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# A systematic modelling and simulation approach for JIT performance optimisation

Y.G. Sandanayake *, C.F. Oduoza, D.G. Proverbs

*School of Engineering and Built Environment, University of Wolverhampton, Shifnal Road, Priorslee, Telford TF2 9NT, UK*

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ABSTRACT

Robust computer aided simulation and modelling tools help to visualise, analyse and optimise complex production processes with a reasonable amount of time and investment. A review of the literature shows that simulation and modelling have not been extensively applied in just-in-time (JIT) manufacturing environments. Also there remains a lack of a comprehensive mechanism to identify the most significant JIT drivers for the purpose of system process optimisation. The prime objective of this study is to close this gap by applying computer based simulation tools and linear mathematical modelling to identify the impact of selected key JIT parameters on performance in an automotive component-manufacturing environment. Research shows that variables such as inconsistent task distribution, variation on operator performance, misconception of total quality management philosophy and lack of set-up time elimination plans disrupt ideal JIT production. In this study, ProModel simulation and modelling software is used to model and simulate different experimental scenarios in order to understand and quantify the impact of selected input key JIT variables on objective functions (i.e. process time and takt time). The outcome is a robust mathematical model that highlights the significance of JIT drivers in the manually operated mixed-model assembly lines.



## 1. Introduction

The simulation, modelling and analysis of manufacturing systems for performance improvement have become increasingly important during the last few decades. Modern computer aided simulation and modelling tools help to visualise, analyse and optimise complex production processes using computer animations within a reasonable amount of time and investment. In this era of globalisation and fierce competition amongst businesses, there is a need to implement new manufacturing strategies to enhance business performance. Time based competition is one such multidimensional approach and just-in-time (JIT) philosophy is designed to achieve high volume production using minimum inventory at the right time based on planned elimination of all wastes and continuous improvement [1]. Simulation and modelling have not been extensively applied in JIT manufacturing to identify key JIT drivers and quantify their impact on operational performance. Also there is little or no research, which introduces a comprehensive mechanism to identify the most significant JIT techniques.

The main objective of this study is to apply computer based simulation tools and linear mathematical modelling to identify the impact of selected key JIT techniques on performance in an automotive component-manufacturing environment. Typical management tools such as 'cause and effect' and 'relations' diagrams are used to identify key JIT drivers to feed into the simulation model. To apply the paradigm of JIT manufacturing, components must be better coordinated to enable consistent, constant and uniform assembly times at each station in an ideal JIT environment. However, research shows that variables such as inconsistent task distribution, variability of operator performance, misconception of total quality management philosophy and lack of set-up time elimination plans disrupt ideal JIT production in the case manufacturing environment. ProModel simulation software is used to simulate different experimental scenarios in order to quantify the impact of input key JIT variables (i.e. line balancing, multifunction employee, set-up time and total quality control, TQC) on objective functions (i.e. process time, PT and takt time, TT). The model will help to identify the significance of JIT techniques in the manually operated mixed-model assembly line. The outcome will be a robust mathematical model that generates key JIT parameters enabling industry practitioners to understand key parameters affecting system performance.

## 2. JIT implementation in production environment

JIT has somewhat become a catchphrase in recent times and has significant overlaps to concepts such as total quality management (TQM), continuous improvement, time based manufacturing

* Corresponding author. Tel.: +44 1902323834; fax: +44 1902323843.
*E-mail address:* yasangee@yahoo.com (Y.G. Sandanayake).

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and business process re-engineering [2,3]. A major constraint in JIT implementation is that there are no universally accepted JIT techniques, as they seem to vary from one culture to another and also from one industry to another. Voss and Robinson [4] stated that the UK has shown a high level of JIT awareness and understanding, but in their study only 10% of responses had 'major' JIT programs. They found that 57% of a sample of 123 companies were either implementing or intending to implement some aspects of JIT. They reported that core JIT techniques such as 'Kanban', 'Cellular manufacturing', 'Statistical Process Control' and 'Zero-defects' had the lowest rating for actual and planned implementation in the UK. They further observed that where some manufacturing companies implement JIT, they concentrate on a subset of JIT practice suggesting that they only focus on easy to implement techniques rather than those giving the greatest benefits.

Most studies suggest that JIT, TQM and Human Resource Management are inter-related and internally consistent practices. Altogether, the unique JIT practices, TQM related JIT practices and Human and Strategic related JIT techniques form a comprehensive and consistent set of JIT practices directed towards performance excellence. The study of Sriparavastu and Gupta [2] concluded that the joint implementation of JIT and TQM techniques resulted in significantly higher performance levels than the results of implementing either one alone. However, most of the studies on JIT philosophy investigate these practices separately. When a manufacturing plant seeks to capitalise on the implementation of one of these streams, the benefits can be maximised by also implementing techniques of the other two streams. Therefore, there should be a synergistic effect of integrating unique JIT practices with TQM and human and strategic oriented JIT practice. A number of articles have been published during the last few decades focusing on the implementation of JIT techniques and the performance of JIT and non-JIT manufacturing plants [5–7]. Empirical research so far involving the study of JIT consists primarily of case studies of specific organisations, which have implemented JIT, and more recently have described simulations and mathematical modelling [8]. Mathematical modelling of JIT generally focuses on the relationship between changes in a variety of production factors and the corresponding specific production performance measures [1].

