*Proceedings of the 2018 Winter Simulation Conference*
*M. Rabe, A.A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, eds.*

# FORD'S POWER TRAIN OPERATIONS: CHANGING THE SIMULATION ENVIRONMENT 2

Michael Higgins
John Ladbrook

PowerTrain Manufacturing Engineering
Ford Motor Company
Dunton Research Centre
Basildon, SS15 6EE, ENGLAND

## ABSTRACT

At the 2001 Winter Simulation Conference, the progress of simulation in Ford Motor Company's PowerTrain Manufacturing Engineering (PTME) department was documented in a paper that focused on the contributions of the department in changing the simulation environment at Ford. This paper reviews the progress, changes, and issues in the intervening years experienced by the UK-based PTME simulation team. It summarizes the development of a toolset from a model building capability to data analysis, to experimentation, and results analysis. It outlines how capabilities have expanded while maintaining quick delivery of results; it references the managements' changing attitude and how academic research has advanced simulation in PTME.

## 1 INTRODUCTION

Prior to 2001, the PTME simulation team was reliant on the Fast Interactive Replacement Simulation Tool (FIRST), which built and ran models of machining lines. Subsequently, two additional collaborative component tools (Winnell and Ladbrook 2003; Winnell and Ladbrook 2004) were developed. These two were the Ford Adaptable Simulation Tool (FAST) (Mebrahtu and Ladbrook 2008) used to model Engine Assembly facilities and the Ford Material Analysis Tool (FORMAT) (Emmerson and Ladbrook 2003) used for Material Flow Analysis (MFA). The latter was not successful due to timely access to the data and a time-consuming process to deliver results.

Keys to success at the time were: Access to 30 software licenses via the network instead of Personal Computer (PC) based security devices, were a result of working with the supplier of the simulation software. This initiative was made available globally and operates today with 100 licenses. Rapid delivery of results was achieved with a modeling strategy that included default and rationalized inputs (Poole 1999) plus inclusive logic that allowed for rapid model building and execution.

The experimentation process was laborious having to purpose-build macros to run alternative scenarios, a method that few understood. Although results were returned to the spreadsheet in which the model was built they were limited and often required a significant amount of time to interpret, which was often extended by the management asking probing questions beyond the capability of the tool.

Overall, simulation successfully supported the manufacturing planning process by providing data and insight for decisions to be made and strategies adopted. Success in influencing planning was achieved by driving the results into the system, but on occasions: the simulation was treated as a tick box exercise.

## 2 THE START OF A NEW ERA

A change of senior management led to a change of attitude towards simulation, which was summed up by the statement "If we are going to use simulation we are going to use it to make decisions based on real data

978-1-5386-6572-5/18/$31.00 ©2018 IEEE

and we are going to consider the results and directions given in our decision making." This was directed at the simulation and management teams as a whole and resulted in the start of the journey that significantly changed the use of simulation within PTME. Acceptance has continued to grow to a level where at a recent meeting one senior manager said "I accept the results indicated by the simulation. I just need to agree with the inputs and assumptions."

Based on the foundations that were in place in 2001, the simulation process was developed to support the management's requirements and provide them with meaningful data and intelligence on how the planned manufacturing systems were predicted to operate. By working closely with managers, their needs were understood and they understood the capabilities of simulation. The continuous demand has resulted in simulation becoming an integral part of the manufacturing planning process. Based on the fundamentals of success: tools for the job as shown in Figure 1, readily available software, and – the key element – rapid delivery of results, steps were taken to advance the toolset.

## 2.1 The Developing Toolset

The integrated toolset shown in Figure 1 was developed to streamline the simulation workflow starting with the analysis of machine failure and cycle time data which are then referenced in the model building interface FAST where the process and relevant model data are input. The model is then built automatically in the simulation software Witness and saved ready for experimentation. Experiments are generated in the Command Generator where it is possible to set up scenarios that evaluate the model by individual operation and by factor such as Breakdowns and Quality as well as being able to vary the inputs, such as the number of pallets. Results from the experiments are stored in an output file that can be read into the results analyzer which generates a standard set of results that are readily understood.

