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Utilizing simulation to evaluate production line performance under varying demand conditions

Thomas McDonald[a], **Eileen Van Aken**[b] and **Kimberly Ellis**[b]

[a]*University of Sothern Indiana, 8600 University Blvd, Evansville, IN 47712 , USA*
[b]*Virginia Tech, 250 Durham Hall, Blacksburg, VA 24061, USA*

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ABSTRACT

Determining how a new production cell will function is problematic and can lead to disastrous results if done incorrectly. Discrete-event simulation can provide information on how a line will function before, during, and after the line is in operation. A simulation model can also provide a visual animation of the line to see how product will flow through the line. This paper discusses the development and analysis of a simulation model of a new manufacturing line. The manufacturing cell is a new motor assembly cell. An analysis of the capability of the line for varying demand levels was conducted for the two main motor types produced on the line. An ARENA® simulation model was developed, verified, and validated to determine the daily production and potential problem areas for the various demand levels. The results show that at all but one demand level, the line is capable of producing to within one unit of customer demand if the required number of workers is present. At the highest demand level, the simulation results suggest that the line is not capable of meeting demand. Additional analysis indicates that multiple workstations could prove problematic with minor fluctuations in demand. Problematic workstations were identified for each assembly area and for the line as a whole.

1. Introduction

Faced with ever-increasing challenges such as the globalization, increased world competition, and increased customer expectations, companies are pursuing strategies to improve their performance and reduce their costs. Discrete-event modeling and simulation (DES) is a popular tool in widely varying fields for identifying and answering questions about the effects of changes on processes. Simulation has been utilized to predict system performance in the automotive industry (Chan, 1995; Chan & Jian, 1999), motion control industry (McDonald *et.al.*, 2002), design cells in lamp manufacturing (Chan and Abhary, 1996), aid in implementing Total Quality Management (Aghaie & Popplewell, 1997), Business Process Reengineering (Doomun & Jungum, 2008), and conversion to constant work-in-process levels, also known as CONWIP (McDonald, et al., 2002b; Li, 2010) Simulation has also been used for modeling value stream maps of a production line (McDonald, *et.al.*, 2002b), modeling complex manufacturing systems (Benedettini & Tjahjono, 2009) and in the identification of

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* Corresponding author Tel.: +(812) 464-1877
E-mail: thmcdona@hotmail.com (T. McDonald)

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bottlenecks (Li, et al., 2009; Li, 2010). Discrete-event simulation models have been found to significantly improve the design, management, and analysis of production systems (Li, et al., 2009; Li, 2010). Li et al. (2009, p. 5021) state that "the main advantage of the simulation-based throughput analysis and bottleneck detection method is that it can identify and pinpoint bottlenecks in complex production lines."

The purpose of this research was to evaluate proposed changes in a line (referred to here as the EVS line) within a high-performance motion control products manufacturing plant in Mexico. This plant is one of several within a larger corporation in the motion control industry, having worldwide operations. The identity of the organization is protected, however, we refer to the plant as Industrial Motors (IM). Motors manufactured in the IM plant are used in applications in the machine tool, medical products, and aerospace & defense industries.

2. Methods and Materials

The EVS line is a new one in the Juarez, Mexico facility of IM, with two types of motors produced and a predicted customer demand at 130 motors/day when the line is at full production. The line is in the process of ramping-up to meet this demand. A simulation model of the line was developed in order to evaluate the capability of the line to produce to the required demand level. The model was used to evaluate the impact of various demand levels on daily production, flowtime, and work-in-process inventory levels. In addition, potential bottlenecks were identified at these demand levels.

2.1 Description of the EVS Cell

The two main motor types produced in the EVS manufacturing line are: TSW and TWP. Each motor type has a stator subassembly and a rotor subassembly that are matched and combined in final assembly to complete a motor. The TSW motor is comprised of six size variants: TSW 112, TSW 132, TSW 160, TSW 180, and TSW 180-365. Due to similarities, variants are combined into three families for the TSW motors (TSW 112, TSW 160, and TSW 180). The TSP motor is comprised of two size variants: TSP 112 and TSP 132. The size variants are used to represent the families for the TSP motors. Table 1 shows the variants and the families used in this paper.