### 2.1. Simulation and modelling in a JIT environment

Chu and Shih [9] have suggested three main research methodologies adopted in JIT studies:

- Development of analytical approach to model JIT production.
- Field or empirical based methodologies addressing the behaviour impact.
- Computer simulation to study related design and adaptability problems.

Since quantitative information is very useful in implementing JIT production techniques, computer simulation can be a valuable tool in the design, implementation and changing JIT practices in a production system [10]. Simulation as a powerful mathematical tool can be used to measure performance of an existing plant as well as plants undergoing the introduction of new production philosophies. Simulation can quantify performance improvements expected from applying the lean manufacturing shop-floor principles of continuous flow, JIT inventory management, quality at source and level production scheduling [11]. It has been widely used as a vehicle to identify and study the internal and/or external factors that affect the success of JIT implementation and to investigate the effect of demand and processing time variances [9]. Chu and Shih [9] outlined two main reasons for use of simulation in JIT studies. Firstly, it can be used to evaluate the relative performance of JIT production with other types of production systems and/or identify factors detrimental to success of JIT implementation. Further, simulation helps to break cultural barriers such as resistance to change by establishing confidence about the new system among top management and trade unions.

Sarkar and Fitzsimmons [5] stated that while many researchers have addressed the concept of JIT techniques, very few researchers have performed any analytical or simulation studies on the JIT philosophy. Sarkar and Fitzsimmons [5] used simulation to investigate the efficiency of push and pull systems using a production line with nine stages sequentially arranged with eight inter-stage storage points. Chu and Shih [9] argued that, 'though simulation has been unanimously accepted as a useful tool for studying JIT production, little effort has been put into synthesising the related literature, nor has the research examined the status quo'. They found that most of the models in use are relatively small in scale and that most of the studies involve only one end product. They concluded that assumptions such as perfect production process (no scrap and waste and no machine breakdowns) may reflect well on the characteristics of JIT but contradicts the actual production environment.

Savsar [12] developed a simulation model to investigate the effect of two different kanban policies (fixed withdrawal kanban and variable withdrawal kanban) in a JIT environment. Detty and Yingling [11] used simulation in an electronic product assembly process to demonstrate the concept of JIT and lean principles in terms of improvement (reduction) in inventory, floor space, transportation, manpower and equipment requirements, time based performance measures (model change over time, order lead time and system flow time) and reduced variability in supplier demand. More recently, Fernando and Luis [10] applied simulation as a tool to modify factors affecting the success of implementing JIT techniques. They developed a mathematical model to estimate how three factors (set-up time, kanban number and operator number) affect performance in terms of total completion time of a U-shape line and also to determine whether these factors interact with each other. However, Fernando and Luis [10] failed to disclose the reasons behind the selection of the three aforementioned factors, their simulation models were generic and lacked any empirical data.

## 3. Conceptual model that relates JIT techniques and performance

Various research studies have been carried out to investigate and measure performance in a JIT environment. However, there is no evidence in the literature of any mechanism to quantitatively relate JIT techniques and practices with system performance [13]. The overall objective of this research is to develop a robust mathematical model that quantitatively links JIT techniques to system performance. Fig. 1 illustrates a conceptual model linking universal JIT drivers to performance.

The left side of this conceptual model lists universal JIT techniques, which theoretically drive enterprise performance. Universal JIT techniques are divided into three groups: Unique JIT, TQM related JIT and Human and Strategic oriented JIT practices. These three categories have similar fundamental objectives of waste minimisation and continuous improvement. This study has applied management tools such as 'cause and effect' and 'relations' diagrams to select key JIT factors ($X_i$) affecting performance ($Y$) in JIT enabled manufacturing environments. Fig. 2 depicts the major steps involved in developing a