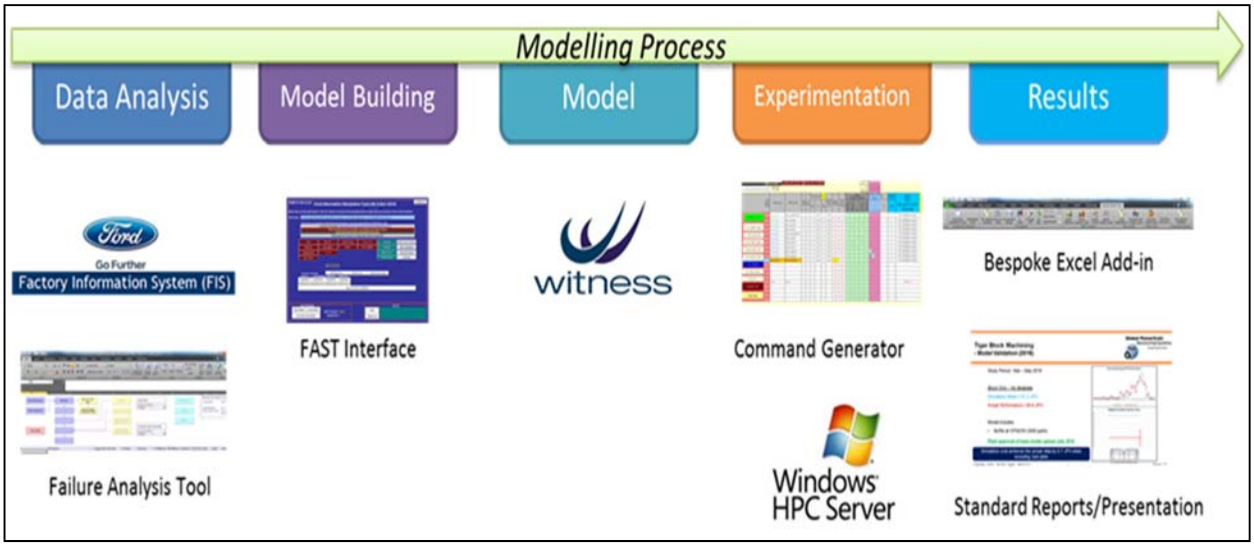


Figure 1: An overview of the 2017 PTME Modeling Process and Toolset.

Up to 2005, the FIRST tool met machine line modeling needs while FAST that of Engine Assembly lines. The transporting of machined components changed from direct location on a conveyor to a palletized conveyor system. This resulted in all lines having the same transport mode and with additional capability only FAST was required to meet our modeling requirements. This allowed a departure from the modeling strategy used in FIRST to a focused development of FAST, which included a higher degree of detail being demanded from the customer. FAST was updated by adding modules that represented the new manufacturing concepts, primarily a number of machining cells under a gantry.

The method of model building remained the same with added menus and templates to capture the input data for the new modules. This update drove changes to the input data included in the models, which were:

- Cycle Times went from a single input to a distribution form.
- Tool change detail was specified per derivative rather than one input for all.
- Failure detail went from generic to specific by machine inputs.

Acceptance of the simulation process grew and there was a desire to model ancillary production processes. Logic, functionality, labor, machines and equipment were added for the tool crib area used to maintain cutting tools, and the gauging process which checks for component quality was included. The tool crib model, a joint venture with Cranfield University, identified that only one of two proposed test machines was required, which in itself was a saving, but significantly it was a legacy for all future installations that followed the common planning and engineering concept.

The simulation modeler now collected extensive quantities of data that were already collected by the Industrial Engineering team. An opportunity to eliminate this duplication was taken through a project with Southampton University (Saghri 2010). The skills brought by the student to reduce the duplication of effort brought about a change in coding practice. This resulted in model building efficiencies necessary to offset the slower build time resulting from increased data input.

Despite building more complex models, more models due to increased program workload, and more models due to increased demand, model building was no longer the bottleneck. The constraints were the ability to generate experiments and provide results to the teams.

### 2.2 The Experimentation Process

Models can be run directly by interacting with the software inputting the warm-up time and runtime before executing the run. Alternative approaches are to use the optimization functions provided by the simulation software or run using a macro file which contains the necessary commands for running and changing inputs within the model.

Optimization was not normally used due to the lengthy time taken to complete an evaluation. When it was used, run lengths were shortened and replications reduced to get direction as to the path to be taken. The best of these were then run for the required number of replications and run length, but this sometimes resulted in instances where they did not relate to our original findings.

Ford PTME developed an approach of using macros to get sufficient insight to make the correct decisions. This was not without issue, the main one being the continual training of new team members. The advantage of using macros was that it allowed us to take one simulation and run many different options. This is achieved by the inclusion of variables used as multipliers to change the input values, hence a zero value would negate the effect of that factor. Equipment within the model is allocated to a zone providing the capability to experiment with individual machines or groups of machines.

On completion of the experiments, the resulting simulation and report files are saved for post-run analysis in the PTME Results Analyzer. As management was presented with more data, they asked for more detail to feed their hunger to make decisions. Today, as requests grow, continued development of the tool grows the capability to run the required experiments.