The demand for EVS determines the required number of each motor type that the manufacturing line must produce on a daily basis. The current production mix is 74% TSW and 26% TSP. The TSW production mix is broken out further into 55% TSW 112, 42% TSW 160, and 3% TSW 180. The TSP production mix is broken out further into 69% TSP 112 and 31% TSP 132. Table 2 shows the production mix for each type and family.

Table 1
TSW and TSP families and their variants

Motor Type	Family for Simulation Model	Motor Variant
TSW	TSW 112	TSW 112 TSW 132
	TSW 160	TSW 160 TSW 180
	TSW 180	TSW 180-365
TSP	TSP 112	TSP 112
	TSP 132	TSP 132

Three main assembly processes are required for each motor: stator subassembly, rotor subassembly, and final assembly. The manufacturing facility has a rotor cell that is shared by the motors, a dedicated stator cell for each motor family, and a dedicated final assembly cell for each motor family as follows:

- Rotor Cell,
- TSW Stator Cell,
- TSW Final Assembly Cell,
- TSP Stator Cell, and
- TSP Final Assembly Cell.

Table 2
Production Mix for the EVS Line

Motor type	Type production mix	Family	Family production mix
TSW	74%	TSW 112	50%
		TSW 132	5%
		TSW 160	42%
		TSW 180	3%
TSP	26%	TSP 112	69%
		TSP 132	31%

Fig. 1 shows a representation of the EVS line. Each cell operates two shifts per day. The first shift is 9.5 hours long with 0.75 hours for breaks resulting in 8.75 hours of available production time. The second shift is 8.5 hours long with 0.75 hours for breaks resulting in 7.75 hours of available production time. Thus, the total production time across both shifts is 16.5 hours, or 990 minutes.