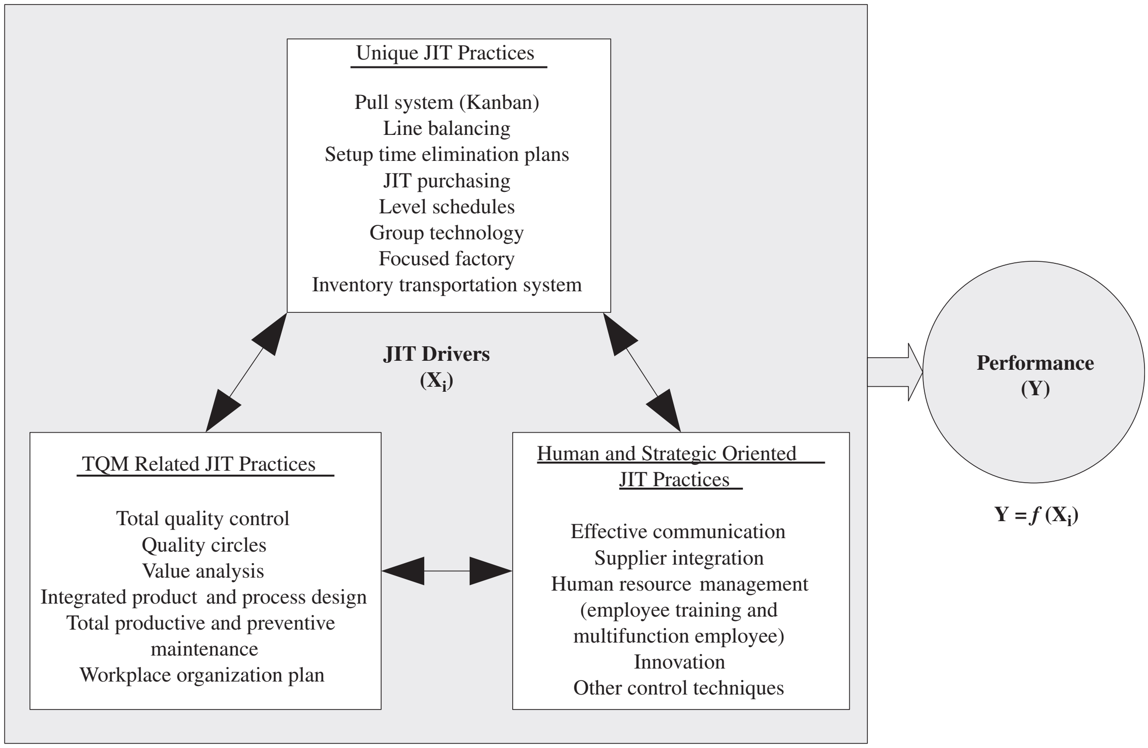


**Fig. 1.** Conceptual model showing relationship between JIT techniques and system performance.

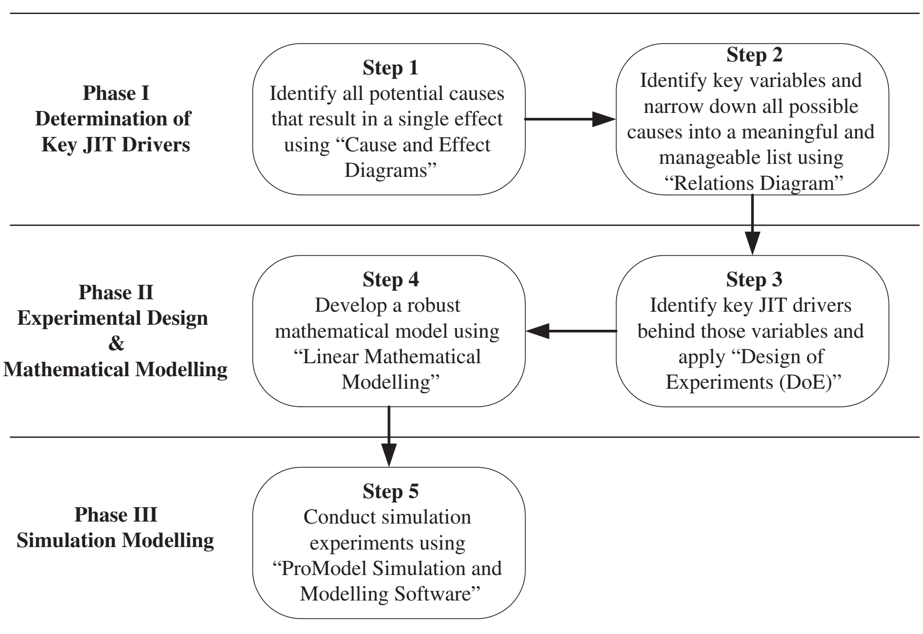


**Fig. 2.** Evolution of robust mathematical model development process.

mathematical model, which captures and quantifies the impact of selected key JIT variables on system performance. The description of these key steps now follows.

### 3.1. Determination of key JIT drivers

Determination of JIT drivers and associated key performance indicators (KPIs) is one of the objectives in this study. Typical management tools such as 'cause and effect analysis' and 'relations' diagrams are used to identify essential JIT parameters and KPIs in a typical manufacturing company. Cause and effect diagram provides a pictorial display of all potential causes that could result in a single possible effect. This approach enables identification of major causes, recommends potential remedial actions and could also indicate potential areas for further exploration and analysis. Relations diagram highlights the root causes contributing to some effect or measurable outcome. These tools facilitate the identification of both primary and secondary causes of a given effect and establish the inter-relationships of a multitude of items that have non-linear relationship to each other. Relations diagram finally narrows down all possible causes into a meaningful and manageable list.

### 3.2. Experimental design and mathematical modelling

The next task is to develop a mathematical model linking key JIT techniques to system performance. Previous simulation studies on JIT manufacturing systems have not examined the interaction effect of more than two parameters at a time [14]. This study has applied the design of experiments (DoE) technique to study the independent and interaction effect of multiple factors on performance. DoE is a statistical technique used to study the effect of several variables simultaneously [15]. The experiments are simple when there is only one factor-influencing outcome. But in an industrial scenario, more parameters come into play. The factorial design method therefore was employed to study the linear effect of multiple factors on performance in a manufacturing environment. It also enables the study of interactions between factors, which is a common occurrence in many processes. Full factorial design experiments are carried out to estimate how the selected JIT drivers ($k$ number of variables) affect system performance of JIT enabled assembly lines. The decision to select full or partial factorial design depends on the number of factors, and the mathematical model linking $k$ number of JIT variables to a measurable KPI is given as follows:

$$Y_n = a_0 + a_1X_{n1} + a_2X_{n2} + a_3X_{n3} + \cdots + a_kX_{nk} + \varepsilon_n \tag{1}$$

where $Y$ is the response (KPI), $a_0$ is the intercept coefficient, $a_1$– $a_k$ are effect coefficients, $X_1$–$X_k$ are JIT parameters and $\varepsilon$ is the error term.