Programming the macros drained our limited resource and impacted the speed to deliver results. The Command Generator interface was fashioned to capture the practice of creating the macros. This reduced the level of retraining and the errors that arose. Today's Command Generator is a combination of university collaborations and team members who identified the need for extended experimentation capabilities. Tomorrows Command Generator will be reprogrammed in a modern language which will make it easier to use, allow for an enhanced experimentation process to meet the management's requirements, and improve the quality of the models.

## 2.3 Results Analysis

To handle the multitude of experiment files, it was essential to automate the process of reading them into a spreadsheet for post processing prior to producing standard tables, charts and graphs. This would have appeared to be straightforward, but it was found that the human approach had been very adept and flexible whereas the machine-based process was intolerant of inconsistencies in the file formats. After much research, methods were engineered to manipulate the structure of the model output file in a way that the data could be read in and manipulated to give the required reports irrespective of the size of the model. This approach allowed for reading of multiple replications either individually or stacked to give differing views of the data that helped improve the understanding of the manufacturing process being studied.

Early forms of the reports were typically a replication of the software output which did not always present well, with the models ranging between 20 and more than 100 operations. The reports included hourly output, busy, blocked, and starved status, but excluded elements added to make the model function. The simplicity of graphical output was essential when communicating with other PTME teams. One of the team's greatest assets is termed the "H" chart shown in Figure 2 which is used for comparing the model to actual output or scenarios. The chart shows the mean as the horizontal line and the vertical line is the upper and lower confidence interval of the data set. The chart displays wording stating if the comparison was good or not.

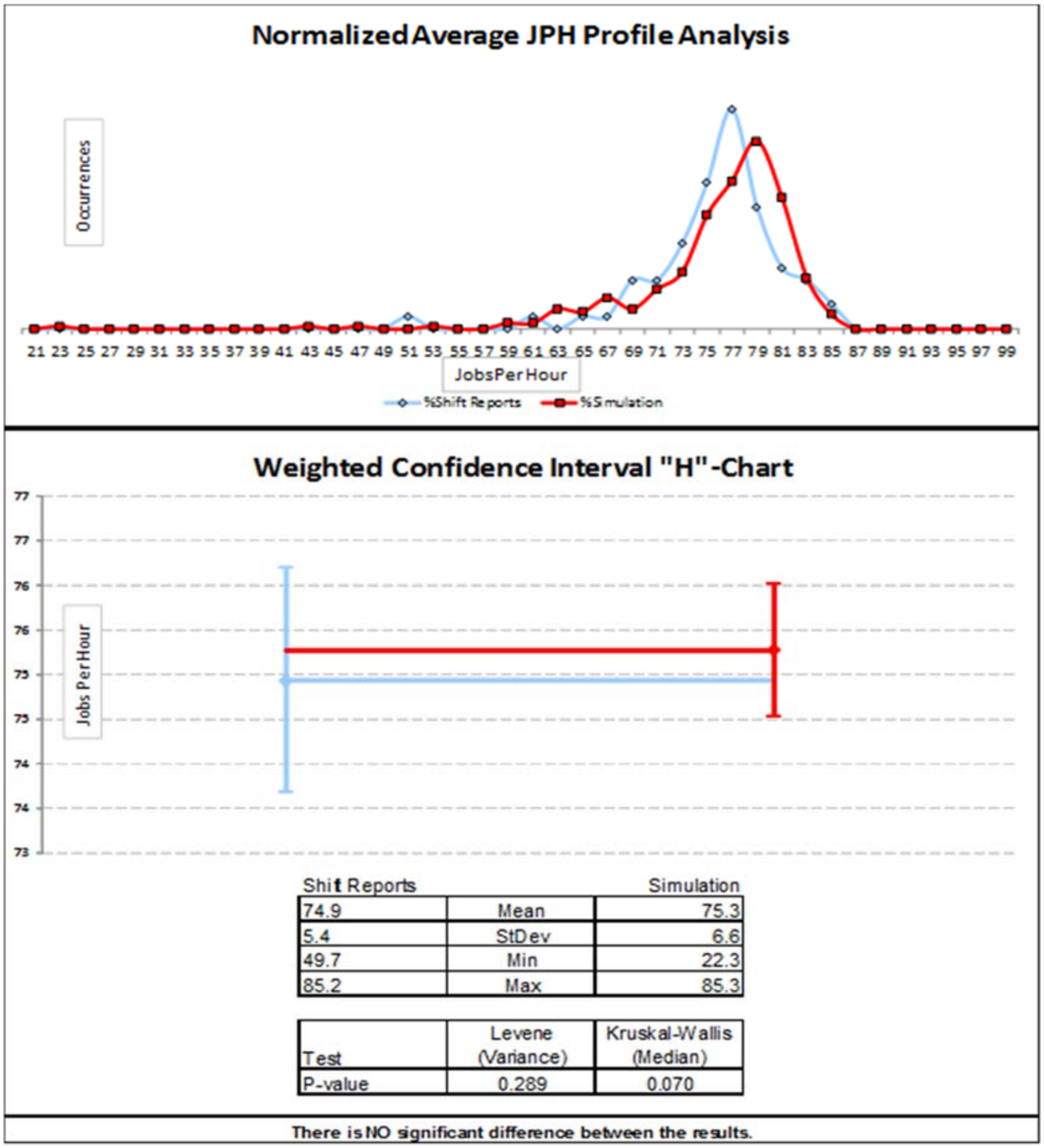
The "H" chart is used in conjunction with a line graph shown in Figure 2 which compares two profiles of output per hour. Initially used in 2007 for comparing the model to actual output profiles, customers could instantly see if the model was aligned or not. Previously, when using the mean output as a metric, there had always been much discussion as to the validity of the model. These charts also drive modelers to deliver better quality models because they know the profiles needed to match.

