

Simulation Study for Investment Decision of the EcoBoost Camshaft Machining Line

J. Ladbrook^{1,2}, B. Tjahjono^{2*}, E. Oakes², R. R. de Sanabria Sales², A.G. de Rueda², U. Lizarazu², C. Temple²

¹Manufacturing Engineering, Ford Motor Company, Dunton Research Centre
Basildon, Essex SS15 6EE, UK

²Manufacturing Department, School of Applied Sciences, Cranfield University,
Cranfield, Bedford MK43 0AL, UK

Abstract

Design/redesign of manufacturing systems is a complex, risky and expensive task. Ford Motor Company's Valencia Engine Plant faces this challenge as they plan to upgrade their machining and assembly lines to introduce the new EcoBoost engines. The research project described in this paper aims to support the transition process particularly at the camshaft machining line by using simulation modelling techniques. A series of experiments were carried out using the simulation model developed, and based on the results of these experiments recommendations were proposed to support the decision as to where to invest on the line. The outcomes from the research project indicated that that investment is required in terms of increasing the capacity of two bottleneck operations through retooling and improving the conveyor routing logic in one key area.

Keywords: Simulation Modelling, Closed-loop Network, Automotive Production Systems

*Corresponding author

Address:

Building 50, Manufacturing Department, School of Applied Sciences,
Cranfield University, Cranfield, Bedford MK43 0AL

Phone: +44 1234 750111 ext 5453

Email: b.tjahjono@cranfield.ac.uk

1. Introduction

After a difficult period in the automotive sector in which sales fell by 40% in some markets, car manufacturers are beginning to thrive once more. Significant challenges however remain as recent fluctuations in the oil price and increased awareness of climate change have greatly influenced the purchasing behaviour of the customers. Part of the Ford Motor Company's responses to this changing environment is the introduction of its new EcoBoost family of engines and the transition to EcoBoost requires that a new model of camshaft enters production. The Ecoboost camshafts differ from existing models in some technical details. Specifically, they require additional grinding operations and cannot be processed on machines that have not been retooled to accommodate the design.

This paper studies the camshaft production line at Ford's Valencia Engine Plant (referred to Ford Valencia hereafter) as it prepares to introduce the full Ecoboost production. This is crucial as Ford Valencia intends to upgrade and reequip its current camshaft production line rather than building a new line to manufacture the Ecoboost camshafts. The research project described in this paper aims to assess how the transition to the new engine model will affect production. Ford have a long history of using simulation to support its decision making process [1] and, like other major US automobile companies [2], make extensive use of simulation in the installation of new or modified production designs.

In this paper, a simulation model has been built and extensively used to evaluate the proposed changes at the Ford Valencia's camshaft production line. Simulation allows manufacturing engineers to experiment with different scenarios (brought about by the transition to all EcoBoost production) to be done on the computer before changes actually implemented on the line.

2. Problem Description

Ford Valencia, currently producing a total of five other engine models, has been a designated manufacturing plant for the EcoBoost engine family. When planning the changes to the line, the emphasis is on reusing existing resources by upgrading and improving the current line. The plant management team has committed to invest on the line to ensure a smooth transition to the new production environment. Incorporating the new Ecoboost camshaft, which demands specialised finishing operations to meet high technical specifications, has the potential of complicating the already complicated line. Simulation is therefore an ideal tool to analyse whether it is possible to move to full EcoBoost production while maintaining or increasing the throughput levels.

The camshaft production line at Ford Valencia is a manufacturing system of some complexity. It comprises 17 different operations, totalling 46 individual machine stations. Divided into three main loops (see Figure 1), all machines are connected through a handling/conveyor system on which components are carried by a finite number of platens. A number of smaller loops are also in place and are used to keep parts near their required operations, particularly for sensitive bottleneck operations.

In the first loop the rough camshaft is prepared for further and more complex operations. Once prepared, the camshaft is processed through operations in the second loop machining each element of the camshaft, giving the ultimate precision of surface finish in the third loop.

<Insert Figure 1 here>

Figure 1: A sketch of the camshaft production line at Ford Valencia

A further feature of the system lies in the use of counters to control the number of platens held on the conveyor system throughout the line. Given that each loop is

closed, with a finite amount of platens circulating within, such a restriction allows for controlling the amount of work in progress (WIP) present on the line at any time. This is further complicated by the use of a number of sub-areas, each with their own target platen count, to govern the distribution of platens throughout the line (see Table 1). A platen is only permitted to leave one area when an empty platen intends to enter from the opposite direction. This practice essentially maintains a number of mobile buffers throughout the line and facilitates a fluid flow of pieces. Such a system works in conjunction with stationary buffers placed strategically before bottleneck operations.

