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Design of practical optimum JIT systems by integration of computer simulation and analysis of variance

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Abstract

This study introduces a framework for re-design of manufacturing systems into practical optimum just-in-time systems by integration of computer simulation and analysis of variance. The conventional JIT approach is mostly applicable to static production systems and the dynamic production systems require a more practical integrated JIT approach. In addition, the re-design of existing dynamic systems into just-in-time systems must follow a practical path, which can be a cumbersome task. This means, a unique practical optimum just-in-time system that considers system's limitations and its dynamic behavior must be designed. To achieve the objective of this study, first, the actual system must be totally modeled and simulated. Second, the integrated simulation model is tested and validated by analysis of variance. Third, the optimum (most fitted) JIT design is developed and tested by modeling actual system's limitations and its dynamic behavior. The framework is applied and tested for an auto production line and a heavy rolling mill workshop.

Keywords: Just-in-time; Simulation; Optimum; Practical; Analysis of variance; Integration

1. Introduction

The in-process inventory costs in manufacturing systems have been a major concern for production managers. Just-in-time (JIT) procedure with kanban (card) controls was first introduced in Japan to control the in-process inventory costs. JIT has a simple goal: producing a product with the desired quality and quantity in the requested period (Cowton & Vail, 1994; Gunasekaran & Lyu, 1997; Liker, 1997; Sakakibara, Flynn, Schroeder, & Morris, 1997; Scholl & Kiein, 1999; Schonberger, 1984, 1987; Wheatley, 1998).

JIT philosophy, which we refer to as theoretical or as conventional JIT seeks zero defective, setup time, inventory, breakdown, transportation cost, and lead-time (Browne, Harhen, & Shivnan, 1996; Monden, 1993; Price, Gravel, & Nsakanda, 1994; Schonberger, 2002). Most experts believe that the preceding goals are very idealistic and a practical, JIT should try to get close to them as far as possible. Several companies in the last 20 years have been restructuring their manufacturing systems to become a JIT or world-class company (Burman, 1995; Caputo & Dulmin, 1997; Fohurley, 1999; Reda, 1987; Schonberger, 1984). JIT is used in Toyota plants in Japan and US, Mercedes Benz in

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Germany and US and in several auto industries in US and around the world. However, these systems *were built* to operate in a JIT fashion.

Kanban is a demand-pull process that requires production-scheduling integration from the final product inventory back through each stage of production to the input of raw material. Careful planning is needed to develop the system's capacity and the potential for bottleneck at each production stage. Moreover, there can be a precise monitoring of the system by kanban. In fact, kanban tries to prevent demand fluctuations or production volumes from the next process to the previous (Huang, Rees, & Taylor, 1985; Huang, Wang, & Ip, 1998; Lee, Lin, & Uzsoy, 1993; Nori & Sarker, 1998; Sewel, 1990; Shannon & Fry, 1993; Takahashi, Nakamura, & Ohashi, 1996). It also minimizes the inventory fluctuations in any process.

Huang, Rees, and Taylor developed one of the very first JIT simulation models with kanban by SLAM (Huang, Rees, & Taylor, 1983, 1985; Pritsker, Sigal, & Hammesfahr, 1989). Their paper evaluated overtime requirements for changes in the number of kanban included in a JIT system, processing time variance and demand levels. They used SLAM II language to model the flow of two kanban and a multiline, multistage production process using Kanban in a pull JIT system. Chan and Smith (1993) assessed some features of a JIT system for a welding assembly line. They discuss the techniques used to develop the JIT models through GPSS/H simulation language. Ezingeard and Race (1995) discuss that the application of JIT techniques in batch chemical processing environment under variable demand imposes significant capacity management problem. Furthermore, the spreadsheet simulation techniques are recommended for JIT modeling. They present a case study to clarify the links between service levels and resource utilization, which can help management decisions regarding timing, levels of stocks and sizing facilities. Welgama and Mills (1995) present a case study of a simulation modeling approach in the design and analysis of a proposed JIT for a chemical company. The simulation approach was used to compare two cell designs and to estimate utilization levels for operators and material handlers under the new JIT system. Gabriel, Bitcheno, and Galletly (1991) argue that computer simulation is an ideal tool for implementation of JIT system due to its wide range of activities. They have developed a software package, which simulates JIT manufacturing system. Rodrigues and Mackness (1998) propose an approach for helping companies in the selection of the most appropriate synchronization approach through simulation models. The models are based on three synchronization approach, namely, JIT, just-in-case and drum-buffer-rope. Schonberger (1987) presents description of 26 JIT implementations in US and Asia. Three JIT ratio analyses are discussed: (1) lead time to work content, (2) process speed to sales rate and (3) number of pieces to number of workstations. Weston (2003) discusses the development of a simulation model of a workshop that is line balanced and operating in JIT fashion. The simulation model takes into account the theory of constraints via Microsoft Excel by considering m parts processed through n work centers. Wu and Kung (2003) investigate the impacts of different market demand patterns on system performance of a plant that implements either JIT or theory of constraint (TOC) in Taiwan. The authors used SIMAN to develop simulation models of a plastic-mold injection plant. The system performance was considered in terms of average work in progress (WIP) inventories and throughput time. They report that both philosophies can have significant improvements on system performance without large investment of capitals. The JIT systems have been advantageous to small, medium, and large production systems in Korea (Kim & La, 2003). The traditional JIT system applied to static production systems have the advantages such as reduced inventories, etc. In fact, the adaptation of JIT system to dynamic production systems is a difficult task because of its sensitivity to production factors. The dynamic production systems deal with high variability of demands, frequent and random machine breakdown, variable defect rates and high absence or separation rates of personnel (multitasking, etc.). They developed JIT production models that are indifferent to production factors and identified the optimal model that reflects the production circumstance of the Korean industries. Then, computer simulation was used to test selected models for the susceptibility of the production factors.

Abdou and Dutta (1993) developed a simulation model for kanban based scheduling in a multistage and multiproduct system. They demonstrated that under a set of operational conditions, the proposed simulation model could obtain a more improved JIT system. Abdul-Nour (1993) analyzed the effects of different maintenance policies and machine unreliability on JIT systems. The Taguchi method together with computer simulation was used to evaluate the effects and collect the required data. Cormier and Kersey (1995) discuss the potential use of computer simulation and operations research techniques for design and analysis of JIT operation of a warehouse. Chengalvarayan and Parker (1991) describe the JIT simulation model of a production line and discuss the possibility of JIT implementation. Egbelu (1991) developed a framework for design and analysis of a JIT manufacturing system based on scheduling, material handling and simulation techniques. Savsar and Jawini (1995); Changchit and Kung (1988); Kung and Changchit (1989); Meral and Erkip (1991); Baykoc and Erol (1998); Sarker (1989) have developed computer simulation models for analysis and assessment of JIT production systems. There are other studies, which highlight the importance of JIT simulation modeling (Gross, 1993; Manivannan & Pegden, 1990; Simulation Optimizes JIT System Design, 1997; Nandkeolyar, Ahmad, & Pai, 1998). Levasseur and Storch (1996) presented a non-sequential JIT simulation model for batches of parts to be routed between operations within the same facility. Hum and Lee (1998); Lummus (1995) present a computer simulation of the performance of a number of scheduling rules under different JIT scenarios. Muralidhar, Swenseth, and Wilson (1992) reported the effects of Gamma, