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A SIMULATION STUDY OF ROBOTIC WELDING SYSTEM WITH PARALLEL AND SERIAL PROCESSES IN THE METAL FABRICATION INDUSTRY

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ABSTRACT

This paper presents the usefulness of simulation in studying the impacts of system failures and delays on the output and cycle time of finished weldments produced by a robotic work cell having both serial and parallel processes. Due to multiple processes and overlapped activities, process mapping plays a significant role in building the model. The model replicates a non-terminating welding fabrication system with duplicate stochastic events caused by system failures and delays. A full factorial model is employed and analyzed to examine the main and interaction effects of five major types of system failures and delays via multiple regression analysis. The analysis derived from the full factorial model shows that material handling carrier delays have the most significant impact on the cycle time. This case study illustrates a modeling approach with system verification and validation revealing fundamental system design flaws which cause a significant loss of production.

1 INTRODUCTION

This project focuses on one of four identical robotic cells employed by metal fabrication company located in mid-south area. The company's product line is very specialized making only I-beam weldments. These beams are a component used in the manufacture of over-the-road trailers. Most I-beams have a mounting plate welded to each end. The customer base includes a number of trailer manufacturers The product has slight variations in beam size, beam length, location of holes in the end plate and welding patterns. The only product feature that has an effect on the fabrication cycle time and throughput is the welding pattern. For this reason the data used in this study was limited to the highest volume item, which constitutes about 70% of the business.

At the time of this study, this business unit had been in operation for only a few months with production throughput never coming close to expectations, nor did it seem to be able to achieve original output specifications.

The project involved multiple suppliers of equipment for the work cells and overhead power and free conveyor system. Analysis of productivity shortcomings by the equipment vendors placed blame on other vendors, and required substantial additional investment. The fabrication company management had retained an industrial engineering consulting firm to help evaluate vendor proposals for improvement and to generate new alternatives. This study was facilitated through inquiry of the consulting firm. These industrial engineers also provided considerable information and data for this analysis. All of the data was reviewed and verified through on-site visits by the modeling team. For the purpose of validation and verification, time studies, photos, videos, and a considerable number of interviews, were done onsite by this simulation team over a period of four months.

2 MODELING APPROACH

Arena 4.0 software was utilized for building the model for this existing parallel processing robotic-welding system. It was determined that simulation of this system was non-terminating because there were two pairs of in process beams left in the system at the end of every day. The setup and warm-up of the actual equipment was also considered negligible. Welding resumes for these beams on the next workday when the operation begins. In addition, the model is a stochastic simulation primarily due to the randomness of occurrence of failures and subsequent system down delays (Law and Kelton 2000, 675). Failures identified include welding machine failure (Welding Failure), delay for available overhead conveyor Carrier (Rack Delay), material handling robot sensed interference (Hit Rack), mounting plate magazine replenishment (Clip Reloading), and miss-feeding of mounting plates (Stuck Clips). Actual automatic machine cycle times are highly repeatable except for these failures.

The modeling approach reflects the parallel processing and continuously repeating cycle operating in a robotic cell (Martin and Choi 1989). Figure 1 below shows the robotic work cell layout.

Due to the cyclical nature of the operation, selection of the cycle breakpoint is arbitrary. Turntable rotation is the most distinct element as this only occurs when the welding robots have returned to their home position. Usually the material-handling robot is also at home position, with the exception of a portion of the cycle where incoming beams are retrieved. Two pair of beams in process that have been left in the system from the previous production shift are on the turntable. One pair of beams is rotated by the turntable into the welding position and a second pair into the load/unload position. Finished beams are removed by the material-handling robot (Robot3) from the turntable and placed into a carrier-mounted rack that is held at a stop on the power and free overhead conveyor. Next Robot3 moves to the slat conveyor escapement to pickup a new pair of beams.

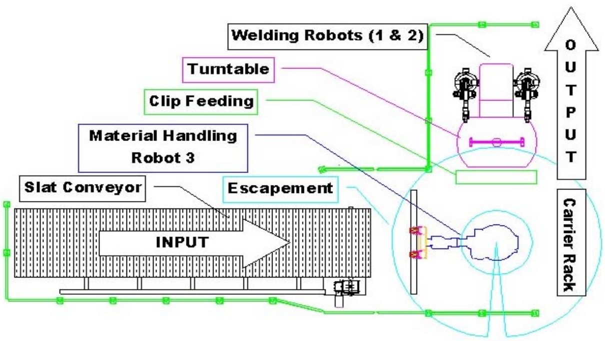

Figure 1: Robotic Work Cell Layout

The modeling approach begins with the step where the turntable rotates two pair of in-process beams that have been left in the system. One pair rotates into the welding position and the other pair to the load/unload position. Robot3 then removes the finished beam pair from the Turntable placing them into the Carrier Rack. Next, Robot3 moves to Slat Conveyor and Escapement station to pickup a new pair of beams.

3 MODEL COMPONENTS

The system is made of several equipment and thus modeling entities. Distinct components include the Slat Conveyor, Robot 3, Escapement, Turntable, Welding Robots, Clip Feeder and Carrier Racks. Each of these is described below.

3.1 Slat Conveyor

Incoming beams are fed into the system using a Slat Conveyor. In the actual system, Slat Conveyor loading is manual and designed to be asynchronous. The escapement at the end of the Slat Conveyor always interrupts the Slat Conveyor operation to prevent jams in a beam squaring operation. During the study of this operation, it was never observed that the system was delayed for incoming beams or clips. System design has provided ample time for the Slat Conveyor to recover from total depletion without cycle delay. While the escapement is a critical path element in the cycle time, there is adequate buffer to decouple lift truck supply and manual loading from the process being modeled. Accordingly, this supports the assumption that the incoming beam supply is infinite, with no waiting for the Slat Conveyor. The Slat Conveyor is shown in the model, but the conveyor drive time is not posted nor used. Conveyor operation is not tied directly to the production cycle as a basic element.

After the beam is released, the cycle time starts recording as the variable TNOW (Kelton, Sadowski, and Sadowski 1998, 28). The beams move toward the end of the Slat Conveyor where an escapement is located. Conveyor is modeled by using a *station* module while the escapement is modeled with a *process* module. The escapement then flips each beam and holds it in a pickup position waiting to be removed by Robot3. Robot3 has two sets of grippers, but picks up only one beam at a time, in sequence' with a notable delay for the alignment and escapement cycle for the second beam. Details of the escapement that is located at the end of the slat conveyor are provided with the escapement description below. Once two beams are retrieved, they are placed on the Turntable load/unload (Side One) where two new clips, one for each beam, have already been placed.

3.2 Robot3

In the real system, Robot3 moves a pair of beams between three stations: the Slat Conveyor, Turntable Side One, and Carrier Rack. A *transporter* module was used to replicate Robot3 activities. To occupy Robot3, an incoming pair of beams at the pickup position initiates a request for transportation. Robot3 parks at its home station responds by moving to the Slat Conveyor station. Finally, Robot3 picks up two beams from the Slat Conveyor station moving to its home station before transferring beams to Turntable Side One.

3.3 Escapement

The current escapement design provides one beam in pickup position for Robot 3. The pickup position beam is automatically replenished immediately after the previous beam is removed. There is an opportunity identified here, as the alignment cylinder has been made a serial component of the escapement process yet with physical modifications could become a part of the asynchronous slat conveyor operation. Escapement time for the first beam of each pair is not on the critical path, but the second beam of each pair is a critical path element due to system design. For this reason potential cycle reduction time is halved when considering a per beam savings as this operation only applies to every second beam. It is also very important to realize that there are simultaneous operations that may become critical path elements after modifications to the escapement. This effect may limit savings, and when combined with the effects of system device failures are all-important to the evaluation of the effectiveness of resolutions. Complexities such as this further justify modeling and simulation as evaluation tools.

3.4 Turntable

The turntable has two sides that are serviced. Side one is facing toward Robot3 for loading and unloading. The two welding robots simultaneously service beams on the other side of the turntable. The function of the turntable is to rotate beam pairs between Turntable Side One and the second side where welding is accomplished. The turntable is another device that has been modeled as a transporter. A transporter with a capacity of two represents the two sides of the turntable with a capacity of two. Robot3 places a pair of beams on the Turntable Side One while the other pair of beams is being welded. When welding for one pair of beams is completed, the turntable rotates, moving unfinished beams into position for welding. The beams that are rotated to the side one position can be processed in one of two ways. If the beams have only one-end welded, they will be picked up and inverted by Robot3 and reloaded in the turntable fixture. For those that are finished and have both ends welded, Robot3 will remove them from Turntable Side one and place them into a Carrier Rack.

3.5 Robot1 and Robot2 (Welding Operation)

Robot1 and Robot2 are physically identical and have simultaneous cycles. They are modeled as the single resource in which a pair of beams seizes, spends about 38.6 seconds for welding clips attached to one end of beams, and then releases the resource when done.

3.6 Clip Feeder

The Clip Feeder is included in the model as a transporter carrying two clips to the clip socket on Turntable Side One. These two clips are welded to the end of each beam. To model this process, clips are created then wait for the signal to be released. Then clips are requested for the transporter from the clip feeder. After clips are placed on the turntable, the clip feeder is freed.

3.7 Carrier Rack

The finished beams moved by Robot3 from Turntable Side One are loaded onto Carrier Rack. A s*tation* module was used to represent the Carrier Rack. The finished beams travel through this station and for the purpose of the model, the entity is disposed.

3.8 Machine Failures and Waiting Time as the Sources of Variation

Machine failures and waiting time that are created by Carrier Rack delays are considered the sources of variation in this simulation, creating a stochastic process in the system. As a result, this study is attempting to analyze whether machine failures and Carrier Rack delays have significant impacts to the number of beams produced. The details of machine failure and waiting time are shown below.

3.8.1 Carrier Rack Delay

This delay occurs when the Carrier Rack that transports finished welded beams to the next station has not arrived at the loading position when needed. In the model, when a rack delay occurs, Robot3 and the turntable are both halted and must wait until the next Carrier Rack moves into position.

3.8.2 Hit Rack

This event is considered a failure for Robot3. The Hit Rack error takes place when Robot3 is unable to release welded beams at the Carrier Rack because of a sensed interference or misalignment between Robot3 and the Carrier Rack. Robot3 and the turntable both stop operations when this failure occurs.

3.8.3 Stuck Clip

The Stuck clip error happens when a clip cannot move into clip socket located on the turntable. Three machines, the clip feeder, turntable and Robot3, all stop when a stuck clip condition takes place. A *Halt* module was used to stop clip feeder, turntable and Robot3 in the simulation model.

3.8.4 Clip Reloading

When manually loading clips into clip magazine, the operator is required to stop the clip feeder, Robot3 and the turntable. The pauses of these three machines were modeled in the same way as the stuck clip condition.

3.8.5 Welding Failure

Welding failure occurs due to one of three events: a seam error, welding robot lockup or tip replacement. Since the welding machine was modeled as a resource, the times to failure and failure times of these events were determined in a *failure* module. When welding failure takes place, only the welding operation stops immediately. The other machines continue working until turntable rotation is needed. Turntable rotation is inhibited by failure to complete the welding cycle.

In the model, the first four failure modes described above were grouped in the same sub-model. Welding failure was included in the welding resources module

3.9 Modeling Time Unit

The time study unit is measured in decimal minutes. Because of the necessary level of precision a unit of one-one hundredth of a minute unit was used for the simulation. Hence, 100 minutes in our simulation is equal to one minute in real time. The time unit of the model was adjusted like this to avoid the tedium, confusion and errors that can result from converting time unit from base 100 to base 60, and to provide the appropriate level of precision.

Since the system being modeled is automated, the times used for transferring and processing are deterministic and set by the computer program that controls the cycle. If there is no down time from transporters and resources, the cycle time spent to produce a pair of beams will remain constant. Thus it is a uniform distribution. However, in the real situation, failures occur randomly, necessitating a stochastic simulation. Down times are caused by such events as Welding Machine Failure, delayed Carrier Rack, Hit Rack, Reloading Clips, and Stuck Clips.

3.10 Run Time

Simulation run time is set to 48,000 minutes (8 hours) reflecting the actual work hours per shift. Since this is a steady-state system, the modeling warm-up period had to be determined in an effort to eliminate the biasing effect of the initial condition (Kelton, Sadowski, and Sadowski 1998, 219). To establish the warm-up period, the cycle time was plotted against a run time of 100,000 minutes. For each run, the system is started empty and with idle initial conditions and no warm-up time. Five replications were conducted and their plots are shown in figure 2.

According to the plot, after 5,000 minutes, the graph appears to be stabilized. This stabilized period continues until around the 15,000th minute and then starts to go up. We arbitrarily selected the warm-up period of 10,000, which is halfway between the 5000th and 15,000th minute.

Simulation was set to run with 100 replications. This number of runs is expected to provide robust statistics for the analysis.

3.11 Input Data

The input data are divided into two categories: 1) constant delay time for each activity and 2) failure and waiting times caused by Welding Machine Failure, delayed Carrier Rack, Robot3 Hit Rack, Clip Reloading, and Stuck Clips. Time distributions of failure and waiting time are shown below in Table 1. A triangular distribution was used for all failures with parameters: 100 (minimum); 3,000 (likely); and 6,000 (maximum).