The main effect of each factor is independent of the remaining factors. The interaction effect is useful to determine the interaction between factors. The following matrix notation (2) is used to express the aforementioned linear mathematical model in a simple way and enables calculation of the intercept, the effect and interaction coefficients and the error:

$$Y = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{bmatrix}, \quad X = \begin{bmatrix} 1 & X_{11} & X_{12} & \dots & X_{1k} \\ 1 & X_{21} & X_{22} & \dots & X_{2k} \\ \vdots & \vdots & \vdots & \vdots & \\ 1 & X_{n1} & X_{n2} & \dots & X_{nk} \end{bmatrix}$$

$$a = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix}, \quad \varepsilon = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix} \tag{2}$$

Applying the least square approach, the regression coefficient of vector '$\boldsymbol{a}$' is expressed as $a = (X'X)^{-1}X'Y$ where $X'$ is transposed matrix of $X$ and $(X'X)^{-1}$ is the inverse of $X'X$. The error ($\varepsilon$) between the experiment and predicted model is described as $\varepsilon = Y - \hat{Y}$, where the predicted response $\hat{Y} = aX$. Multiple linear regression analysis is hereby used to identify the critical parameters.

DoE, therefore, is used to identify critical JIT drivers by fitting a polynomial to the experimental data in a multiple linear regression analysis. The next step of the mathematical model development process involves simulation experiments with the model.

### 3.3. Simulation using ProModel

ProModel is a simulation tool for modelling various manufacturing and service systems. Manufacturing systems such as job shops, conveyors, transfer lines, mass production, assembly lines, flexible manufacturing systems, cranes, JIT systems and kanban systems can be modelled by ProModel [16]. The simulation software provides a powerful, visual modelling system enabling the rapid evaluation of alternative operating conditions and business scenarios to support and aid business decisions [17]. It provides facilities for conducting experiments, running multiple replications, data acquisition and automatically calculating confident intervals. ProModel provides Stat::Fit utility package to analyse user-input data and fitting an appropriate empirical distribution. This simulation and modelling software is useful to conduct experiments in order to determine whether changes in a given input JIT variable affects the objective function and the significance of the effects without disrupting the current manufacturing processes. It further enables the determination of the best combination of input factor values to optimise the objective function value. ProModel simulation software therefore, was used in this study to model JIT enabled assembly line, and to identify, modify and optimise JIT techniques that affect plant performance. The simulation model helps to establish cause and effect relationships between key JIT drivers ($X_i$) and performance ($Y$).

## 4. Research methodology

A case study approach was adopted where by data was collected through a range of techniques including open ended and structured interviews (with top managers, plant managers and production line associates), direct observation of the plant in operation, and a review of documents and archival records. These methods were arranged in such a manner as to minimise the disruption to the assembly lines while ensuring maximum cooperation and support from respondents. Documents reviewed included hard copies of reports, minutes of meetings, plant layouts as well as electronic documents stored in general areas such as 'co-operated information systems for global manufacturing (CIGMA)'. The researcher was able to observe plant in operation and attended daily progress meetings. The field notes, opinions and facts were further discussed during interviews, which were carried out to identify production and JIT implementation related problems, their causes and KPIs.

## 5. Case study: '*X*' Manufacturing (UK) Ltd.

'X Manufacturing (UK) Ltd.' is a subsidiary of 'X Corporation' in Japan. They produce an extensive range of over 110 product varieties of air conditioner units, heaters, blowers and panels for world leading automotive manufacturers such as Toyota, Honda, Jaguar, MCC and Land Rover. The company has 1600 employees to satisfy sporadic demand for its products and manufactures approximately 17.8 million parts per year in nine process lines and 11 assembly lines. In this organisation, there are two major production lines—process and assembly lines. The company has an ongoing continuous improvement program; however, production lines have been experiencing longer production lead time than the order receipt lead time. Consequently, the company was unable to cope with high demand for their products. The result is that production lines started issuing production plans based on forecast information, which led to over production or even shortages when production plans were different from the order.

The production system considered in this research is a heater assembly line, which is a mixed model assembly line producing heaters for 'MCC' and 'NCC' automobile manufacturers. Fig. 3

shows the production process of the 11 station heater assembly line.

This is a manually operated assembly line and raw materials are available at each station. All the required parts and components are pulled as batches from the warehouse and subassembly lines while the heater production process passes through the final assembly line. The configuration is a single piece flow assembly line with provision for a conveyor belt to move the product between stations. The company tends to implement material requirement planning to avoid the risk of material and part shortage during the production process. The line uses typical JIT tools and techniques such as pull system (Kanban), 'takt time', and continuous flow of production for make-to-order processes. The company has implemented line-balancing techniques, set-up time elimination plans, TQC, level schedules, group technology and cellular manufacturing in most of the production areas. However, the production lines still faced problems due to delay of final product delivery to the customer for various reasons. The main reason behind this delay is the long PT. Fig. 4 shows the cause and effect diagram depicting the detailed relevant causes for PT and TT.

Nine major factors affect PT and TT namely, machine breakdown, line balancing, TQC, labour idle time, supplier performance, automation, customer demand, group technology, repairs, rejects and returns. These are critical factors determining the success or failure of the company's JIT philosophy. The lack of these factors, however, affect PT and TT negatively.