In 2015, a member of the team challenged the fundamentals of the statistics behind the "H" Chart. The result is that we now have three tests to compare output profiles to establish if they are similar. Testing done confirmed that the initial approach had been sound, but the Levene and Kruskal-Wallis tests were added to our report as more recognizable statistical tests. The management's desires for different presentation and reports have been and are still being added to the standardized report set. Thus, regardless of who runs the experiments, the look of reports is the same making the review process easier. So, our principle for presenting results is simple charts and data that readily convey meaningful information to the customer.

Such charts are a buffer profile chart which records the buffer size and displays it as a line graph showing how the buffer fluctuates over time. This has been used to help determine stock levels between lines and to convey to production if they had an opportunity to move pallets between different locations.
In addition, Zou (2007) researched run length and combined it with six sigma techniques and reference to Robinson's work (1995; 2002) on this subject. He developed a run length analysis chart that – through a graphical output – provided an aid to determine the required run length for each model.

The key performance metric in PTME is Jobs per Hour (JPH). Other metrics are by shift or day as used by production or by the month for a higher management performance report. A single chart was created to show daily weekly, and monthly periodic outputs. The monthly report resulted in criteria for planning models being defined as the average output for no one month should fall below the target. Review of the lowest days output can ascertain the factors that caused the poor performance.

This is achieved by identifying the duration of all failures over $X$ minutes and when they occurred during that day. A table is created to show by operation the factors contributing to poor performance enabling the modeler to cross-reference the failure to the input data and theorize on the potential failure mode that could have caused this issue. This information is fed back to the process and maintenance teams who take action to reduce or eliminate such a failure from the existing facility or in machines being designed. This is a powerful use of the simulation and one of the major intangible benefits derived from the work done especially when considering the number of new machines purchased by Ford.



| Shit Reports | | Simulation |
|---|---|---|
| 74.9 | Mean | 75.3 |
| 5.4 | StDev | 6.6 |
| 49.7 | Min | 22.3 |
| 85.2 | Max | 85.3 |

| Test | Levene (Variance) | Kruskal-Wallis (Median) |
|---|---|---|
| P-value | 0.289 | 0.070 |

There is NO significant difference between the results.

Figure 2: A line graph and “H” chart showing simulation v actual profiles.

A waterfall chart identifies major losses by category. This can focus attention on where effort is required to increase throughput. As the PTME experimentation process allows zones for being run independently, there is the capability to present the hourly output over time for each zone. From this, individual bottlenecks are identified as well as the variance of output in each zone. By running zones in combination starting with the bottleneck and adding adjacent zones, the impact of each zone on the bottleneck can be established to ascertain where improvement is required.

There have been many charts developed and produced as standard output in presentations and reports. When presenting only those that are appropriate to the area under discussion are issued. However, all of these charts – which are now automatically generated by importing the report files – make it easy to pull key metrics from the simulation data. These macros have been added to Microsoft Excel in its own ribbon, making it look very professional.

The simulation process bottleneck became experimentation capacity. Initially, this was addressed by running multiple experiments on a single PC utilizing the available network licenses and aided by increased central process unit rates and multiple-core PCs capacity.

A development that would have utilized PCs while they sat idle worked in principle but contravened the Information Technology Departments (ITD) policy. However, the ITD proposed an internal cloud solution known as High Powered Computer (HPC), which utilized capacity on a cluster of processors. This was similar to the research into improving simulation execution speed undertaken with Brunel University (Mustafee et al. 2006). The final implementation was the result of a 2011 tripartite initiative to deliver increased experimentation capacity. The simulation team modified the command generator to communicate with 40 remote HPC processors, while ITD modified the HPC manager to recognize the software, manage the submissions from the command generator and save the report files while the software supplier modified the internal functionality of their software to communicate with the HPC.