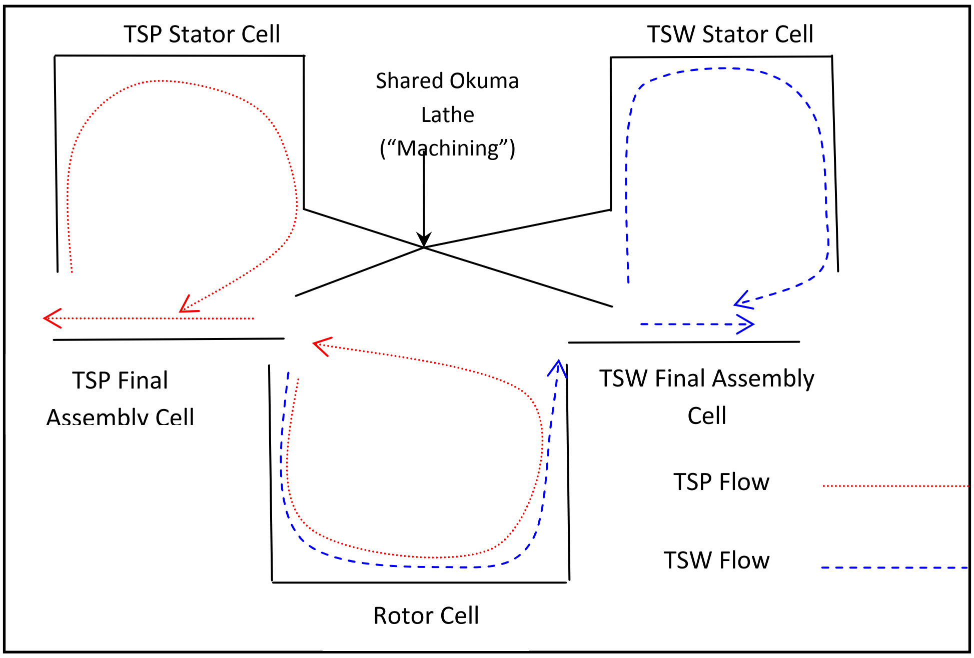

Fig. 1. Production flow for EVS line

The Rotor cell is comprised of seven serial workstations. Table 3 shows the workstations in their order of processing along with the workstation modal processing times, the percent deviation from processing time, and the weighted processing time. Three workstations in the Rotor cell require a set-up. Two workstations in the Rotor subassembly cell also have additional processing times that must be completed. For example, once the worker has placed the rotor on the cooling station, the rotor must cool for an additional 400 – 600 seconds, depending on the size of the rotor, before it can proceed to the next workstation. The TSW stator cell is comprised of 24 serial workstations. From Fig. 1 it can be seen that the “Machining” workstation is shared between the TSW and TSP stator cells. Table 4 shows the workstations in their order of processing along with the workstation modal processing times, the percent deviation from processing times, and the weighted operator time. Five workstations in the TSW stator cell require a set-up. Set-ups are required between motor sizes (112, 132, 160, 180) for the “Machining,” workstation and between families for the other workstations with set-ups. Five workstations in the TSW stator cell also have processing times in addition to the operator touch times. The TSW final assembly cell is comprised of 16 serial workstations. None of the workstations in the TSW final assembly cell have additional processing times or set-ups. Table 5 shows the workstations in the TSW final assembly cell.

Table 3
Rotor cell information

Workstation	Percent Deviation	112/132 Processing Times (sec)	160/180 Processing Times (sec)	Weighted Processing Time (sec)	Set-up Time (sec)	First Pass Yield
Heat Rotor Core*	15%	30	30	30	300	100%
Insert Shaft into Rotor Core	5%	20	20	20	N/A	98%
Cool*	15%	30	30	30	N/A	100%
Grind	1%	480	480	480	N/A	100%
Turn Rotor OD	15%	240	420	298	300	98%
Balance	10%	300	400	332	300	98%
Inspect	5%	60	60	60	N/A	98%

The TSP stator cell is comprised of 20 serial workstations and shares the “Machining” workstation with the TSW stator cell. Table 6 shows the workstations in their order of processing, along with the workstation modal processing times, the percent deviation from processing time, and the weighted operator processing time. Two workstations in the TSP stator subassembly require a set-up. Set-ups are required between motor sizes (112, 132, 160, 180) for the “Machining,” workstation and between families for the other workstations with set-ups. Five workstations in the TSP stator subassembly also have processing times in addition to the operator touch times. The TSP final assembly cell is comprised of 20 serial workstations. None of the TSP final assembly workstations require additional processing times or set-ups. Table 7 shows the workstations in the TSP final assembly cell.

2.2 Simulation Model Description

Using the detailed information obtained about the EVS line, a simulation model was developed to determine if the proposed line would be capable of meeting a demand level of 130 motors/day. The simulation model is comprised of seven sub models. There is a submodel for each cell described above: Rotor, TSW Stator, TSW Final Assembly, TSP Stator, and TSP Final Assembly. The other two sub-models are concerned with the arrival of incoming orders (Arrival Logic) and the accounting for the completed orders (Shipping). The model also uses global variables to determine the daily production and the work-in-process inventory for each component in the model. The following sections describe the sub models and the global variables.

Each of the motor types is a separate ENTITY type in the simulation. A variable is associated with the percent mix for each motor type and each family (see Table 2 for the production mix). The VARIABLES for these percentages are TSWDMD and TSPDMD for overall motor type demand and TSW112, TSW160, TSW180, TSP112, and TSP132, respectively for each family’s demand. Five CREATE blocks are used to determine the arrival of each of the motor families. The VARIABLE for daily demand, DEMAND, is used to determine the number of each motor family that enters the system on a daily basis. For example, to calculate the demand for TSW 112 motors with a daily demand of 130 motors/day, the equation is:

$$(130\ motors/day)*0.74*0.55 = 53\ motors/day\ .$$

Table 4
TSW stator cell information

Workstation	Deviation	TSW 112 Processing Time (sec)	TSW 160 Processing Time (sec)	TSW 180 Processing Time (sec)	Weighted Operator Time (sec)	Set-up Time (sec)	First Pass Yield
Tap housing	3%	114	120	144	117	300	99%
Weld housing	10%	570	600	720	587	600	100%
Weld lifting lug and weld cleanup	5%	0	400	480	178	N/A	95%
Machining (Okuma)	2%	594	594	594	594	600	99%
Insert Slot Liners	3%	114	120	144	117	N/A	97%
Tape ID of Core	10%	1,140	1,200	1,440	1,174	N/A	100%
Wind Coils Manual	5%	769.5	810	972	792	600	99%
Insert Coils (Phase 1)	5%	2,622	2,760	3,312	2,670	N/A	100%
Insert Coils (Phase 2)	10%	2,622	2,760	3,312	2,670	N/A	100%
Insert Coils (Phase 3)	15%	2,622	2,760	3,312	2,670	N/A	100%
Remove Tape from ID	10%	399	420	504	411	N/A	100%
Route leads / color code phases	15%	1,425	1,500	1,800	1,467	N/A	80%
Form Endturns	5%	342	360	432	352	N/A	95%
Lace Windings	15%	855	900	1,080	880	N/A	99%
Joyal Prep	10%	228	240	288	235	N/A	100%
Joyal Terminals and cool	5%	342	360	432	352	600	99%
Stator Test	3%	114	120	144	117	N/A	85%
Varnish Prep	5%	228	240	288	235	N/A	100%
Varnish Preheat*	1%	228	240	288	235	N/A	100%
Varnish Dip*	1%	456	480	576	469	N/A	100%
Varnish Drip*	3%	228	240	288	235	N/A	100%
Varnish Cure*	3%	228	240	288	235	N/A	100%
Cool Down*	3%	228	240	288	235	N/A	100%
Varnish Clean Up	10%	399	420	504	411	N/A	100%

After creation, each entity is assigned the processing times for all workstations it will be processed on, a rotor size (RotSize) ATTRIBUTE, and a machine size (MCSize) ATTRIBUTE by an ASSIGN block. The rotor size and machine size ATTRIBUTES are used to determine when workstations in the rotor and stator cells must go through a set-up. An explanation of how these ATTRIBUTES are used for set-ups is provided in a later paragraph. The motor family determines the ATTRIBUTES as shown in Table 8. The first motor entering the system every day is routed to the stator assembly to begin immediate production. The other motors are held at a PROCESS block titled either “TSP Takt Control” or “TSW Takt Control.” The Takt Control blocks have processing times equal to the *takt* time of each Stator Cell. As the order is released into the system, an ATTRIBUTE marking the entry time is recorded. This ATTRIBUTE is used in calculating the flowtime through the system and is discussed at the point in the model where that is calculated. When the orders are released from the Takt Controllers they are routed to the stator subassembly to begin processing.

Each motor type (TSW and TSP) has its own stator assembly submodel. Orders arrive from the Arrival Logic submodel and begin processing through the appropriate stator subassembly. There is a PROCESS block for every workstation listed in the TSW and TSP stator cell sections (see Tables 4 and 6, respectively). Each workstation is comprised of at least a STATION, PROCESS, and ROUTE block. The STATION block receives routed motors. The PROCESS block SEIZES the appropriate worker for that process and delays the motor for the assigned processing time and then RELEASES the worker. The processing time for each workstation is assigned to each motor just after creation in the Arrival Logic Submodel. The ROUTE block sends the motor to the next workstation in the process. Workstations that have operator and additional processing times have an additional PROCESS block to handle the additional processing time.

Workstations requiring a set-up have additional logic to HOLD the first motor of that family or size until the workstation can be set-up, then proceeds through the set-up PROCESS (seizing the worker, delaying for the setup time, and releasing the worker) before it can be processed on the workstation. The HOLD block compares the MCSize ATTRIBUTE of the current motor to the MCSize ATTRIBUTE of the previous motor. If the ATTRIBUTES are different, the current motor is held until a worker and the workstation are available for set-up. After the workstation is set-up, the motor is processed on the workstation as usual.

Workstations with first pass yield percentages have additional logic to check to see if any rework or scrap has been created. The workstation PROCESS seizes the worker, delays for the processing time, and then INSPECTS to see if the part is good based on the appropriate first pass yield percentage. If the part is good, the worker is released and the part is routed to the next station. If the part needs to be reworked, the worker immediately reworks the part before being released and the part is routed to the next station. Workstations that can have both rework and scrap have a similar logic as the rework, except an additional DECISION block is required after the INSPECT block to determine if the motor is to be reworked or scrapped. If the motor is scrapped, it is sent back to the appropriate workstation to be started as a “new” order.

Table 5
TSW final assembly cell information

Workstation	Deviation	TSW 112 Processing Times (sec)	TSW 160 Processing Times (sec)	TSW 180 Processing Times (sec)	Weighted Operator Time (sec)	First Pass Yield
Install thermistor connector	10%	285	300	360	293	90%
Install terminal lug hardware	15%	570	600	720	587	85%
Insert bearing into end bell	5%	57	60	72	59	99%
Insert shaft key	5%	19	20	24	20	98%
Insert rotor into end bell	10%	57	60	72	59	99%
Install stator over rotor / drive end bell assembly	10%	114	120	144	117	99%
Install spring washer and sensor bearing with o-ring in second end bell	10%	114	120	144	117	99%
Install Air Guide and route sensor bearing lead.	5%	266	280	336	274	99%
Install second end bell onto rotor/end bell/stator assy. Route thermistor and sensor bearing leads.	10%	114	120	144	117	95%
Sleeve Wire sensor and thermistor wire with corrugated tubing	15%	57	60	72	59	95%
Install hook nuts and hardware & Torque end bell screws	3%	228	240	288	235	99%
Install connector bracket	15%	114	120	144	117	98%
Electrical test	10%	285	300	360	293	95%
Install label and overlay	5%	29	31	37	30	99%
Install shaft seal	5%	43	45	54	44	99%
Rust Proof and package	3%	143	150	180	147	100%

Table 6
TSP stator cell information

Workstation	Deviation	TSW 112 Processing Times (sec)	TSW 160 Processing Times (sec)	TSW 180 Processing Times (sec)	Weighted Operator Time (sec)	First Pass Yield
Install thermistor connector	10%	285	300	360	293	90%
Install terminal lug hardware	15%	570	600	720	587	85%
Insert bearing into end bell	5%	57	60	72	59	99%
Insert shaft key	5%	19	20	24	20	98%
Insert rotor into end bell	10%	57	60	72	59	99%
Install stator over rotor / drive end bell assembly	10%	114	120	144	117	99%
Install spring washer and sensor bearing with o-ring in second end bell	10%	114	120	144	117	99%
Install Air Guide and route sensor bearing lead.	5%	266	280	336	274	99%
Install second end bell onto rotor/end bell/stator assy. Route thermistor and sensor bearing leads.	10%	114	120	144	117	95%
Sleeve Wire sensor and thermistor wire with corrugated tubing	15%	57	60	72	59	95%
Install hook nuts and hardware & Torque end bell screws	3%	228	240	288	235	99%
Install connector bracket	15%	114	120	144	117	98%
Electrical test	10%	285	300	360	293	95%
Install label and overlay	5%	29	31	37	30	99%
Install shaft seal	5%	43	45	54	44	99%
Rust Proof and package	3%	143	150	180	147	100%

Table 7
TSP Final Assembly Cell Information

Workstation	Deviation	TSP 112 Processing Time (sec)	TSP 132 Processing Time (sec)	Weighted Operator Time (sec)	First Pass Yield
Install Shrink tube	10%	105	145.0	117	99%
Connect thermistor & Install Corrugated tube	10%	600	829.0	671	90%
Press non drive bearing onto rotor.	5%	120	165.0	134	99%
Install Spacer	10%	30	41.5	34	99%
Install Snap ring onto shaft	10%	30	41.5	34	99%
Install clamp plate and snap ring onto Bearing	15%	180	248.0	201	98%
Install end bell onto bearing / rotor assembly	15%	300	415.0	336	95%
Install 2 snap rings and key	10%	150	207.0	168	95%
Lower stator assembly onto rotor / end bell assembly	15%	180	248.0	201	99%
Apply loctite and install fan Secure with snap ring	5%	120	465.0	227	99%
Heat and Install bearing	10%	30	41.5	34	99%
Install Seal in Drive end bell	5%	60	83.0	67	95%
Heat and Install Drive end bell	10%	150	207.0	168	95%
Install Tie Rods	10%	360	498.0	403	99%
Assemble/install Connector Bracket	10%	360	498.0	403	95%
Torque Tie Rods	10%	180	248.0	201	95%
Install key	5%	20	28.0	22	98%
Electrical Test	10%	300	415.0	336	95%
Install label and Plastic overlay	5%	30	41.5	34	99%
Rust Proof and package	3%	150	207.0	168	100%

