observation period to be spread over a longer duration when studying multiple activities as continuous observation of one process loses potential data from all the other processes that occur simultaneously. This improves the long-term reliability of the results as data may be recorded over a period of a week, for example, rather than just a day for each process.

There is an issue of activity sampling that it is a *sample*. In any sampling technique potential for error is introduced. Activity sampling cannot provide the precise values that continuous study can provide, and it is a matter of opinion and the particular circumstances of each case whether this accuracy can be sacrificed for a considerably shorter data collection period.

C. Reduced Chance of Disturbance

Any simulation is concerned with the observation and recreation of a process in its natural state. There are many ways in which observation can disturb how a system acts normally. These include an observer simply becoming an inconvenience, or the act of observation altering behaviour.

A circuit of observation helps to greatly reduce this risk of altering system behaviour as an observer is present for only a very short period of time overall.

D. Collection Period

When similar periods of observation time are invested in both a continuous study and an activity sampling-style study, the activity sampling study will produce results spread over a larger period. This is preferable as it helps to remove the risk of corrupted data produced by random fluctuations or unusual conditions. This should improve the accuracy of the data obtained in its representation of usual conditions.

E. Data Collection Types

In the examples discussed so far the data collected has been the proportion of time a worker has spent working, or the 'utilisation' of that worker. Utilisation can be used in simulation programs to slow the speed of a workstation according to how often it is in use. This is an effective way of sharing resources in correct proportions over different workstations.

It is possible to adjust this technique slightly to allow it to record different information required in a simulation study. Utilisation is used in the following case study to approximate individual process times for each workstation, by dividing the overall production rate of products by the percentage utilisation at each workstation.

An important part of simulation is the use of process timings or distributions [24]. By recording on each circuit the number of products produced since the last circuit which are awaiting further work, it is possible to form an estimation of the time required by averaging the period by the produced figure for the last interval. Although it does not produce exact timings, over a number of values it should produce an estimation of either the average or distribution. An example of how the averaging works is shown in Table 1.

In Table 1, three items are produced in the first circuit (with duration of 10 minutes). Therefore they are calculated to have an average time each of 3.33 minutes. This process continues with each circuit and, depending on process times, the average over several cycles should imitate the overall average process time. This method can be made more sensitive by shortening the length of time the circuit lasts, however caution should be exercised when reducing the circuit length – a particularly short circuit relative to process length will result in a highly irregular pattern, with several jobs completed one cycle and no jobs completed the next.

This method could be extended in certain circumstances to estimate process time distributions, plotting the average times in a histogram. This will require more jobs per cycle to produce a suitable variation of average process times and plot the histogram in any detail, and also more observations to improve its accuracy. With a suitable amount of average times, the histogram can be formed by dividing the average times into groups to form the distribution. This process itself should also improve accuracy, as with even exact process timings they must still be separated into groups to form the distribution.

There are some difficulties when calculating average process times from items produced over a time period. It is important that there is a storage bin so that the products can be counted. As processes are part of a flow system, confusion will occur when products are removed for the next process. Either a clear record of products being removed from storage must be available or, alternatively, display boards or a similar method of display are required to track production, rather than counting in a storage bin.

Table 1 Example of averaging in circuit of observation

Iteration	Process Time		Circuit	Circuit
	Individual	Cumulative	Noted	Average
1	2.33	2.33	1	3.33
2	3.27	5.60	1	3.33
3	3.11	8.71	1	3.33
4	3.05	11.76	2	3.33
5	2.42	14.18	2	3.33
6	2.97	17.15	2	3.33
7	3.16	20.31	3	2.50
8	2.57	22.88	3	2.50
9	2.43	25.31	3	2.50
10	3.07	28.38	3	2.50
11	2.52	30.90	4	2.50
12	3.23	34.13	4	2.50
13	3.07	37.20	4	2.50
14	2.45	39.65	4	2.50
15	3.04	42.69	5	3.33
16	2.59	45.28	5	3.33
17	2.49	47.77	5	3.33
18	3.01	50.78	6	2.50
19	3.21	53.99	6	2.50
20	2.42	56.41	6	2.50
21	2.49	58.90	6	2.50
Average	**2.80**			**2.86**

V. METHODOLOGY TESTING – HENDERSON DOORS

The case study at Henderson Doors was intended to establish the general validity of as many as possible of the methods suggested earlier. These included the use of the 'Circle of Observation', and an assessment of the ability to map DSM charts directly into the Simul8 application.