<Insert Table 1 here>

In reality, manual intervention exists in the line's operational practices and a degree of flexibility is required in order to maintain throughput levels. Occasions in which operators are required to interact with the line include the following.

The distribution of platens throughout the line is perceived not perfect and problems may ensue if there are too few platens assigned to a given area. Under certain conditions, this can cause the system to become blocked as pieces are not transferred from area to area. Conversely, under different conditions an excess of platens in an area may also cause blockages on the line. Careful planning of platen numbers and control logic is required to avoid such a scenario. If this is inadequate then manual intervention is employed to correct the line.

Technical constraints in some operations create a localised imbalance on the line. There are two varieties of camshaft, intake and exhaust, and it is desirable to achieve a production 1:1 ratio, because an engine will always need a pair of intake and exhaust camshafts. Some operations, due to technical reasons, disrupt this balance by having considerably greater capacity to process exhausts than intakes. This can often create imbalances particularly in loop one that impact on production. Manually adding intakes

or exhausts to the line, outside of the set demand schedule, is one common solution to this issue.

A specialised grinding process, noted as OP43, operates only in the processing of Ecoboost camshafts but it has given rise to a new issue in which it can starve other operations of empty platens or vice versa. This can severely affect the throughput or even block the whole line. The current solution to this issue, where Ecoboost camshafts are produced in small test batches, is to manually release platens for the operation only when required.

The project attempts to address the above problems within the wider framework of examining the transition of Ford Valencia to an all-Ecoboost environment. These issues feature in a number of experimentation scenarios that examine the impact of various constraints on the line and how these will affect the Ecoboost production. It is this type of investment decision, which according to Chai et al [3], is often driven by a number of internal factors such as the facility, flexibility, quality, delivery and know-how. Ultimately, the question is posed as to whether investment in the line is required to make this transition and, if so, where it should be directed.

3. Related Work

Ford Valencia's camshaft production line is a complex manufacturing environment that is, understandably, not much covered in detail in the body of literature. Nonetheless, there remains a great deal of literature concerning key aspects of the camshaft production line. These include, the conveyor system, constant WIP (CONWIP), distribution of platens, output of the line and the use of simulation in manufacturing.

With regards to the amount of WIP on the line and the balance of different components, the Rate Conservation Law (RCL) [4] states that any system under stationary input and steady state conditions should have an output rate that is equal to its input rate. The

RCL is relatively generic and therefore also works for subsystems and subgroups of parts assuming that they meet these conditions. In particular, this can be used to extend the Little's law [5] to many circumstances including those occurring in the manufacturing environments. Based on Whitt's [6] and Little and Graves' [7] work, it is clear that Little's law applies not only to any flexible line –given that they hold a limited number of platens– but also to the different products moving through the line. This allows for an estimation of the amount of WIP in the system at any given time.

As compiled by Shamsur [8], the Theory of Constraints (TOC) has become "an overall theory for running an organisation" [9]. While originated as a management theory, TOC has since been applied to manufacturing environments in the form of a series of principles based on the drum-buffer-rope methodology (DBR) [10]. The underlying principle, in relation to this project, is that time or resources invested in improving non-bottleneck operations is not transferred to throughput levels. Golmohammadi and Ghazanfari [11] note that "most of the literature research has applied TOC concepts and rules for very simple process flow" and set out to apply TOC principles, with the aid of simulation, to production planning in an automobile environment. In addition to that, Umble et al [12] also described practical applications of TOC to a real world production situation.

Part of the complexity in the camshaft production line studied at Ford Valencia is related to the fact that the line is a closed loop network using complex Material Handling Systems (MHSs) that connect the workstations. MHSs are usually made of platens moving along the conveyors and the routing logic used to control these conveyors can significantly impact the output rates. There is a vast body of literature that examines the rule by which such systems are governed. For example, Sanchez-Salmeron et al [13] examined some of the issues surrounding the use of carrier and conveyor logic while Bozer and Hsieh [14] developed a methodology to estimate

waiting times and WIP in closed-loop conveyors. They further developed this research by including the risk of blockages and recirculation in their analytical model [15]. Gershwin and Werner [16] presented an analytical method to evaluate production rate and distribution of work-in progress in a closed-loop network with finite buffers and unreliable machines. Starvation and blockage of machines in closed-loop networks have been studied in the transitory and steady states by Resano and Luis [17]. However, multiple-loop MHSs do not seem to receive the same attention as their single-loop counterparts in the literature.

The constant work-in-process (CONWIP) technique [18] has been implemented by Ip et al [19] in both single-loop and multiple-loop systems, although their research did not specifically mention MHS. Raman et al [20] proposed an analytical approach to determine the quantity of material handling equipment (MHE) required for effective handling of products among facilities. However, this does not dwell on how the loops interact with each other in multiple-loop MHS. Jain [21] provides a useful analytical method for estimating adequate buffer sizes. Once again, however, this does not account for the system as a whole as the interactions between conveyor loops are omitted.

One of the advantages of computer simulation application is the possibility to analyse various what-if scenarios before committing to the physical modification to the system [22] and consequently simulation techniques to aid investment decision making have been topical research in manufacturing for some time. Omar et al [23], for instance, applied simulation to evaluate two design options of a high-speed machining transfer line in order to maximise the productivity of the line. Simulation has also been used by Wang et al [24] to compare the performance of an assembly line operated with fixed workers on static workstations and with moving workers along the assembly line. In a slightly different context, Chatha and Weston [25] enhanced the decision support

framework by combining simulation with systems thinking and demonstrated the concept to support management decision in designing manufacturing enterprises.

Whilst various analytical methods exist in the body of knowledge, the problem related to productivity optimisation of a closed-loop network involving many unreliable machines and finite buffers remains practically challenging. It is therefore the aim of the work described in this paper to make use of simulation modelling to study and assess the performance of the camshaft production line at Ford Valencia.

4. Methodology

The basic simulation model used in this study was built by Papare [26] using a combination of Witness[®] (a discrete-event simulation package) and the Ford's proprietary secondary user interface. The model was first built according to the CAD layout of the factory. This is a very crucial requirement that such a model should resemble reality, i.e. the actual line layout. Ford's proprietary user interface has been programmed in such a way that the model can be generated automatically, allowing non simulation experts (i.e. manufacturing engineers) to quickly build the model with minimal knowledge of Witness[®]. Figure 2 shows a screenshot¹ of the simulation model showing Area 100 in Figure 1.

<Insert Figure 2 here>

Figure 2: Screenshot of the simulation model

Significant modifications and updates have been made to this model to ensure that it represented the current state of the camshaft line at Ford Valencia. These changes primarily involved machine allocation logic and the implementation of a new platen management system that maintained a number of mobile buffers throughout the line.

¹ Due to the size the model, only part of the whole model can be presented here

Additional work focused on the development of relevant machine breakdown distributions. Breakdown data was obtained from Ford's global machine monitoring system (known as POSmon) for the period of the study. This raw data which was then further processed and a breakdown distribution, which specified the Mean Time Between Failures (MTBF) and the Mean Time To Repair (MTTR), was developed for each machine on the line.

The purpose of this, and other modifications, is obviously to assemble an accurate digital representation of the actual camshaft line. Only such a validated model could be used as the basis for experimentation. Traditionally, statistical validation of this basic model would come through a comparison with the actual line. To this end, output figures for the line were obtained for approximately 3 months (the same months were used when collecting breakdown data). Based on this data, throughput was calculated for each shift and a distribution of the actual line's output was obtained. The application of Mann-Whitney and Levene tests [27, 28] allowed for a statistical comparison between the actual line's throughput and the model's throughput.

Development of a validated model allows for experimentation to determine the areas for investment on the camshaft production line. A number of potential scenarios were proposed in agreement with Ford Valencia's management team, and subjected to a simple hypothesis testing. In one particular case, i.e. determining the optimum platen numbers, sensitivity testing was employed to evaluate the impact that changing a single variable (distribution of platens) had on a number of different areas.

5. Experimentation

A series of experiments were conducted using the updated simulation model. The first experiment outlines the process used to validate the model. This is then followed by an experiment detailing the addition of minor improvements to the operation of the line.

Further experiments study the impact of changing platen distributions and batch sizes to the line's performance, especially the utilisation of machines in some key operations. The subsequent experiments focus on investigation of the Ecoboost transition by mixing the production of existing camshafts with Ecoboost camshaft, or by producing entirely Ecoboost camshafts.

All the experiments carried out were run for at least 30 days with a warm-up period of two days. These were selected on the basis of previous simulation model and the results can be said to represent normal (i.e. steady-state) conditions. Data was collected each shift with two shifts per day of 7.5 hrs each. The key performance measure in each experiment is the throughput. This is expressed as jobs per hour (JPH), i.e. the number of completed camshaft pairs leaving the line every hour.

5.1 Experiment 0 – Model Validation

Objective

The purpose of this experiment was to validate the simulation model by demonstrating that it produces an output distribution statistically similar to that of the Valencia camshaft line. This would provide confidence that the developed model is accurate and can be used as the basis for further experiments.

Method

This experiment concerns with a comparison of simulation model with the actual line using a 3 month historical data, a sufficient period for which relevant output and breakdown data is readily available. Breakdown data was converted into distributions and entered into the model, while output figures were used to calculate the JPH of the line for over 70 shifts.

The model itself, logically configured to resemble Ford Valencia's capacity during the period of the project, was run for a simulated time of over 100 shifts in addition to a warm-up period of 4 shifts. The latter was determined using an in-house statistical tool. Batch sizes and inputs into the model were derived from the output figures for the period; most notably these involved three non-Ecoboost engine models. The number of platens available to the system was held at historical levels.

Results

With the data collected, it was possible to compare the throughput of the simulated model with that of the actual line. In this case, both the average rate of throughput and its spread were calculated and compared. The latter applied the principles of Mann-Whitney and Levene tests to statistically contrast the systems. From Figure 3, it can be seen that the output distributions from both systems are broadly similar. It was also apparent that the output of the simulation model was not statistically distinct from that of the actual line. This lends validity to the model and permitted its use in further experimentation.

<Insert Figure 3 here>

Figure 3: Comparison between the actual and simulated output distributions

5.2 Experiment 1 – Improved Model

Objective

The validated model, as described above, represents the Valencia line as it was in the period when the breakdown data was collected. Since then, a number of improvements have been made to the line. These recent changes are not always used and there is no satisfactory data available as to their impact, but it is necessary to model their introduction and potential impact on throughput. This experiment will therefore

establish the impact of these changes and provide a base model for use in later experimentation.

Method

This experiment is concerned with three distinct changes to the production line:

- 1) The introduction of a bypass mechanism that allows empty platens to proceed directly from the elevated area to OP30. This shortens the time empty platens spend travelling through the line.
- 2) The use of conveyor control logic near OP43 that prevents unneeded empty platens from moving towards OP50. This, again, is intended to increase the rate of empty platens serving OP30.
- 3) An additional loop that keeps parts in the area of OP77 if they have not been processed by that operation but need to be. Given that OP77 is used exclusively by Ecoboost camshafts, which are not yet running in this model, the logic of this improvement was verified through testing but its impact was not evaluated.

Each individual improvement was made to the validated basic model and their impact gauged in terms of throughput and the time empty platens take to return to OP30 from OP100. The input profile (in terms of batches and engine models) remained the same as in the previous experiment. Similarly, platen numbers remained unchanged at the default level.

Results

As shown in Table 2, these improvements to the model increase the JPH. Individually the addition of both the bypass and the platen logic (as noted, the loop at OP77 is only

used in an Ecoboost environment) are beneficial but when used together, they lead to a throughput increase of 7.14% from the basic model validated in Experiment 0 (see Figure 3). This is reflected in the finding that the addition of the elevator bypass reduces the time needed for an empty platen to return to OP30 (from OP100) by 68%. These improvements are integrated into the subsequent experiments detailed below.

<Insert Table 2 here>

5.3 Experiment 2 – Platen Numbers and Distribution

Objective

As noted before, the distribution of platens on the line forms an additional constraint on the system. Based on the current production environment, incorporating the improvements introduced in Experiment 1 above, this experiment examines the degree to which the output of the system is influenced by platen constraints.

Method

For the purposes of maintaining a desired platen distribution, the camshaft line can be divided into six areas. Each of these has a set number of platens allocated to it and, within a degree of flexibility, an area will not allow a platen to exit or enter if it has exceeded its minimum or maximum platen limits respectively.