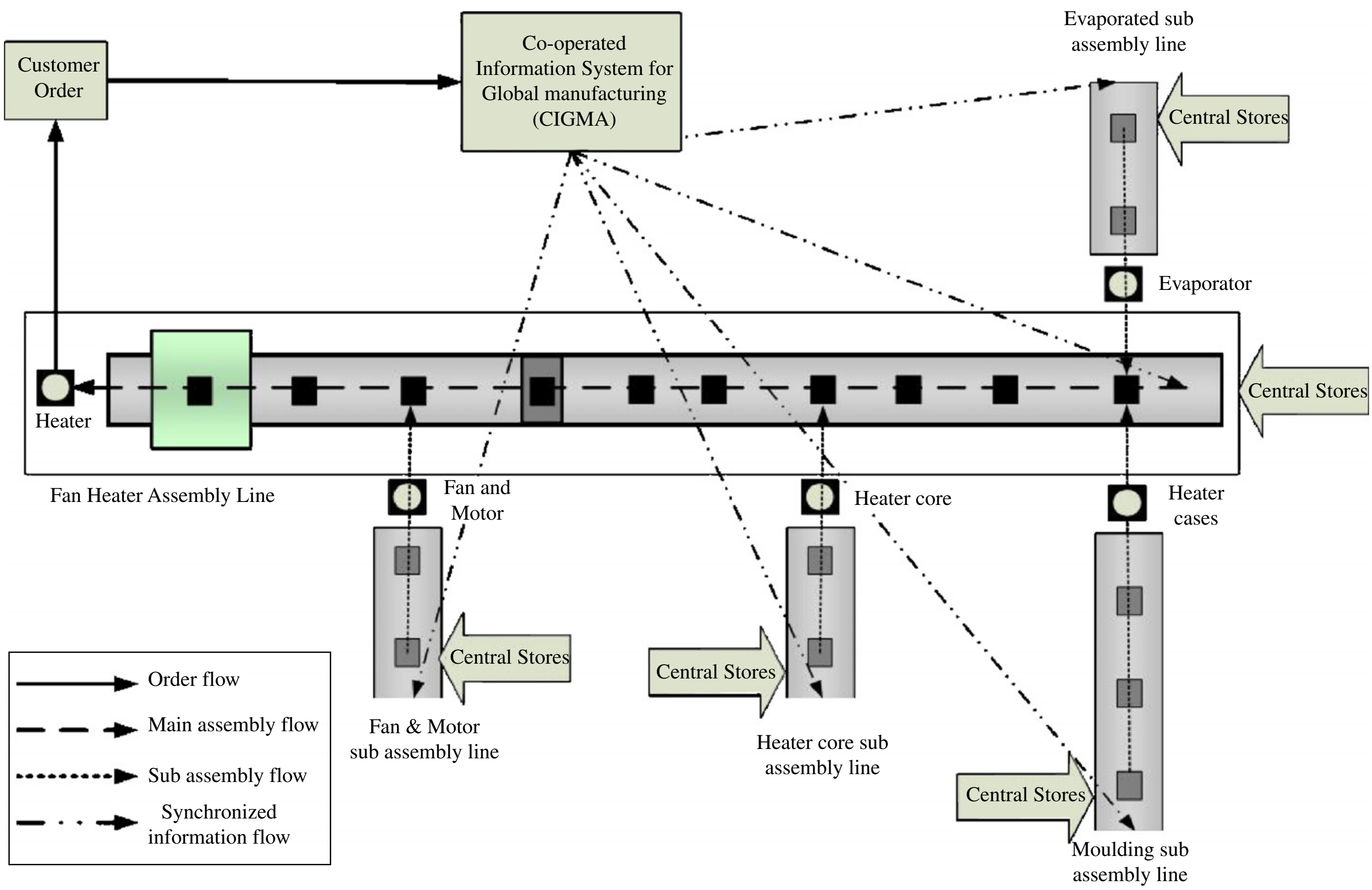


**Fig. 3.** Production process at 11 station heater assembly line.

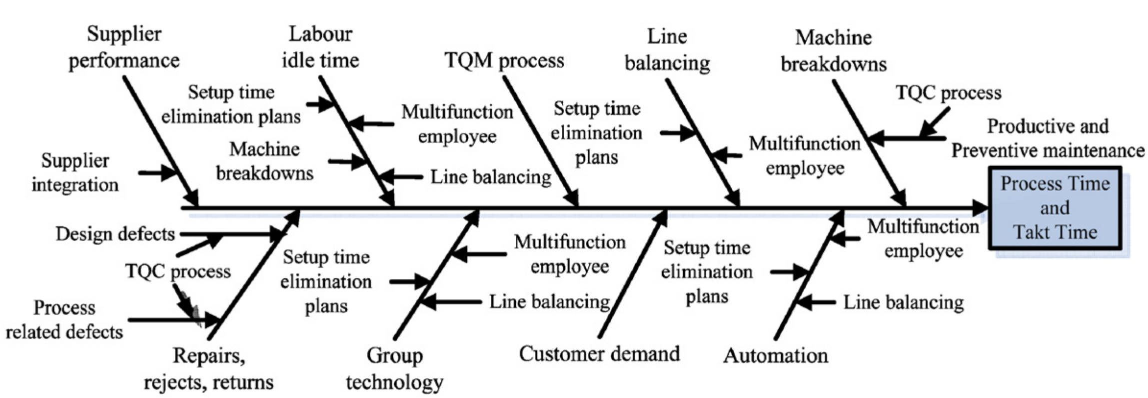


**Fig. 4.** Cause and effect diagram analysis for process and takt times.

Having identified all primary and secondary causes, the next step was to identify the key issues affecting PT and TT. Fig. 5 shows the relations diagram applied to identify key drivers for PT and TT. According to the diagram, 'process and takt times' are major concerns with nine (0,9) causes. In this diagram 'TQC process', 'multifunctional employees', 'line balancing' and 'set-up time elimination plans' are key JIT parameters, which have direct and indirect impact on the PT and TT. Their values are (4,0), (4,0), (4,2) and (4,0), respectively. It was concluded, therefore that these four factors are the major JIT variables affecting PT and TT, and were subsequently investigated by simulation experiments to understand their various impacts on the JIT model.