PC Henderson Ltd is located on the North Bowburn Industrial Estate in Bowburn, County Durham. Established in 1931, PC Henderson Ltd is one of the largest manufacturing employers in the area. PC Henderson Ltd specialises in making sliding door gear and garage doors. The study at PC Henderson was to model the final assembly stage of the garage door section of the business.

A fully mechanised line is used to roll metal doors which are then drilled with holes according to the door design. They are then stored awaiting painting. The painting plant uses a dry powder process that is also highly automated to paint the doors. A complete cycle of the paint plant lasts approximately an hour during which doors are completely coated and then allowed to dry in ovens. After painting, doors are then stored again awaiting final assembly.

The final assembly line consists of five main work areas, a buffer table before the second area, and a wrapping table for wrapping doors when requested. The stages of the assembly line are outlined below;

Work Area 1 (FA1): Used to fit the external locking points to the door, while door sits vertically.

Buffer Area: Single table with rollers and capacity for one door. Used to lower doors to horizontal position.

Work Area 2 (FA2): Door lowered to horizontal position. Part of the frame is fitted to the door.

Work Area 3 (FA3): Between FA2 and FA5 there is a single continuous roller line for sliding doors along. Further parts of frame/mechanism are fitted in this area.

Work Area 4 (FA4): Door barcode scanned to register completed door. Some final parts are added.

Work Area 5 (FA5): Door rolled onto wrapping table. Door wrapped if required, and then harness looped around door. Door then raised and lifted onto pallet.

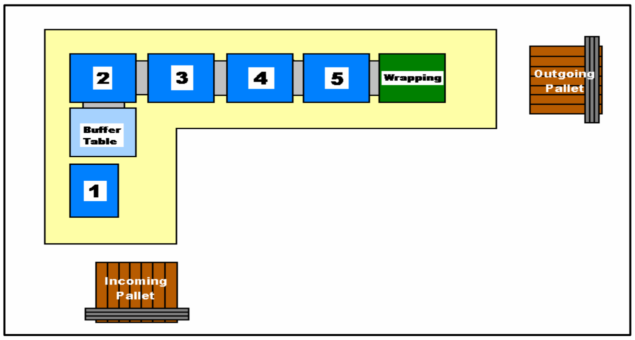


Figure 3 Final assembly lines

The layout of the work areas are shown in Figure 3. Each workstation is supplied using a kanban system stocked by support staff, and small parts such as screws are supplied from eye-level shelving.

Above the assembly line, two computer monitors display the amount of doors previously produced, split into divisions for each hour. This enables constant feedback to the line on their targets and whether they are being met, and for management to monitor performance easily.

Ideally each workstation (FA1 to 5) would have had a sizeable buffer between each workstation. This would enable the output of each workstation to be monitored for each circuit. The final assembly line was a one-piece-flow line, with each workstation passing work onto the next without a storage stage. This meant that the performance of each workstation could not be monitored simply in terms of items produced, as each workstation worked at effectively the pace of the slowest.

To find a way to estimate the *actual* work time of each workstation, the utilisation was monitored at each. The utilisation of each workstation was then used to estimate the time spent working on a product as a fraction of the total rate it passed along the assembly line. So if a workstation was working at a rate of 100% overall, its process time would be the same as the products being produced. With only 50% utilisation, then the process time would drop to half the production rate. Overall the production rate in the simulation will be the same, but rather than one 'process' block for the whole line, it is split into individual workstations. This is crucial as in the future it is then possible to simulate changing the configuration of the line as well as the number of lines themselves.