Changing these numbers can impact on the line's output but there is obviously an extremely wide variety of possible platen configurations. A sensitivity analysis was conducted to discover in which areas an increase in platen numbers was most beneficial. Based on these observations, and some further testing, the system was run with the platen configuration listed in Table 3.

<Insert Table 3 here>

Results

The change in throughput noted from this platen configuration was an increase of 2.3% on the result achieved in Experiment 1. It can be concluded from this both that platen numbers do have an impact on throughput levels and that the default platen configuration used in Ford Valencia is a constraining factor. An increase in platen numbers in some areas does, based on the simulation analysis, lead to an increase in the output rate. There is a balance to be struck, however, as the sensitivity analysis in Table 4 indicates, and an increase of platens in one area may be complemented by an increase in another. Similarly, the impact of platen numbers is not identical across the line but varies from area to area. An optimum distribution will therefore increase/decrease platen numbers in more than one area. The results shown in Table 4 will build on the validated model from Experiment 0.

<Insert Table 4 here>

5.4 Experiment 3 – Batch Sizes

Objective

This experiment looks to quantify the impact of changing batch sizes on throughput. This is of particular importance given the allocation of machines at OP20 and concerns that this could be a limiting factor on production. By using smaller batch sizes, it is hoped to increase the equipment utilisation at this operation and thus increase throughput.

Method

The key variable in this experiment is the size of the batches employed. Three separate runs were staged with the batch size being set to 250, 150, and 50 respectively. Platen numbers were as default and the input profile remained as current (i.e., non-Ecoboost engine models). The results were then compared to those of Experiment 1.

Results

Table 5 below compares the change in JPH to the results obtained in Experiment 1. In the latter, the batch sizes varied according to the historical data instead of being rigidly uniform. As can be seen, changing the batch sizes cannot be said to produce any major changes in the throughput of the line.

<Insert Table 5 here>

Nor is there any significant difference between the batch sizes. The smaller option (batch size of 50) does produce a marginally higher JPH than that of 250 but not noticeably so. While it may be worthwhile to employ a smaller batch size in future, this should not lead, on the basis of this simulation, to any major productivity gains. To a large extent, the flexibility of the line to manufacture different camshaft derivatives is supported by the automatic machine changeover allowing smaller batch sizes to be introduced without compromising the performance of the line. In fact, during the transition between certain derivatives, the line is also capable of processing both derivatives in parallel, especially on critical operations, which means increasing the capacity of the machines.

5.5 Experiment 4a – Product Mix

Objective

Currently, batches on the camshaft line are comprised entirely of one engine model, e.g. an intake and an exhaust (at a 1:1 ratio) for a 2.0L VVT engine. One possible strategy for introducing the Ecoboost engines into the line is to decouple these inputs into the line. This may increase capacity through more efficient utilisation of critical machines. The experiment to test this is outlined below.

Method

This experiment concern with running the line with four different derivatives arranged in the combinations 3-2 and 1-4 (as opposed to the traditional 3-4 and 1-2 arrangement). It is notable that derivatives 1 and 2, an intake and exhaust respectively, are Ecoboost components. The model was configured to produce this pattern and some minor changes, as suggested by Ford Valencia, were made to the routing logic at OP20 and OP50. Batch sizes were set to 250 and platen numbers remained unchanged.

Results

The performance witnessed during this experiment was not too impressive. Average hourly throughput actually dropped significantly by 29.48% when compared to that achieved in Experiment 1. On examination, it was found that the major constraint was the distribution of platens between OP30 and OP43. The latter operation is used only by Ecoboost derivatives but if starved by platens then it may bring production to a halt. Conversely, oversupplying OP43 risks reducing the output of OP30 and thus contributes to a lower JPH. This is a problem that is addressed in the next experiment.

5.6 Experiment 4b – Improved Product Mix

Objective

It was felt that the above experiment was constrained by an additional and unforeseen factor, i.e. the problems of balancing platen numbers between OP30 and OP40. Addressing the issues raised above will allow for a more accurate appraisal as to whether changing the product mix of the line will produce a higher JPH.

Method

The base setup of the model remains the same as that of Experiment 4a with two changes. Additional routing logic was applied to OP30 in an attempt to balance the needs of this operation with that of OP43. In addition, the number of platens in use was

increased across the areas, from 100 to 600, to that of Experiment 2. Each of these improvements was applied separately and then finally in combination.