### 5.1. Components of the performance measurement model in experimental design

In order to optimise line performance in a JIT environment, PT and TT are the most suitable and relevant KPIs and the best objective functions to measure. Line balancing, set-up time elimination plans, TQC and multifunction employee are key JIT variables, which have a significant influence on PT and TT. Preliminary studies now confirm that the number of assembly stations, set-up time, time spent on quality control and the number of associates manning the assembly line are key variables affecting performance and productivity in a JIT environment. The number of stations and line associates are equal in heater assembly line 3 and these two JIT drivers are therefore considered as one factor.

### 5.2. Experimental design

A three factor mathematical model (3) developed in this study is expressed as

$$Y = a_0 + a_1A + a_2B + a_3C + a_4AB + a_5AC + a_6BC + a_7ABC + \varepsilon \quad (3)$$

where $Y$ is the PT or TT, $a_0$ is intercept coefficient, $a_1$–$a_3$ are effect coefficients, $a_4$–$a_7$ are interaction coefficients, $\varepsilon$ is error term and JIT parameters $A$, $B$ and $C$ as listed in Table 1.

For a two-level full factorial design, experimental design is quantitatively expressed as $2^3$, where there are three factors affecting PT and TT.

### 5.3. Assumptions and constraints of the model

The following assumptions and limitations were imposed on the simulation modelling experiments:

- Raw materials and parts are always available at stations.
- Assembly line is flexible and new assembly stations can be introduced according to demand.
- Model incorporates 100% quality check, where there is a 1% chance that a part will be found defective, which is acceptable.
- Set-up times are assumed to be constant at each station, but however depend on the product type.
- No line stoppage occurs during production, upstream and downstream worker/s, team leader and setter are available to help associates at critical workstations.

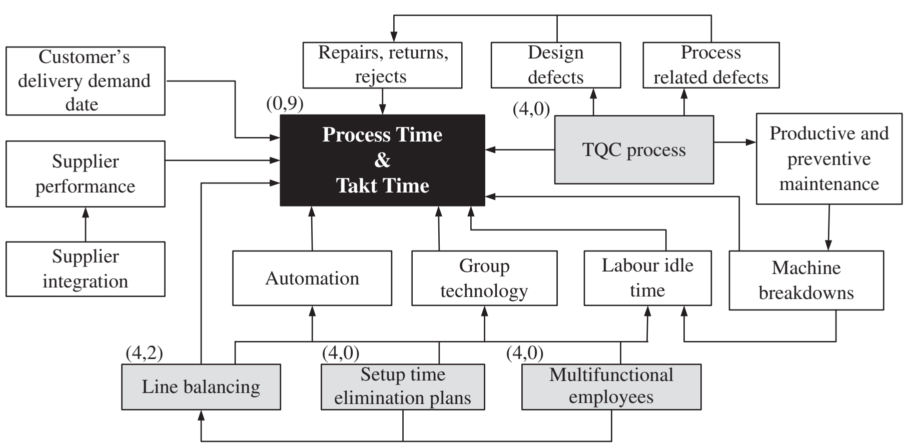


**Fig. 5.** Relations diagram analysis for process and takt times.

**Table 1**
Factors and levels for the experimental design

| Factor | JIT driver | Description | Lower value ('–' code) | Upper value ('+' code) | Reason |
|---|---|---|---|---|---|
| *A* | Line balancing or multifunction employee | Number of stations or number of line associates | 11 Stations (14 line associates) | 13 Stations (16 line associates) | Lower value is identified when the line is balanced to a lower number of stations due to low demand or non-urgent product where upper value defined for high demand urgent product |
| *B* | Set-up time elimination plans | Set-up time | 10 min | 20 min | Lowe set-up time defined when there is a change between two products of same family (e.g. from right hand NCC top left hand NCC). Higher value defined when there is a change between two families (e.g. from NCC to MCC) |
| *C* | TQC | Time spent on quality control | Without QA network (0 s) | With QA network (5 s at each station) | Higher value defined when every associate spent at least 5 s per product for quality control at every assembly station where as low value defined when there is no quality controlling |