Table 8

Rotor Size and Machine Size Attributes

Motor Family	Rotor Size	Machine Size
TSP 112	1	1
TSP 132	1	2
TSW 112	1	1
TSW 160	2	3
TSW 180	2	4

The Varnishing processes require batching of the product to flow through an oven. These workstations have additional logic that controls the batching of the stator subassemblies. The motor variants are batched in groups of 12 units (112 models), 9 units (132 models), or 6 units (160 and 180 models). The stator subassembly enters the workstation and then enters a DECISION block to determine the motor family. The DECISION block separates the subassemblies by family and sends the subassembly to an ASSIGN block that sets the batching size for each family. If the current subassembly is of a different family than the previous subassembly, the previous subassemblies are sent through the workstation in a batch consisting of the subassemblies of that family that is waiting. For example, if there are 8 TSW 112 subassemblies waiting for the batch size of 12 to be reached and a TSW 132 is the next subassembly, then the 8 TSW 112 subassemblies are processed and the batching for the TSW 132 subassemblies begins.

After the last workstation in the cell a RECORD block is used to determine the flowtime of the stator. The flowtime is calculated by subtracting the entering time from the current time. After processing on the last workstation is complete, the motor is sent to a MATCH block to be paired with a rotor of the same size and type before proceeding through final assembly.

The Rotor assembly submodel utilizes duplicate CREATE blocks from the Arrival Logic Submodel to create the same number of rotors as stators. The processing times for each workstation in the rotor subassembly are assigned just after creation of the motor. The rotor assembly takes less time than the stator assembly, so the rotor begins 9.5 hours after the stator. Because the rotor cell is feeding both the TSW and the TSP cells, its *takt time* must be less than or equal to the total production time divided by the total demand. After release from the Rotor Takt Controller, an ATTRIBUTE is marked with the current time so that the rotor flowtime can be calculated. As with the stator subassembly sub models, the rotor assembly submodel has the appropriate logic to handle set-ups (based on RotSize rather than MCSize), processing, and rework. The rotor workstations are shown in Table 3. After the final workstation, the time it takes a rotor to be processed is calculated by using a TALLY block to determine the interval between when the rotor entered the system and when it was completed. After the rotor assembly is completed, it is routed to the appropriate (TSW or TSP) MATCH block to be mated with a stator and sent to final assembly.

Each motor type has its own final assembly submodel. Stators and rotors are matched according to motor type and family just prior to entering the final assembly submodel. After the stator and rotor is matched, an ATTRIBUTE is marked to record the time the motor entered the final assembly process. This ATTRIBUTE is used to calculate the flowtime through the final assembly cell. There is a PROCESS block for every workstation in the TSW and TSP stator subassembly section. Each workstation is comprised of at least a STATION, PROCESS, and ROUTE block. The STATION block receives routed motors; the PROCESS block SEIZES the appropriate worker for that process and delays the motor for the assigned processing time then RELEASES the worker. The processing time for each workstation is assigned to each motor just after creation in the Arrival Logic Submodel. The ROUTE block sends the motor to the next workstation in the process.