Results

Table 6 compares the throughput rate to previous experiments. Most obviously the combined changes to platen numbers and routing logic lead a considerable increase on that achieved by Experiment 4a. That the JPH is comparable to that of Experiment 1 suggests that mixing the inputs into the line is a valid method of transitioning towards an all-Ecoboost environment with no loss of output.

<Insert Table 6 here>

5.7 Experiment 5 – Ecoboost Current Production Line

Objective

This experiment examines the possibility of switching over to Ecoboost production without making any investment in changing the line's logic or capacity.

Method

The model required few changes for this experiment. The basic setup remained essentially that of Experiment 1 with platen numbers unchanged from the default. The only difference in this scenario is the inputs; only the Ecoboost camshafts were admitted to the model. This allowed for a study of major constraints and bottlenecks that may impact on the new production schedule. A second experiment was then run that incorporated the improvements made to the platen routing logic in Experiment 5.

Results

The major finding of this experiment is that populating the line with Ecoboost derivatives led to a 38.89% decrease in JPH compared to Experiment 1 (see Table 7).

This is obviously a very significant drop in productivity. Crucially, the addition of logic to balance the platen demands of OP30 and OP43 does not lead to any notable increase in throughput. It can be concluded then that the cause of the low performance of the previous experiment was due to other factors. This indicates that the real problem lies in the allocation of machines and their ability to process components. What limits the output in this case is not the platen numbers but instead the machine capacity.

<Insert Table 7 here>

5.8 Experiment 6 – Ecoboost Upgraded Production Line

Objective

Given the machine constraints identified above in Experiment 5, alterations to the logic of bottleneck operations are necessary if Ecoboost camshafts are to be produced at current throughput levels. What follows is an evaluation of one future scenario identified by Ford Valencia in which the capacity of two bottleneck operations (OP20 and OP50) has been increased.

Method

Ford plans for the camshaft production line to be dedicated to Ecoboost products. This includes significant changes to the machine allocation logic at OP20 and OP50 – two key areas of the line. The model used for this experiment reflects these changes with a new machine configuration used for these two operations. There were three major scenarios examined in this experiment:

1. Changing the machine allocation logic in OP20 and OP50 but leaving the model otherwise unchanged.
2. Changing the machine allocation logic in OP20 and OP50 and improving the routing platen logic.

3. Improving the routing platen logic but only changing the machine allocation logic in OP20. This would allow for an analysis as to whether OP20 or OP50 was the critical bottleneck.

Results

Compared to previous throughput levels achieved (see Table 8), this line configuration produces some interesting results. Without improving the platen routing logic, the JPH is inferior to Experiment 1 but is still markedly superior to that of the previous experiment. This suggests that investment in improving the logic of OP20 and OP50 is of some benefits gained in full Ecoboost production. The addition of routing logic leads to a further improved performance over the previous scenario by 9.51%. Output is still slightly lower than that of the current line but not significantly so.

Finally, it can be seen that investing solely in retooling OP20 is of little use as throughput remains around levels noted in Experiment 5. This strongly indicates that OP50 is the bottleneck operation; a deduction borne out by observations made during the experiment where this operation was working at effectively 100% capacity.

<Insert Table 8 here>

6. Discussion

Using the simulation model of the camshaft production line at Ford Valencia allowed for an investigation into where future investment could have the greatest impact in this production system. Section 5 details the various experiments that were carried out into both potential improvements to the current production line and possible approaches towards introducing full Ecoboost production. The results of these experiments, under those headings, are further elaborated on below.

6.1 Improvements to Current Line

The first major group of experiments revolve around potential improvements to the existing production line. They can be applied to a future all-Ecoboost environment but are primarily concerned with the system as it is. In particular, some additions to the line –such as the elevator bypass and additional platen routing logic– are already present, but not fully utilised. Both improvements are intended to channel empty platens back to where they are needed and thus reduce the amount of time a platen is not contributing to the flow of material through the system. The time that empty platens spend circulating through the line was decreased by over 30%. The introduction of these features leads to a significant 7.14% increase in throughput. If a comparison with a future Ecoboost scenario is to be meaningful then it is this system that results must be compared against.

Other system variables examined include the number of platens on the line and their distribution across various sub-areas. Altering this configuration produced a throughput increase of over 2% but there remains scope for further refinement in this area. What is worth noting is that this provides an additional constraint on the throughput of the system. Changing the distribution of platen numbers alters the flow of parts on the line by permitting additional parts to circulate in critical areas. An increase in platens in one particular area (such as area 200) can be of considerably more benefit than increasing the number in another. Conversely, too many platens in one area can cause blockages in the line. An optimum distribution of platens may require increasing numbers across several areas.