It should be noted that the study relates to the actual workstations, rather than the staff at each workstation, so a low utilisation does not relate to the time spent working by staff. It simply reflects that the three teams of staff divide their time between different workstations. By adding the utilisation of all the workstations together, the total is 290% (or 97% per staff team). While this reflects time *any* work was occurring at that location (so perhaps only one member of staff was actually working rather than both) it generally demonstrates that overall staff utilisation was very high and work was well balanced between teams.

The production figure for each circuit was easily observed from overhead monitors. Each door is barcode scanned at workstation 4 after assembly work, and this is registered on each monitor. This meant the production rate for each circuit was recorded quickly and without error.

Due to the variety of products passing through the assembly line, it was important to ensure that this was accurately recorded. Initial discussions confirmed that product type could have a significant impact on process times, and therefore would require careful consideration. By examining the outgoing pallet it was possible to note down the recently produced types of product. This also helped to ensure the production figure for the last circuit was correct.

The circuit that was devised involved three separate locations, to give a complete view of the final assembly line. The first position was a head-on view of the first work area FA1, where observation of the initial workstation and incoming pallet are located. The second position allowed observation of the workstations two to four (FA2, FA3, and FA4) and the monitor which displayed the production data. The third location observed the wrapping table, later workstations and also the outgoing pallet to note the product types (FA4, FA5).

The circuit required approximately four to five minutes to complete. With a circuit every ten minutes, the remaining five were used to collate the data and plan next steps or make notes. Later any remaining time was used to enter data immediately into an excel spreadsheet.

VI. SIMULATION CONSTRUCTION

The simulation has been constructed using the 'Simul8' modelling software. The simulation model that has been constructed is relatively small, making use of product type labelled 1 to 4 and the 'jobs matrix' feature to route each type through the system with correct timings at each workstation. The job matrix can be cut-and-pasted from Excel, which has a grid that will automatically update as more results are added or edited.

The job matrix is a command list for the simulation that lists process times at each workstation for each type of product. Specific times can be defined within the matrix, or they can be assigned distributions that have been constructed earlier. Table 2 shows the job matrix for the simulation which is generated in

Excel from the results and can then be copied into the job matrix on Simul8.

Table 2 Job Matrix for Simulation

Work Type	Job	Workstation	Distribution	Changeover
1	1	Collect Pallet	Collect Pallet	0
1	2	FA1	2.45	0
1	3	FA2	2.41	0
1	4	FA3	0.84	0
1	5	FA4	1.26	0
1	6	FA5	1.6	0
2	1	Collect Pallet	Collect Pallet	0
2	2	FA1	2.53	0
2	3	FA2	2.49	0
2	4	FA3	0.87	0
2	5	FA4	1.3	0
2	6	FA5	1.65	0
3	1	Collect Pallet	Collect Pallet	0
3	2	FA1	3.14	0
3	3	FA2	3.09	0
3	4	FA3	1.08	0
3	5	FA4	1.61	0
3	6	FA5	2.05	0
4	1	Collect Pallet	Collect Pallet	0
4	2	FA1	4.99	0
4	3	FA2	4.9	0
4	4	FA3	1.71	0
4	5	FA4	2.56	0
4	6	FA5	3.26	0

The simulation model consists of a work centre for each workstation on the line, with process times referencing from the job matrix. The allocation work centre is used to distribute doors according to the percentage distribution of doors to be tested. Although this will not produce the exact same order of doors in the storage bins (number 1 to 4 for each product type), it will produce the same percentage proportions. The results for each configuration are processed in trial tests of 20 complete runs with different random numbers used each time, and results are given as an average over all twenty runs.

The main point of note is the wrapping table area. A proportion of doors are routed to the table for wrapping, while the rest are sent directly on to FA5. This proportion is variable depending on the order, but currently is set at 80.6% which is the percentage of observed doors that were wrapped over the observation period.