Workstations with first pass yield percentages have additional logic to check to see if any rework or scrap has been created. The workstation PROCESS seizes the worker, delays for the processing time, and then INSPECTS to see if the part is good based on the appropriate first pass yield percentage. If the part is good, the worker is released and the part is routed to the next station. If the part needs to be reworked, the worker immediately reworks the part before being released and the part is routed to the next station. Workstations that can have both rework and scrap have a similar logic as the rework, except an additional DECISION block is required after the INSPECT block to determine if the motor is to be reworked or scrapped. If the motor is scrapped, it is sent back to the appropriate workstation to be started as a “new” order. In each final assembly submodel (after the last workstation) there is a RECORD block that determines the flowtime for each motor. The flowtime is calculated by subtracting the entry time attribute assigned at the beginning of the final assembly submodel from the current time. After processing on the last workstation in the cell, the motor is sent to the shipping submodel.

The shipping submodel is used to calculate the total number of motors, the total number of each family of motors, and the flowtime. A RECORD block is used to count every completed motor and separates the motors out by family type.

There are six global VARIABLES that are included in the model: 1) NumShip, 2) RotInSys, 3) TSWSTAT, 4) TSWASBL, 5) TSPSTAT, and 6) TSPASBL. NumShip is assigned in the Shipping Submodel and is used to calculate the average number of motors built each day. The other five variables are used to determine the average work-in-process for rotors, TSW stators and final assemblies, and TSP stators and final assemblies. RotInSys tracks the number of rotors in the system. RotInSys is increased by one when a rotor enters the rotor cell and is decreased by one after a rotor is matched to a stator and enters the appropriate final assembly cell. TSWSTAT and TSPSTAT track the TSW stators and TSP stators, respectively. TSWSTAT and TSPSTAT are increased by one when a TSW or TSP order, enters the system. As with the RotInSys variable, TSWSTAT and TSPSTAT are decremented by one when a rotor and stator are matched and enter the final assembly process. TSWASBL and TSPASBL track the number of final assembly units for TSW and TSP, respectively. As a matched rotor and stator enter the final assembly cell, the appropriate (TSW or TSP) variable is increased by one. Once the motor has been completed, the variables are decremented.

2.3 Model Verification and Validation

The model was verified by ensuring that parts moved through the correct submodel (e.g., TSW motors were only processed in the TSW cells), that parts flow correctly (e.g., serially through the cell), and that rework and scrap were properly handled. After verification, Welch’s method was used to determine the warm-up period required for the model to reach steady-state. The warm-up period is 10 days. Ten replications of the model were then run for 110 simulated days to collect average data on 100 simulated days. The model was validated at the 100 motor/day demand level by having IM associates view the model to determine if the model appeared to perform as expected.

3. Results

At the request of IM, the playbooks for demand levels of 65, 75, 85, 95, 100, and 130 motors per day were developed. Playbooks included information on meeting daily production requirements and potential bottlenecks or problem areas. At each demand level, the simulation model tracked the overall average daily production. That is, the model tallied the total number of motors, regardless of model or type, produced each day. Table 9 shows the daily production for each demand level. All demand levels produced the required daily demand on average, with the exception of 130 motors/day.

Table 9

Daily Production at Each Demand Level

Demand Level	Daily Production (motors)
65 motors/day	64.97
75 motors/day	75.97
85 motors/day	85.94
95 motors/day	95.99
100 motors/day	99.97
130 motors/day	109

The simulation model results show that at all but one demand level, the line is capable of producing to within one unit of demand if the required number of workers is present. At a demand level of 130/day (which is the current expected demand for the line), the simulation results suggest that the line is not capable of meeting demand. The simulated production for this demand level is 109 motors/day (21 short of daily demand), while actual daily production as reported by IM is approximately 100/day. Several reasons could explain the difference between the simulated 109/day vs. the actual 100/day at the 130/day demand level. First, the simulation model assumes that there are sufficient workers to perform the tasks (in other words, the actual worker assignment matches the planned worker assignment). Second, the model assumes that supplier quality and on-time-delivery are 100%. Lastly, the first pass yields used in the simulation model may not be representative of actual FPY achieved on a day-to-day basis.