Success was immediate, submitting up to 200 experiments per session. The negative was to upset other users by consuming all available licenses. This issue was resolved by the purchase of 40 run-only licenses to match the number of processors on the HPC. This approach gave the capacity to run the experiments required and provided to the management the opportunity to ask more questions, driving up the use of simulation as we responded to that fundamental need of rapidly answering questions.

After three years, we are again facing a capacity issue, and during 2017 we have focused on the code within the models and are ensuring that it is as efficient as we can make it. Inroads into improved methods of coding the logic and reducing the complexity of functions that are called many times have been made resulting in a 15% reduction in runtime.

### 2.3.1 Failure Input

The data analytics process managing the data collected from the line monitoring systems is critical to the success of simulation. The worksheet originally created by Lu (2005) when she researched Modelling Breakdowns at Southampton University was updated in 2016 by PTME and their North American colleagues, making it a globally agreed tool. The tool captures the intelligence of the human in analyzing the raw data giving a consistent approach to eliminating discrepancies in the data, such as removing duplicate records, overlapping data in other operations and removing breaks before creating time between failure and time-to-repair distributions that can be read into the FAST interface.

Including a time-between-failure distribution, which had been considered but not until we had a resource with the time to research, test, and compare the proposal the negative exponential form was superseded. Initial attempts created biased results, but further research and application of variable ranges, especially for the larger extreme values, overcame the issues making this method standard practice in the Ford PTME group. Overall, it made little difference to the line output, but it gave confidence in knowing that the time between failures was represented as observed.

A long-standing assumption had been that failures longer than 10 hours were false data and these were excluded from the input distributions. This was true to some extent, but the production team's data showed extensive failure times, so we had evidence for accumulating data to form longer failure times. This clearly demonstrated the benefit of working with subject matter experts and not just assuming that the electronic reporting was factual. The key lesson is that it is essential to understand your data, and to help with this, we have added a data analyst to the team and are exploring other data analytic techniques.

This summarizes the PTME toolset, which has increased productivity and standardized the approach. It has helped enhance our understanding of the way our facilities function, but it does not eliminate the art of understanding of a way a line runs, which is where the value is added. The tools do not generate the "What ifs" or answer the "What ifs" that require a thought process and imagination that we have yet to capture, but will be working towards in the future.

### 2.3.2 Other Modelling Tools

Discrete event simulation is our core method of modeling, but it is not the only one; having a tool for the job means having the right tool. Many questions can be answered with a simulation model, but you should always ask yourself, is it the correct and most efficient way to answer the question? Sometimes just understanding the question will yield an answer.

Such an example was related to the location of a subassembly facility and the number of vehicles required to deliver parts from a marketplace to the subassembly line without impacting line performance. The answer came from knowing how long it took to deliver a load and if that did exceed the demand. The calculation indicated that no model was required, but the customer just had to be convinced, which is one of the most challenging parts of a modelers work, as per Carson (1986).

Any process can be modeled, but before modeling everything, ask yourself if it is the most efficient way to represent the process under review? Two of the following three examples show how PTME started simulating an activity and then found an improved way of representing it. Associated with this was a hope that the engineers of the function and owners of the data would use the model rather than third party modelers.

The first example was the tool crib. When validating the model's performance, it was found that the results were not significantly different to those obtained by calculation. The result of the project was a simulation model that was less efficient due to the time to process the additional data and logic. The alternative algorithmic method that represented the tool crib could easily be used by a tooling engineer to obtain answers to his own questions in a time that it would take them to get the modeler to understand the data and question.

The tool was used by the tooling department and after presenting to their customers they added further process functionality by adding to and enhancing the algorithms. These additions would have taken a considerable time and expertise to program into our generic model and hindered the rapid delivery of results. By having clear objectives and boundaries, the simulation team’s workload was reduced by giving the subject matter experts a model they could use.

A second example was the Material Flow Analysis model (MFA) that replaced the previous software FORMAT (Pan 2007), which was built to represent the supply material from an internal marketplace to an assembly line. FORMAT was a self-contained model that included the assembly process, vehicle routes, unit loads, marketplace locations, and delivery frequencies. Although effective, rebuilding the assembly line was duplicated effort requiring a high level of expertise and knowledge of the material handling process, hence the team was reliant on one modeler who on leaving was difficult to replace.

Material flow was included in FAST when subsequently a simpler method was conceptualized on how to model this. The concept of modeling vehicle delivery was determined to be a function of travel time plus time to handle the parts and the usage rate. This rationalization allowed the material flow process for being integrated into FAST eliminating the need for a second model. Still requiring a high level of expertise and effort, the inclusion of material flow in FAST was unsuccessful as it impacted other mainstream tasks.