Changing batch sizes is a slightly different way of tackling a similar problem. The allocation of machines in some areas can be restrictive when dealing with a combination of two or more engine models. The cause of this is technical constraints that limit the number of machines available to process intakes for different engines.

Smaller batches would therefore distribute this load over more machines. Indeed, it was found that there was a productivity gain of 0.94% from decreasing the batch size. Unlike the platen numbers, this would not be an issue in an all-Ecoboost environment but can be of use when designing the transition to this. Machine allocation at critical operations must be carefully managed when the Ecoboost engine is introduced to the line in significant numbers.

6.2 Ecoboost Transition

On establishing a benchmark figure and studying the impact of various factors on the line, it is possible to examine the transition of the Valencia camshaft line to full Ecoboost production. This was done so in a number of experiments which propose three distinct scenarios –a transition period in which the inputs into the line are purposefully mixed; the running of the Ecoboost engine on an unchanged current line; and the introduction of the Ecoboost engine with revised machine allocation at bottleneck operations. These experiments and their results are analysed below.

6.2.1 Changing Product Mix

A key constraint on introducing Ecoboost derivatives into full scale production is the capacity of the operations currently employed on the line. Only a selection of machines is capable, without technical retooling, of processing the new camshaft models; this in turn may reduce the capacity of Ecoboost production. This is studied in more detail below but one proposed solution to this problem during the transition phase, when production of other engine models must also be maintained, is in changing the product mix on the line. Currently camshafts are produced as per engine type but this new strategy would deliberately manufacture an intake from one engine alongside and exhaust of another. The expectation is that this would increase line capacity by increasing the number of machines in use at any moment.

As can be seen from the experiments, the initial results did not bear this expectation out. Most notably, line throughput dropped by 29.48%. Closer examination, however, suggested that the major cause of this decline was not directly related to the mix of products but rather related to the introduction of the Ecoboost parts into the line. It became apparent that there was a potentially serious problem with the allocation of platens between two operations. If the correct balance is not struck between these areas, then one could potentially starve the latter with a resultant drop in throughput. This is a problem that has been encountered, on a smaller scale, in the actual line during Ecoboost test runs. Potential solutions to this constraint were identified in changing the routing logic that governed the flow of platens between these machines and increasing the number of available platens in the area. When the experiment was repeated with these alterations in place a significantly higher throughput was observed.

Compared to the output achieved from the initial experiment, the addition of these improvements produced an output rate that was almost identical (difference of 0.15%) to that obtained from the current production line. This indicates that changing the product mix going into the line is a viable strategy for introducing Ecoboost components during the transition phase. There is key disclaimer, however, in that this must be accompanied by the investment needed to implement the improvements identified in the platen routing and numbers. The latter will be a constant issue when looking to produce Ecoboost camshafts and is also applicable to the other experiments that involve this.

6.2.2 Ecoboost: No Investment

The ideal scenario for Ford Valencia is the transition to an all-Ecoboost environment without requiring significant investment or alterations to the existing production line. Experiment 6 tested whether this was feasible by loading only Ecoboost derivatives and without making any changes to the logic or machine allocation on the line. The

results were not impressive with a 38.89% drop in throughput when compared to current production. Further experimentation and investigation proved that this fall was not due to a lack of potential improvements in platen use (whether numbers or routing logic) but stemmed from capacity constraints at bottleneck operations. Changes to platen logic or numbers had a negligible impact on output rate. Any attempt to simultaneously run two Ecoboost derivatives (intake and exhaust) on an unchanged line will encounter this limit on throughput. Increasing the output rate requires either mixing the product mix on the line (thus avoiding a scenario in which both Ecoboost intakes and exhausts are being processed at the same time) or retooling a number of machines in these key operations to increase the capacity to produce Ecoboost components.

6.2.3 Ecoboost: Investment in Key Operations

On establishing that further investment was required to maintain throughput while moving to full Ecoboost production, it is necessary to examine the impact of investing in key operations. One possible scenario is that in which identified bottleneck operations have been substantially retooled to increase their throughput capacity. These changes allow for the dedication of additional machines to the production of the Ecoboost engine. As such, this scenario represents the final stage of the transition process.