During the simulation model construction, several modifications have been made to determine the best model structures.

The first new setup to be tested was to double the capacity at the ‘choke point’ on the line, FA1 and FA2 stations as shown in Figure 4. By doubling this capacity, five extra staff are required and daily output is increased to 177 doors per day. It is possible to reduce capacity back to the original 124 leaving the new workstations unmanned. However, this still does not meet the required maximum capacity. Workstation utilisation is improved slightly to 37%.

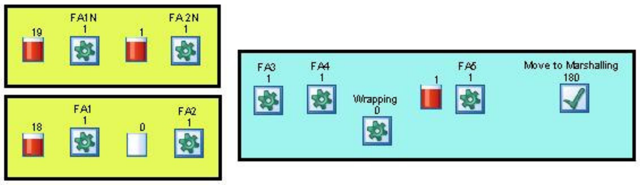


Figure 4 Modification 1

The second setup (Figure 5) is to install an entirely new second line, identical to the first. This doubles capacity to 247, which can still be reduced to original levels by just operating one line. However, again capacity is insufficient. Workstation utilisation returns to the original level of 36%.

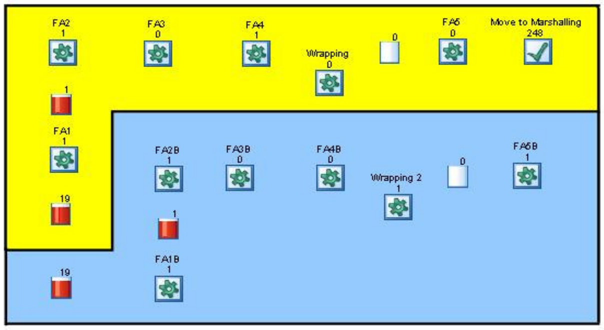


Figure 5 Modification 2

To attempt to increase capacity to modification 1, a third area with another duplicate of FA1and FA2 work areas, and a second area duplicating FA3-5 was added as shown in Figure 6. An intermediate storage area was also included between the FA2 and FA3 stages. This was found to smooth production along the lines significantly and improve performance. However capacity was high in the first section leading to work-in-progress building up significantly in the intermediate buffer. Overall, the daily capacity was 373 doors per day which represents a surplus of 112 doors a day capacity. Utilisation is significantly improved to 51%. In total, a maximum of 19 staff would be required for this configuration.

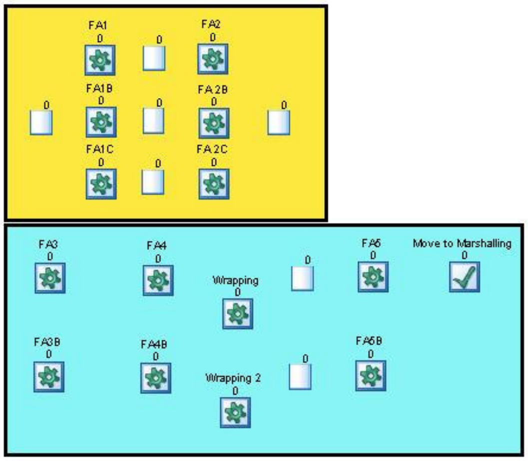


Figure 6 Modification 3

The final modification as shown in Figure 7 removed excess capacity from the first half of the line, reducing the staff requirements to 14. This creates in effect two lines similar to the existing one, with a midway junction between the two which allows work from line 1 in the first half to be transferred if required to the second half of line2. Maximum capacity falls to 316 doors per day, still a surplus of 55 over the required level. Unfortunately, this configuration leads to a fall in average workstation utilisation to 46%.