The very successful MFA development was based on the conceptualization previously mentioned, but this time it was modeled in a spreadsheet. Developed as an MSc. project with the University of Southampton, Osman (2012) accepted the challenge to create the model, which was subsequently enhanced by Khalwadekar and included an easy-to-understand Heat Map of vehicle movement. The addition of the Heat Map moved modeling from providing data to be a plant safety aid (Higgins et al. 2018). The third example was a Market Place Sizing calculator (MPS). Similar to the MFA tool is was created by Martinez (2012) as an MSc. project at the University of Southampton. The objective was to develop a tool that would standardize the process of calculating the size of the Marketplaces and the number of racks required. The tool, which included a range of methods for storing parts provided the number of racks and type that the layout team needs to provide space for. As with the MFA, key data were pulled into the model, which drove a standard practice into the process. This saved significant time in building these models and error checking was able to identify where data were lacking.

This model met all our criteria easy to use and quick to run and deliver results. It required only one hour training and put a tool in the hands of the material handling engineers that would yield the same result given the same input. This could not be said about the previous practice. MPA and MPS have yielded significant benefits, since their introduction being used to avoid a building extension evaluated the introduction of a new engine while an old one declined, identifying that the existing space was sufficient and evaluated the relocation of a marketplace leading to a proposal that saved three vehicles. Most importantly, it has been used to drive pedestrian safety into our plant layouts.

## 3 RESEARCH

There has been a long and successful association between the Ford PTME simulation team and Universities stretching back to 1991. It has greatly benefitted all including 13 universities and 258 students as of June 2018. The following recent examples of research expand on collaborations discussed previously elsewhere in this text in Sections 2.1, 2.2, 2.3.2, and 2.3.2, but this only represents the contribution of the few. PTME very much appreciates everyone's contribution to making them a successful team.

Wilson from the University of Greenwich worked on modeling Energy (Wilson et al. 2016). Based on energy usage data collected, he developed a spreadsheet that links to the simulation model output to calculate Kilowatt hours. This resulting model can be used by the Environmental team to determine what operating strategies can be used to save energy.

Mulvany from the University of Greenwich researched usage of compressed air (Mulvany et al. 2017). This will deliver a tool that will help to size compressors based on data and should negate the practice of adding safety margins and cost. The vision is that leakage standards will be set and in future machines will be monitored to ensure the leakage has not become excessive.

Chiroma from the University of East London developed an approach to use symbiotic simulation (Chiroma et al. 2016) that will help to model existing facilities. Currently, failure data can be downloaded into a model through a version of our data analytics tool. This is seen as a first step to revolutionizing simulation in Ford particular in the plants, where the vision is to have ready-to-use models that can help production analyze their issues and identify potential solutions.

The potential of this seems endless, but will require that the data used are valid and requires an extended experimentation process and procedure. It will require all the key ingredients for successful simulation: correct tools for the job, access to software, and a quick response. In the production environment, where we envision deploying our toolset one day, the response will have to be minutes, because they cannot afford to wait for results to be provided.

## 4 SUPPORT

Since 2001, PTME have made significant advances in the way simulation is used to the point where it is expected. To see the results from the simulation models, engineers expect questions answered and a comment rarely heard prior to that time – but commonly heard now – is, "what does the simulation say?" In 2017, expansion continues with the Ford of Europe Director of Power Train Operations requesting efficiency improvement funding be supported by simulation data. This initiative led to the training of 23 people from eight plants who with continued support from PTME are building models to support plant actions that are increasing throughput and making savings.

PTME continue to develop the toolset to meet the goals of delivering the required model and results in the shortest time to improve on a 15:1 return on investment in our team and software. We will not achieve this alone. It will require further collaborations with research institutes, plant modelers, production teams, manufacturing teams, and continued support from management.

Despite all the tools, automated processes, and artificial intelligence, experience has shown that modeling is not a job that is readily done alone. Even for an experienced modeler, it is sometimes difficult to see the wood amongst the trees. People who can understand the manufacturing process, who can conceptualize models and comprehend the art and science of modeling are the key to supporting new and experienced modelers.

Support also comes from engineers who understand the operating of a line and the generation of data. It is essential that modelers build relationships with other team members as they are the lynchpin to bringing the data and logic together. One way we have achieved this is through continual reviews with our customers ensuring that they agree how the data are used in the model. Management are also experts, not in modeling, but in business. Thus, they may be aware of changes in planning that can avoid wasted modeling or experimentation time. It should, therefore, be ensured that they are part of the kick-off meeting and any review process.