As it can be seen from the results, investment in these operations does have an obvious impact on throughput. Output rate rose by upwards of 20% on the result achieved without retooling as capacity in these key areas is increased. Investment in these bottleneck operations can therefore be seen as a prerequisite for transitioning to full Ecoboost production while maintaining output rates. When further improvements are made to the platen distribution and routing logic, the throughput of this all-Ecoboost line increases to within 1% of the level witnessed with the improved current line. To put this in perspective, it is still slightly higher than the production rate of the current line

(which does not fully utilise the improvements introduced in the model) and it can be expected that further experimentation with platen numbers can yield further improvement. This strongly suggests that with the right investment in the right areas it is possible to move to an all-Ecoboost environment while maintaining throughput levels.

A further question is just where the impact of investment is mostly keenly felt. Increasing the capacity of bottleneck operations is, as noted above, is essential but retooling machines on this scale is a costly enterprise. A further experiment therefore examines the throughput levels that can be obtained from retooling one operation or the other and notes which operation would provide the greater return on investment. This identifies the major bottleneck operation and that an increase in capacity here is essential for moving to Ecoboost production.

7. Conclusion

The camshaft line at Ford Valencia is a complex manufacturing environment in which throughput is limited both by machine capacity and constraints introduced by the finite number of platens on the line. Addressing these areas can potentially lead to increases in the output rate when meeting both the current demand profile and when making the transition to full Ecoboost production. Reducing the average batch size can benefit production through increased machine utilisation in key operations. Similarly by increasing the number of platens on the line or redistributing the existing ones may reduce the impact of this constraint by easing the flow of parts throughout the line. Other ways of managing the use of platens are already in place on the line, in particular, the use of an elevator bypass and an additional conveyor loop can dramatically reduce platen travelling time. Further investigation into these features is

recommended. Their impact is beneficial both for the current and the planned Ecoboost production operation environments.

With respect to this transition to the Ecoboost, three distinct scenarios have been examined. All three were found to face the same issue with balancing platens between operations. This is a problem caused by the introduction of Ecoboost camshafts, which require a unique grinding operation, into the line on any scale. The simulation model was modified with additional conveyor logic and platens in order to overcome this constraint. This is an area that must be addressed when the new engine model is introduced in the actual line.

When using the above logic, however, it is possible, based on the simulation model, to make a smooth transition to the new production environment while maintaining throughput. It has been identified that investment in retooling key operations (particularly OP50) is of critical importance when running the line with only Ecoboost parts. Full Ecoboost production therefore requires that there be investment in increasing the capacity of these bottleneck operations. With these improvements in place, the simulation model was found to come close to matching current throughput levels. It is expected that further work in these areas, particularly platen distribution and routing logic, could further increase the output rate.

One observation made throughout the experimentation process was that none of the above changes led to an imbalance in the ratio of engine intakes/exhausts being produced from the line. Local imbalances were observed at certain points but in each experiment the final output was split almost evenly between intake and exhaust. Initial concerns expressed regarding an unbalanced line can be attributed to observations in one local area and/or actions taken to correct any perceived imbalance.

From the above, it is apparent that it is possible to move to full Ecoboost production while maintaining current throughput levels. This is, however, dependent on investment in two key areas: *the routing logic used for handling Ecoboost platens* and *the retooling of two bottleneck operations* to increase their capacity. Further increases in throughput can also be secured through work with changing the distribution of platens throughout the line. Investment in these areas will aid in securing Ford Valencia's smooth transition to the production of the new Ecoboost engines.

This project has produced a validated simulation model of the camshaft production line. Nonetheless, as Ecoboost components require a unique machining process which could cause conflict with other operations, further investigation is required to develop new conveyor control to manage the interaction of these operations.

From the research point of view, the problem related to productivity optimisation of a closed-loop network involving unreliable machines and finite buffers is known as the non-deterministic polynomial-time (NP) hard, which is difficult to solve analytically. Therefore, despite the various methods exist in the literature, this study has demonstrated that simulation remains a favourable technique used in industry. Furthermore, simulation combined with optimisation can be used to obtain near-optimal solutions for practical problems in large and complex model in a relatively short time. The work of Vitanov et al [29] is an example of such technique.

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Ladbrook, J.; Tjahjono, Benny; Oakes, E.; de Sanabria Sales, R. R.; de Rueda, A. G. ...

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