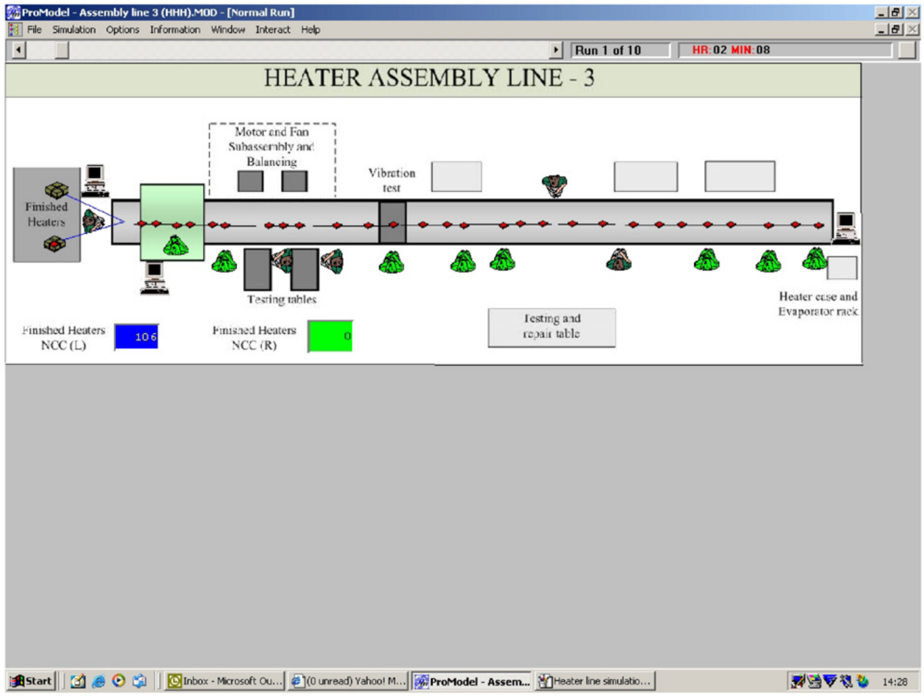


**Fig. 6.** Screenshot of experiment with ProModel with factors applied at a higher level.

**Table 2**
Experimental trials and results for $2^3$ factorial design

| Response | Line balancing ($A$) | Set-up time ($B$) | TQC ($C$) | Replication 1 | | Replication 2 | |
|---|---|---|---|---|---|---|---|
| | | | | Process time (min) | Takt time (s) | Process time (min) | Takt time (s) |
| R1 | – | – | – | 396.0 | 73.8 | 397.8 | 73.8 |
| R2 | + | – | – | 299.4 | 48.6 | 299.4 | 49.2 |
| R3 | – | + | – | 396.0 | 73.8 | 397.2 | 73.8 |
| R4 | + | + | – | 309.6 | 48.0 | 309.6 | 49.2 |
| R5 | – | – | + | 421.8 | 78.6 | 423.0 | 78.6 |
| R6 | + | – | + | 330.0 | 48.6 | 330.6 | 49.2 |
| R7 | – | + | + | 421.2 | 78.6 | 423.6 | 79.2 |
| R8 | + | + | + | 334.2 | 48.0 | 334.8 | 49.2 |

- No allowance for machine breakdowns and repair times in the model. Preventive maintenance assumed to be performed during non-productive time.
- For parts assembly, first come first served rule applies.
- Assembly line works under ideal JIT conditions.

### 5.4. Simulation experiments

Simulation experiments were started with determination of assembly times at each station using a stopwatch. Auto::Fit function of Stat::Fit software was used to automatically choose the appropriate continuous or discrete distributions to fit the input data. Modelling elements such as 'locations', 'entities', 'path networks', 'resources', 'processing' and 'arrivals' were defined using ProModel simulation software. One of the most important features of ProModel is the ability to reproduce and randomise replications of a simulation model [16]. Fig. 6 shows a screenshot of animation with ProModel when all the factors are at their higher value.

**Table 3**
Factorial fit for PT and TT

| JIT factor/s | Process time (PT) | | Takt time (TT) | |
|---|---|---|---|---|
| | Coefficient | $p$ Value | Coefficient | $p$ Value |
| Intercept | 364.01 | 0.000 | 62.51 | 0.000 |
| $A$ | –45.56 | 0.000 | –13.76 | 0.000 |
| $B$ | 1.76 | 0.000 | –0.04 | 0.771 |
| $C$ | 13.39 | 0.000 | 1.24 | 0.000 |
| $A\times B$ | 1.84 | 0.000 | –0.11 | 0.392 |
| $A\times C$ | 0.56 | 0.035 | –1.24 | 0.000 |
| $B\times C$ | –0.71 | 0.012 | 0.04 | 0.771 |
| $A\times B\times C$ | –0.79 | 0.008 | –0.04 | 0.771 |

### 5.5. Analysis and mathematical modelling

Table 2 shows the combination matrix for $2^3$ full factorial design with outputs as PT and TT for two replications each in a heater assembly line. Statistical analysis and factorial fit for the above experiments are presented in Table 3.

Analysis of the main, two-way and three-way interactions was obtained at 0.05 significance level ($\alpha$) and coefficient and $p$ values are presented in Table 3. An effect is deemed significant, if $p$ value is less than or equal to $\alpha$ and vice versa. According to the analysis, $p$ values for all effects and interactions on PT are less than 0.05 ($\alpha$). Therefore, all the effects and interactions on PT are significant. However, factorial fit shows that the main effect and interaction effects of set-up time on TT are greater than 0.05. In this case study, the coefficient of line balancing (multifunction employee) shows the highest impact on both PT and TT compared to the other JIT drivers as well as for the two and three-way interactions. PT and TT therefore decrease when the number of stations (number of employees) changes from lower to upper values. The performance indicators can be optimised by introducing more assembly stations (more employees) with better line balancing (improved multifunctional ability). PT increases when set-up time and time spent on quality control change from lower to upper values. The impact of TQC on PT is greater than those for set-up time but lower than for line balancing (multifunction employee). As expected, set-up time and its interactions have no impact on TT. This is because set-up time occurs at the completion of one batch, whereas TT occurs between two successful end products. Table 3 therefore demonstrates the outcome from modelling and simulation of key JIT drivers in an automotive component-manufacturing environment with a view to optimising PT and TT.