Table 1: Distributions

Distributions	**Time to Failure**	**Failure Time**
Hit Rack	TRIA(16,000; 17,000; 21,000)	TRIA(488; 510; 545)
Stuck Clip	TRIA(12,443; 13,090; 15,548)	TRIA(387; 413; 557)
Reloading Clip	TRIA(3,000; 4,000; 5,000)	TRIA(193; 244; 312)
Rack Delay	TRIA(508; 1,050; 2,010)	TRIA(92; 232; 318)
Welding Failures		
• Welding Lockup	TRIA(38,450; 40,000; 46,554)	TRIA(400; 700; 900)
• Changing Tip	TRIA(15,840; 16,020; 18,445)	TRIA(400; 700; 900)
• Seam Error	TRIA(24,320; 28,800; 30,120)	TRIA(400; 700; 900)

3.12 Output Data

The output data includes the number of beams produced and cycle time spent to produce a pair of beams. This included lost production time for Welding Machine Failure, Hit Rack, and Stuck Clips as well as waiting time caused by reloading clips and delayed Carrier Rack. The histogram below shows the distribution of the average of number of beams produced derived from 50 replications. The resulting average number of beams is normally distributed with mean of 287.78 and standard deviation of 7.23. See Figure 3.

3.13 Validation

The validation process was performed to determine that the output closely resembles the real system. The assumption was tested that when there is no failure and delayed time occurred in the system, the cycle time to produce a pair of beams would be 2.14 minutes or 2 min 8 sec. The outcome obtained from running the simulation shows the cycle time

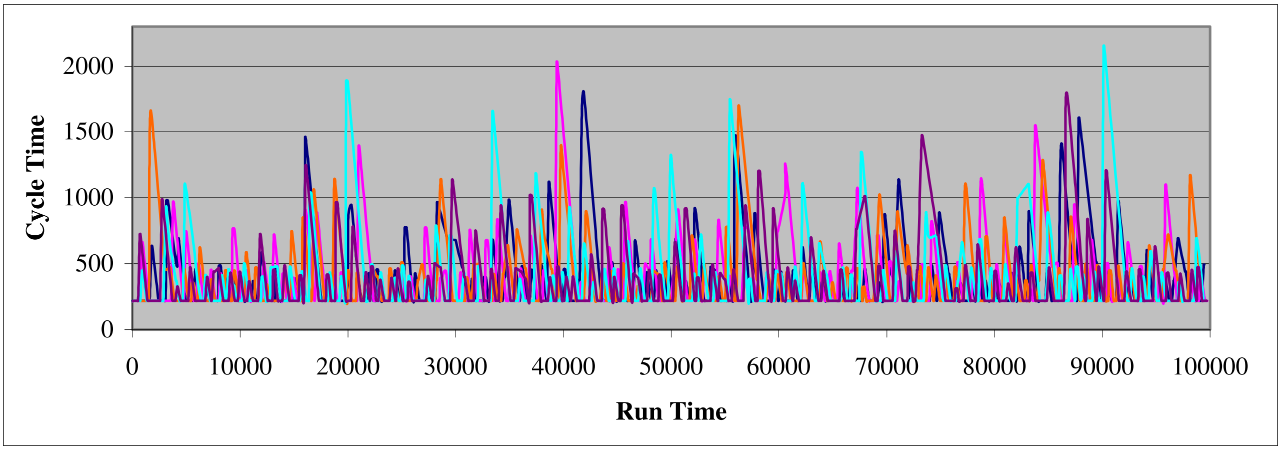

Figure 2: Five Replications without Warm-up

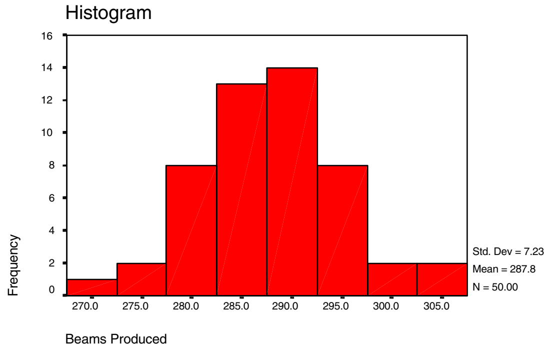

Figure 3: Beams produced with 50 replications

of 2.1768 minutes or 2 min 10 sec, resulting in two-second difference. This discrepancy of 2 seconds was caused by the difference in decimals between the actual time and the simulation time assigned to *transporter* modules. However, this discrepancy is not significant and is not considered to influence validity of the simulation model.