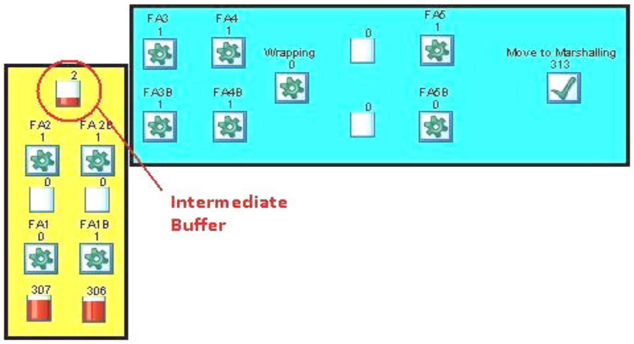


Figure 7 Modification 4

The simulation shows that a buffer with a capacity of just 5 doors is required in this configuration to prevent unnecessary work stoppages and the 5 door level is unlikely to be exceeded due to a good balance in work rate between first and second halves. It also allows work to be moved from one parallel line to another, to smooth flow.

The test results were summarised in Table 3. Modification 3 has the highest average utilisation of 51.2%, but firstly the surplus capacity is unnecessarily large and it requires a higher level of staff. Modification 4 has therefore been chosen despite its slightly lower workstation utilisation. Staff utilisation will still be very similar to the original line due to a similar layout; however the efficiency should be improved with the intermediate storage area providing some smoothing in the process. An excess maximum capacity of 55 doors allows for expansion in the future, while the capacity can be scaled back to original levels of staff and output by closing parts of the line during periods of lower demand.

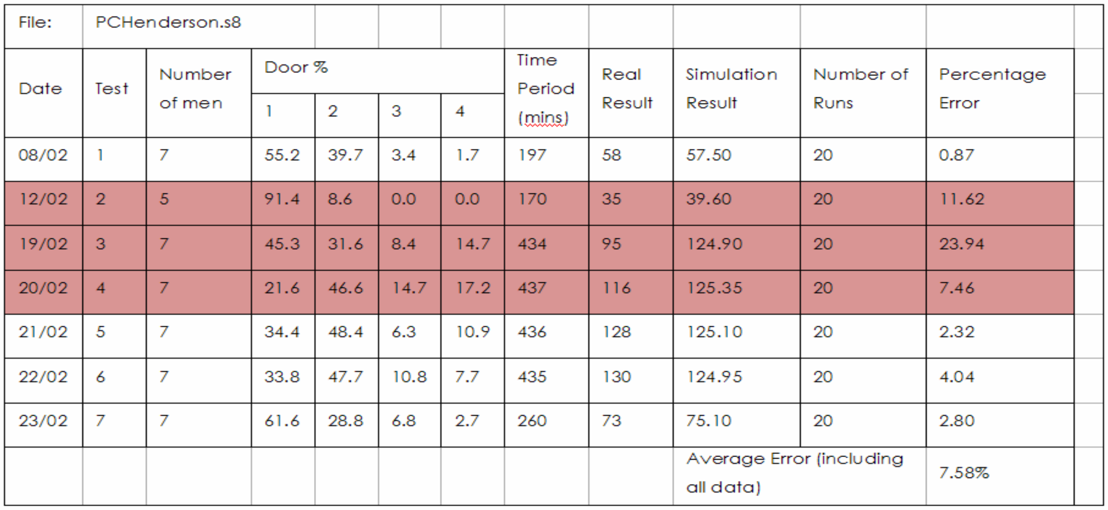
Table 3 Summary of test results

	Required	**Produced (average, 10 runs)**	**Surplus/ Deficit**	**Workstation Utilisation %**	**Staff**
Final	261	124.85	-136.15	36.7	7
Mod1	261	177.05	-83.95	37.2	12
Mod2	261	247.15	-13.85	36.3	14
Mod3	261	373.45	112.45	51.2	19
Mod4	261	316.65	55.65	46.4	14
Workstations	261	266.77	5.77	100.0	12

I. SIMULATION TESTING

The simulation was tested using real production from the factory at PC Henderson. This involves setting up a simulation to run using the real life inputs of the system (i.e. in this case the product distribution by percentage and the working time) and studying the output and comparing it with the real-life result. The results of this process are shown below in Table 4.