Experience has shown that the same question can be asked at different levels, and a different answer will result ranging from "no we are not doing that" to "yes we are going to." Using all this expert knowledge in your model, your understanding, and through your team meetings bring the business together to make the correct decisions.

Ladbrook and Januszczak (2001) indicated how WebEx is providing collaborative support as did Taylor et al. (2005). Today, collaborative human-to-human support is a key to success. It allows expert advice for being shared across different continents and enables the attendance of remotely located PTME engineers to support management reviews. Through WebEx, they are directly involved and far likelier to follow up on a task than if just sending an email. Other benefits of this approach are the global simulation teams aligning themselves as well as being an excellent medium for training and support – How else could you train ten plant managers at once as the impact of their time out of the office could significantly impact the business. Today, this method is an accepted way of doing business.

## 5 WHERE TO NEXT?

PTME believe the generic approach is the right approach to modeling. During the life of FAST, many people have contributed to the development and it has become difficult to maintain due to limited documentation. A fundamental change made in 2013 was to use the Lanner software Simba which provides an Application Program Interface (API) to other software (Waller 2012). After considering how to reduce build time it was decided to custom-program the next generation of FAST. This has begun and there are efficiency benefits to processing data and build methods already.

Currently, we are continuing to develop our symbiotic simulation capability. As we go forward, this will be the cornerstone of everything that we do. Good data will be integral to future success and, therefore, it is believed analytics will grow along with machine learning and AI to provide valid data sets. These datasets will form the foundation for the existing models and for future models, as they will be the source for our comparator data. Given the valid data, this will eliminate the effort currently put into data analysis with the exception of determining what improvements could be made for new equipment.

An essential outcome of symbiotic simulation will be the need to generate multiple experiments based on the conditions within the model with rapid execution to provide answers for production. This process needs to identify the bottleneck and determine what is causing interference to the extent that it is possible to extract which failures cause the issues. This may mean that not just failure times are entered into the model but they are linked with the associated fault codes. For future planning, it is envisioned that simulation will determine the configuration of the optimum layout and cycle times to meet the demand. It is believed for future models that it is essential that many people interact with a model to understand, which effect their actions have on the facility and the business. This all leads to more experiments and further analyses to understand the impact different factors have on throughput. Therefore, what is needed for successful simulation?

- Models that run themselves to align with current production.
- Planning models built from data repositories.
- Diagnosis of results and generation of experiments.
- Computational power to undertake the experiments and give rapid results.

- The capability for all to interact with models and ask their own questions.
- Optimization techniques that drive facility and plant layout development.
- The ability to model rapidly changing data sets, as they occur in launch and support launch.

## REFERENCES

Carson, J. S. 1986. "Convincing Users of Model's Validity Is Challenging Aspect of Modeller's Job". *Industrial Engineering* 18:74-85.

Chiroma, E., J. Ladbrook, and H. Abdalla. 2016. "Investigation into ERP-based Symbiotic Simulation Project Implementation on Ford Engine Production Line: Challenges, Opportunities and Prospects". In *Proccedings of the 15th International Conference on Modeling and Applied Simulation,* edited by A. G. Bruzzone et al., 26th–28th September, Cyprus.

Emmerson, J. A. and J. Ladbrook. 2004. "Modelling the Internal Delivery of Materials to Engine Machining and Assembly Lines in Ford Motor Company Using Component Based Simulation". *UK Operational Research Society Simulation Workshop (SW2004), 23rd–24th* March*,* Birmingham.

Higgins, M., G. Khalwadekar, and J. Ladbrook. 2018. "Deterministic Simulation and Graphical Representation of Powered Material Handling Vehicle Movements to Enhance Pedestrian Safety". In *Proceedings of the Operational Research Society Simulation Workshop 2018 (SW18),* edited by A. Anagnostou et al., 19th-21st March 2018, Stratford, UK, 134–145.

Ladbrook, J. 1998. *Modelling Breakdowns – An Inquest*. M Phil. School of Manufacturing and Mechanical Engineering, University of Birmingham, UK.

Ladbrook, J. and A. Januszczak. 2001. "Fords PowerTrain Operations – Changing the Simulation Environment". In *Proceedings of the 2001 Winter Simulation Conference*, edited by B. A. Peters et al., 863-869. Piscataway, New Jersey: IEEE.

Lu, L. 2005. *Modelling Breakdowns*. MSc thesis. School of Mathematics, University of Southampton, UK.

Martínez, M. A. 2012. *Develop Guidelines for the Sizing Of Internal Market Place*. MSc thesis, School of Mathematics, University of Southampton, UK.