Moreover, to confirm the validity of this simulation, a Welsh ANOVA F-test was conducted to compare the number of beams produced per day derived from the simulation as compared to actual production data. Ten data sets of the average number of beams produced are shown in Table 2.

3.14 The Comparison of Simulation and Actual Outputs

The descriptive statistics shown in Table 3 reveal an average of 278.7 pairs per day (8hrs/day) obtained from actual operations and 287.3 pairs from simulation. Notice that the variance across these two groups is not equal as the p value associated with the F ratio is smaller than 0.05 (see Brown-Forsythe, Levene, and Bartlett tests in Table 4 below). Hence, the standard t-test that assumes the variances are equal can't be used. Instead, we use the Welch ANOVA F-test that applies for unequal variance tests. The test can be interpreted as an F test in which the observations are weighted by an amount inversely proportional to the variance estimates. This has the effect of making the variances comparable (Sall, Lehman, and Creighton 2001, 147).

Table 2: Average Number of Beams Produced

Rep #	Simulation Output/Day (Pairs of Beams)	Data #	Actual Outputs/Day (Pairs of Beams)
1	282	1	261
2	291	2	253
3	282	3	281
4	288	4	328
5	286	5	258
6	291	6	274
7	283	7	302
8	291	8	278
9	293	9	267
10	286	10	285

Table 3: Means and Std Deviations

Level	Number	Mean	Std Dev
Actual	10	278.70	22.56
Simulated	10	287.30	4.11

Table 4: Test of Equal Variance

Test	F Ratio	DFNum	DFDen	Prob>F
Brown-Forsythe	6.8320	1	18	0.0176
Levene	7.4063	1	18	0.0140
Bartlett	17.7687	1	.	<.0001

The Welsh ANOVA test shown in Table 5 indicates that the numbers of beams produced per day of these two groups are not significantly different. The probability (p = 0.2642) is much larger than the selected 0.05 (see details below). This result supports the validity of our model in that the numbers of beams produced from simulation are not significantly different from the number of beams produced by the actual system.

Table 5: Welsh ANOVA Testing for Equal Means but Allowing Unequal Standard Deviations

F Ratio	DFNum	DFDen	Prob>F
1.4066	1	9.5971	0.2642

4 EXPERIMENTAL DESIGN

In this study, simulation is thought to be a mechanism that turns input parameters into output performance. Five independent variables are taken to account as input parameters and as the factors that affect the variation to the outcome; these variables are welding machine failure, delayed Carrier Rack, Robot3 Hit Rack, Clip Reloading, and Stuck Clips. The number of beams produced, measured in pairs, is the output performance measure. Experimental design was aimed at finding the significant factors affecting the output and predicting the output when variations of inputs occurred.

4.1 Designing for Exploring All Main Effects and Interaction Effects

A multiple regression model was selected as the appropriate tool to screen for all main effects and interaction effects caused by the five continuous variables (welding machine failure, delayed Carrier Rack, Robot3 Hit Rack, Clip Reloading, and Stuck Clips) on the production output. To explore the full factorial effects using a standard least square procedure, 100 replications were used. This number of replications yielded a high power for the test of model fit and the model fitted well with the data. This is shown in the following section.

4.2 Screening for Main Effects and Interaction Effects

The parameter estimates derived from least square method, shown in Table 6, indicates that three main effects and an interaction effect are significant. Main effects include rack delay, hit rack, and welding failure. The only significant interaction effect was between hit rack and rack delay. These effects have significantly contributed to the variance in the number of beams produced.

The result of effect tests, Table 7, confirms the significance of three main effects and the significance of the rack delay-hit rack interaction effect. Notice that the main effect: "rack delay" is the most significant factor followed by welding failure and then hit rack.

Table 6: Parameter Estimates

Term	Est.	Std Error	t Ratio	Prob>|t|
Intercept	373.0137	14.1512	26.36	<0.001
Rack Delay	-0.0042	0.0011	-3.71	0.0004
Hit Rack	-0.0074	0.0024	-3.10	0.0028
Welding Failure	-0.0070	0.0019	-3.54	0.0007
Hit Rack* Rack Delay	0.00001	0.000004	-2.16	0.0346

Table 7: Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Rack Delay	1	1	321.7239	13.7676	0.0004
Welding Failure	1	1	292.7673	12.52852	0.0007
Hit Rack	1	1	225.1043	9.6329	0.0028
HitRack* Rack Delay	1	1	108.7149	4.6522	0.0346

4.3 Goodness of Fit Test

This test is conducted to see how well the model fits the data. R^2, the proportion of variation explained by the model, is the statistic used to indicate the goodness of fit of the model. This model had an R^2 of 0.61 as shown in Table 8 below. This indicates that 61 % of the variance in the data can be explained by the model. The ANOVA, shown below in Table 9, with F ratio of 3.4345 and p<0.0001, supports the fit of data by the model. Specifically, this indicates that the model with these factors does a better job of predicting than simply using the mean.