Table 4 Comparisons of real result and simulation result



File:	PCHenderson.s8										
Date	Test	Number of men	Door %				Time Period (mins)	Real Result	Simulation Result	Number of Runs	Percentage Error
			1	2	3	4					
08/02	1	7	55.2	39.7	3.4	1.7	197	58	57.50	20	0.87
12/02	2	5	91.4	8.6	0.0	0.0	170	35	39.60	20	11.62
19/02	3	7	45.3	31.6	8.4	14.7	434	95	124.90	20	23.94
20/02	4	7	21.6	46.6	14.7	17.2	437	116	125.35	20	7.46
21/02	5	7	34.4	48.4	6.3	10.9	436	128	125.10	20	2.32
22/02	6	7	33.8	47.7	10.8	7.7	435	130	124.95	20	4.04
23/02	7	7	61.6	28.8	6.8	2.7	260	73	75.10	20	2.80
									Average Error (including all data)		7.58%

Each test involved setting the run time of the test in working minutes (length of the day in minutes removing minutes spent on breaks), and the percentage of doors in each category. A trial of twenty runs was then conducted, with the result being an average of the doors produced over each of the runs. Running each individual test is completed using different random numbers in the simulation package. The alteration of random numbers essentially changes the 'random behaviour' of the simulation at any given point, so it is important that multiple trials are run to give a good overall perspective of the system's performance.

The simulation produces an error on average of just over 7 percent on average. The most significant error (over 10%) is marked as red on the table. These certain days experienced unusual conditions that led to variations in performance.

The estimation of utilisation affects the process timings that were calculated for each workstation. As with any sampling technique, there is a change of error. Using the equation 2, the 95% confidence intervals for the utilisation estimate (N=41) are shown in Table 5. These error calculations show that the error in the utilisation estimations is significant. However, the whole simulation has been tested and has been shown to have a very low average error. Therefore it is reasonable to conclude that these levels of error are unlikely, or at least balance each other.

In fact, this part of the simulation improves the performance of the activity sampling method when they are used in conjunction with each other. For example, to achieve a maximum 5% error with 95% confidence, the study of FA1 would require 426 individual observations, which is a significantly larger investment in observation time. However, by using a wide range of production data to validate the model, a high level of accuracy on each individual component of the simulation is less necessary.

Table 5 Utilisation estimates and 95% confidence range

Workstation	Estimate % utilisation	± % for 95% Confidence	Overall Estimate, %
FA1	79	12.7	66.3-91.7
FA2	78	12.9	65.1-90.9
FA3	27	13.9	13.1-40.9
FA4	41	15.4	35.6-46.4
FA5	52	15.6	36.4-67.6

Over the observed period, there was an uneven balance in the type of product that was observed through the line. While a significant number of Canopy products (1 & 2) were observed, a very small number of Tracked products were available for observation. The average distributions of products are shown in Table 6.

Table 6 Average Distribution of Products

Product Type	Products Observed	Overall Percentage
Canopy Unframed, 1	64	73.3
Canopy Framed, 2	26	24.1
Tracked Unframed, 3	2	1.7
Tracked Framed, 4	1	0.9

Clearly with so few products observed in the tracked category, there is a huge risk that those that are observed are exceptional timings and do not represent the standard time of production. However, Canopy products form the vast majority of the output of PC Henderson (stated by the company as over 80%). This will have the effect of reducing any error in the timings proportionately, with 80% of the error inherent in the timings for canopy products and just 20% of the error in the tracked estimations affecting the result. The tests of the model with these estimations show that the model performs sufficiently overall in tests with more than 80% canopy products. However, more error is increasingly likely with an increasing number of tracked products, and with 75% canopy products error reaches above 7%. This should be noted in any future investigation results.