Potential bottlenecks were identified for the rotor cell and each subassembly. Potential bottlenecks were determined by evaluating a combination of the average number of units of work-in-process (WIP) waiting in the queue before each workstation and the average time each unit spent waiting before processing on each workstation. Addressing these potential bottlenecks would decrease the time required to produce a motor, reduce WIP, and improve the line’s ability to handle small fluctuations in demand. Table 5 lists the potential bottlenecks for each subassembly and the rotor cell. The bolded items in Table 5 represent bottlenecks that either affect both motors types (TSW and TSP) or significantly affect that cell. For example, the “Machining” workstation affects both motor types because the workstation is shared between both stator cells.

At the 130/day demand level, there are several workstations that significantly impact the TSW Stator Cell. The worker assignment may have an impact on these workstations. That is, several of the bolded workstations in Table 10 share workers (e.g., Worker 1 is assigned to both “Tap Housings” and “Weld Housings”). Increasing the number of workers in the TSW stator cell could improve the flowtime and WIP and increase the daily production to 130/day.

4. Discussion and Conclusions

For this case application, a simulation model of a proposed future state of the EVS production line was developed to analyze the production capabilities of the cell. The model analyzed the impact that demand levels of 65, 75, 85, 95, 100, and 130 motors/day would have on daily production. From the results of the simulation model, potential bottlenecks at each demand level were also identified. The model shows that at the demand levels of 65, 75, 85, 95, and 100 motors/day, the cell should be able to produce to within one unit of the required demand given the quality levels and processing times provided by IM. For 130 motors/day, the “Machining” processing time must be reduced to 457 seconds to meet demand.

Table 10
Potential bottlenecks at each demand level

Demand Level	Subassembly	Potential Bottleneck
65/day	TSW Stator	Form Endturns, Joyal Prep and Terminals, Stator Test
	TSW Assembly	Insert Shaft Key, Install Bearing, Install Terminal Lug Hardware
	TSP Stator	Remove Tape
	TSP Assembly	None
	Rotor	Heat Rotor Core
75/day	TSW Stator	Remove Tape, Route Leads/Code Phases, Weld Lug and Clean
	TSW Assembly	None
	TSP Stator	Tape ID of Core
	TSP Assembly	Insert Slot Liners
	Rotor	Heat Rotor Core, Balance
85/day	TSW Stator	**Machining**
	TSW Assembly	Install Bearing, Install Terminal Lug, Install Thermistor Connector
	TSP Stator	**Machining**
	TSP Assembly	Insert Slot Liners
	Rotor	Heat Rotor Core, Balance, Inspect, Turn Rotor OD
95/day	TSW Stator	**Machining, Wind Coils, Tape ID of Core**
	TSW Assembly	Electrical Test
	TSP Stator	**Machining**
	TSP Assembly	Insert Slot Liners,
	Rotor	Balance, Heat Rotor Core, Turn Rotor OD
100/day	TSW Stator	**Machining**
	TSW Assembly	Assemble Shaft to Rotor, Insert Rotor into Endbell, Insert Shaft Key
	TSP Stator	**Machining**
	TSP Assembly	Connect Thermistor, Insert Spacer, Install Snap Rings and Key,
	Rotor	Balance, Heat Rotor Core, Turn Rotor OD
130/day	TSW Stator	**Machining, Weld Housings, Tap Housing, Varnish Prep, Joyal Terminals, Stator Test**
	TSW Assembly	Insert Slot Liners
	TSP Stator	**Machining**
	TSP Assembly	Connect Thermistor, Insert Spacer, Install Snap Rings and Key
	Rotor	**Heat Rotor Core**

An area of future work is to investigate the placement of a “trigger” in each of the stator subassembly cells that would initiate an order for a rotor. That is, instead of starting a rotor 9.5 hours after a stator is started, an order for a rotor would be initiated after a stator was finished at a particular workstation. A second area of future work is to analyze the impact of improving critical supplier quality and on-time delivery. The most critical supplied parts could be included in the model with their corresponding quality levels and on-time-delivery performance. Earlier work with IM on another line suggests that supplier quality levels may have a more significant impact on line performance than supplier on-time delivery (McDonald, *et.al*, 2002a). A third area of future work is to investigate the impact of changing how often each motor family is produced (i.e., the “every part every”, or EPE). This research only considered producing every motor family every day, but the model could be revised to find the impact of changing to an EPE of every week or any other timeframe.

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