A normal probability plot was used to compare the relative magnitude and statistical significance of main and interaction effects of JIT variables. Figs. 7 and 8 show normal probability plots of the effect on PT and TT when $\alpha$ is at 0.05. Points located at a significant distance from the fitted line denote the important effects in the normal probability plot. Non-important effects are located very close to the fitted line.

The following regression equations (4) and (5) have been derived for the PT and TT where $A$ is line balancing (multifunction employee), $B$ is set-up time and $C$ is TQC:

$$PT = 364.01 - 45.56A + 1.76B + 13.39C + 1.84AB + 0.56AC - 0.71BC - 0.79ABC \tag{4}$$

$$TT = 62.51 - 13.76A + 1.24C - 1.24AC \tag{5}$$

The company can use the above mathematical models to predict PT and TT by assigning upper and lower values of aforementioned factors.

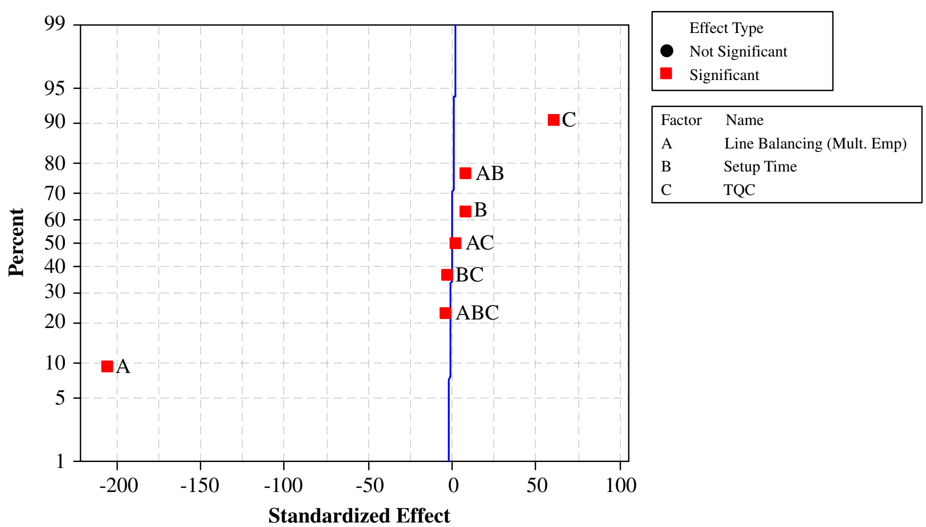


**Fig. 7.** Normal probability plot for the standardised effect on PT (response is process time (min), $\alpha = 0.05$).

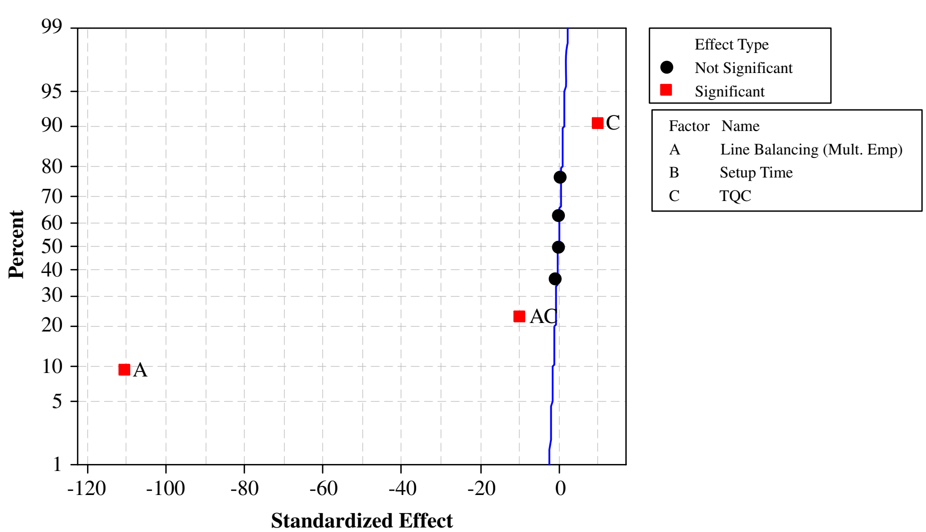


**Fig. 8.** Normal probability plot for the standardised effect on TT (response is takt time (s), $\alpha = 0.05$).

## 6. Conclusions

A five-step approach to identify the impact of selected key JIT techniques on performance using computer based simulation tools and linear mathematical modelling has been presented. This included the use of a comprehensive mechanism to identify the most significant JIT drivers using conventional management tools such as cause and effect analysis and relations diagrams. The approach developed benefits from its simplicity and operability. However, the complexity of experimental design and mathematical modelling increases with the number of key JIT techniques. The case study approach applied aforementioned systematic and efficient methods to identify key JIT variables (i.e. line balancing, multifunction employee, set-up time and TQC) and KPIs (i.e. PT and TT) for the mixed model automotive component assembly line. This research study used the simulation modelling with ProModel software and linear mathematical modelling to identify the impact of key JIT drivers on performance. Line balancing (multifunction employee) stood out as a significant parameter with a high impact on PT and TT. The results of the simulation analysis show that PT and TT can be further reduced by eliminating set-up time and time spent on quality control. The mathematical model developed here will enable industry practitioners to understand the impact of key JIT techniques on system performance and thereby provide guidance on its improvement.

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