Mebrahtu, H. and J. Ladbrook. 2008. "Simulation and Performance Improvement Process at Ford Powertrain Operations". In ICS 2008 – EUROSIS, 9th–11th June 2008, Universite de Lyon, Lyon, France, 126–132

Mulvany, R., A. Arokiam, H. Belaidi, J. Ladbrook, and M Higgins,2017. "Optimisation of Compressed Air Systems Energy Usage through Discrete Event Simulation: Compressor Performance". In *Proceedings of the 31st European Simulation Multiconference (ESM 2017)*, 25th–27th October, Lisbon Portugal: Instituto Superior Tecnico, 328–335.

Mustafee, N., A. Alstad, B. Larsen, S. J. E. Taylor, and J. Ladbrook. 2006. "Grid Enabling FIRST: Speeding-up Simulation Applications Using WinGrid". In *Proceedings of the Tenth IEEE International Symposium on Distributed Simulation and Real-Time Applications (DS-RT'06)*, edited by E. Alba et al., 157-164. Piscataway, New Jersey: IEEE.

Osman, M. 2012. *A Simulation and Analysis tool of Material Flow Ford Power Train Manufacturing.* MSc thesis, School of Business, University of Southampton, UK.

Pan, R. 2007. *Simulation of Material Movement*. MSc thesis, Engineering School of Computing and Technology, University of East London, UK.

Poole, R. 1999. *Investigation into Machine Detail Simplification Techniques for Witness Simulation Models*. MSc. thesis, School of Manufacturing and Mechanical Engineering, University of Birmingham, UK.

Robinson, S. 1995. "An Heuristic Technique for Selecting the Run-length of Non-terminating Steady-state Simulations". *Simulation* 65(3):170-179.

Robinson, S. 2002. "A Statistical Process Control Approach for Estimating the Warm-up Period". In *Proceedings of the 2002 Winter Simulation Conference*, edited by E. Yücesan et al., 439-446. Piscataway, New Jersey: IEEE.

Saghri, S. 2010. *Business Process Improvement using Structural System Analysis and Design Method*. MSc thesis, School of Mathematics, University of Southampton, UK.

Taylor, S. J. E., S. Robinson, and J. Ladbrook. 2005. "An Investigation into the Use of Net-Conferencing Groupware in Simulation Modelling". *Journal of Computing and Information Technology* 13(2):95–106.

Waller, A. 2012. "Witness Simulation Software". *Winter Simulation Conference,* edited by C. Laroque et al., article 436, 9th–12th December, Berlin.

Wilson, J., A. Arokiam, H. Belaidi, and J. Ladbrook. 2016. "A Simple Energy Usage Toolkit from Manufacturing Simulation Data". *Journal of Cleaner Production* 122:266-276.

Winnell, A. and J. Ladbrook. 2003. "Towards Composable Simulation: Supporting the Design of an Engine Assembly Line". In *Proceedings of the 17th European Simulation Multiconference (ESM)*, , edited by D. Al-Dabass, 9th–11th June, Nottingham Trent University, 431-436.

Winnell, A. and J. Ladbrook. 2004. "Collaborative Component-based Simulation: Supporting the Design of Engine Assembly Lines". In *Proceedings of the 2014 Operations Research Society Simulation Workshop (SW2004)*, 23rd–24th March, Birmingham.

Zou, Q. 2007. *Support the Planning of a New Machining Line Facility – Cylinder Block Line Simulation*. MSc thesis, School of Mathematics University of Southampton, UK.

## AUTHOR BIOGRAPHIES

**MICHAEL HIGGINS** graduated with a Bachelor of Science in Mathematics and Physics in 2011 and in 2014 gained an MPhil (Eng) through his research into the application of Discrete Event Simulation within the automotive industry. He has worked with Ford Motor Company since 2012, where his current role is within PowerTrain Manufacturing Engineering (PTME) as Lead Simulation Development Engineer. He has gained a holistic view of powertrain manufacturing and has utilized simulation as a tool across several functions within PTME including plant and production engineering roles. He is currently researching and developing methods to increase usability and widen the application of the Ford Simulation Toolset. His email address is mhiggi37@ford.com.

**JOHN LADBROOK** has worked for Ford Motor Company since 1968, where his current position is Simulation Technical Specialist. In 1998, after 4 years research into Modeling Breakdowns he gained a M. Phil. (Eng.) with the University of Birmingham. In his time at Ford, he has served his apprenticeship, worked in Thames Foundry Quality Control before training to be an Industrial Engineer. Since 1982, he has used and promoted the use of Discrete Event Simulation and in 2013 the team was awarded the Witness Project of the year. In this role, he has been responsible for sponsoring many projects with various universities making developments in Modelling Energy and Symbiotic modeling as well as extending university links. In November 2016, he was made an Honorary Professor at the University of East London. His email address is jladbroo@ford.com.