I. DISCUSSIONS

The computer model predicts full capacity of the existing line to be 124 doors per full working day. The average workstation utilisation is also quite low, with only 36% of time is working time at each workstation (the rest is either wasted waiting for products to be passed down the line, or waiting for the area immediately down the line to clear). Based on the order history supplied (March-April 2006, shown in Figure 8), the assembly line is required to produce a maximum of 261 doors per day. This fluctuates quite significantly, as shown below, which means the line is required to not just provide the maximum output but also be flexible enough so production can be reduced if required. This means that one large continuous flow production line is not adequate (which makes it impossible to shut down parts of it to reduce capacity without stopping production entirely) and indicates some sort of modular system is required.

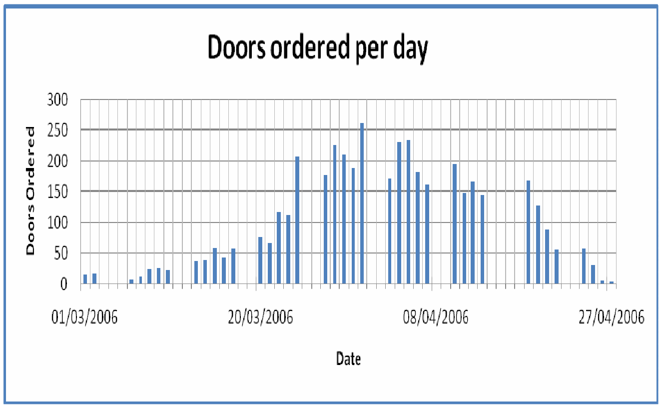


Figure 8 PC Henderson order history

Based on the original simulation, it is estimated that the error of the configuration trials in this study will be below 5%. This is because the configurations that have been tested have been closely based on the original model of the existing line that was shown to be highly accurate. There is a chance that in altering the configuration of the line the error in the simulation will be significantly increased. However, it is felt that a significant increase in error is unlikely.

The circuit of observation technique was observed to drastically reduce observation time, when compared with direct observation techniques. In testing the technique at PC Henderson Doors Ltd, each circuit commenced every ten minutes. Usually after a period of approximately five minutes the circuit was complete, which allowed five minutes for data entry and some preliminary analysis work.

The simulation, which was produced from the data collected, performed admirably when the amount of observation time was a little over six hours. The average error of the simulation was just 2.51%. This is an excellent level of accuracy, considering the low amount of some types of products that were observed (over 95% of observed products in the system were just two variants) and the estimated wide variation of accuracy at a component level in the simulation.

Simulations that can be constructed with such little required observation time are extremely valuable. They remove a significant element of guesswork in early stages planning and decision-making in manufacturing environments.

As the study continued, it was noted that this method of observation sampling and simulation were ideally suited to be used in conjunction with each other. While a sampling system inherently contains a degree of error within it, the simulation itself essentially helps to 'double-check' this error. The process of building the simulation of these components, each with their individual error, and testing the error of multiple components on a larger scale helps to ensure that the error within the components is balanced by the system's component error as a whole.

II. CONCLUSION

There is a great need for a reduction in the time invested in simulation. It improves the value and flexibility of the process. The longer a simulation takes to construct the higher the chance it will suffer from redundancy before it can help solve the problem it was intended to create.

Data collection should be regarded as an integral part of this process, often forming the majority of the time invested in the problem. The natural method of continuous observation is simply inadequate and there is much potential for improvement. The 'circuit of observation' method provided a far superior method of data collection, reducing the observation time on a manufacturing line to a mere six hours. From these observations, the model produced was tested and observed to have an average error of just 2.51%. This error figure was not just caused by the short observation time, but it was also increased due to a lack of product variation in the observed period.

Such a model provides an excellent method of problem solving. Multiple scenarios can then be tested using the devised model, and this much reduced cycle time provides a significant improvement in the value of the entire simulation method. Reducing the time required enables the possibility of management being trained and carrying out the simulation, which in turn reduces many of the other problems possible in simulation such as a lack of familiarity with the system.

The manufacturing community would find an improved flexible nature in simulation a way to increase its use and spread the method to a wider variety of areas, achieving Foster & Rose's goal of its use becoming more widespread.

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