Table 8: Goodness of Fit

Summary of Fit	
RSquare	0.6102
RSquare Adj	0.4326
Root Mean Square Error	4.8341
Mean of Response	288.5
Observations (or Sum Wgts)	100

Table 9: ANOVA

Analysis of Variance				
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	31	2487.9729	80.2572	3.4345
Error	68	1589.0271	23.3680	Prob > F
C. Total	99	4077.0000		<.0001

4.4 The Full Factorial Model

It is evidenced that three main effects led by rack delay and an interaction effect created by rack delay and hit rack comprise the significant effects on the number of beams produced. However, we want to emphasize that the full factorial model including all main effects and all interaction effects play a significant role in the validation of the predicted outcome. To test for the validity, the predicted outcome derived from this model will later be plotted against the actual outcome from the simulation. The difference between predicted and actual outcomes or residuals is used to substantiate the validity of the model.

4.5 Actual and Predicted Plot

The scatter plot of actual response values against the predicted values shown in Figure 4 gives the view of how the predicted values are close to the actual values. The sloped line shows where the actual and the predicted outcomes are equal. The vertical distance from a point to this sloped line reveals the residual, the difference of the actual and the predicted value. The scatter plot shows that all the dots gather around the sloped line, reflecting the moderate accuracy of the predicted values.

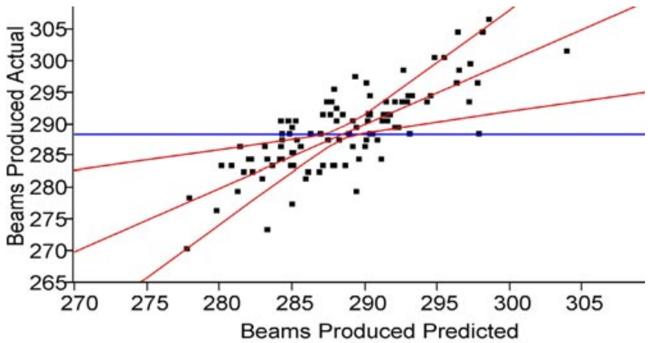

Figure 4: Actual versus Predicted Plot

Another interpretation made from this scatter plot is the model fit. As shown in the plot, the horizontal dashed line represents the mean of the actual values. The scatter plot shows that the model provides the data that fit more with the sloped line, the line identifying the perfect fit, than the horizontal line, the line identifying the predicted value without a model.

5 CONCLUSIONS

In conclusion, the full factorial model provides an efficient prediction of the number of beams produced. Three main effect caused by three factors including rack delay, hit rack, and welding failure as well as rack delay and hit rack interaction are the factors that significantly affect the changes in the number of beams produced. The full factorial model provided the predicted output, which is not significantly different from the actual output. This leads to the confidence of using the model as a tool to predict the outcome. The model also leads to the awareness of rack delay, which is the most important factor to the output. It is recommended that reduction in Carrier Rack delay will contribute significantly to the increase in the number of beams produced via its main effect and its interaction with hit rack. It is necessary that the rack carrier system be reanalyzed to find the cause that leads to the significant amount of rack delay, which results in a loss of production. Proposed solutions could be tested using the model to determine related savings of time. This could provide measurable and verifiable means for justification of equipment modifications.

6 FURTHER STUDY

This simulation model is for a single robotic work cell. It can provide a basis for justification of equipment and programming modifications, particularly changes within the cell. The most significant error had to do with Carrier Rack delays, which is actually a function of the four Robotic Cells being arranged in an operating series. The overhead conveyor configuration is known to be the culprit, but analysis of various alternatives and their effect on throughput requires that four of these models be linked into a single model with modeling to include the overhead power and free conveyor operating characteristics. This is quite a daunting task, but would provide tremendous insight into the effect that a change or multiple changes would have on throughput. These results could then be used for justification of expenditures in this most complex, interrelated fabrication system.

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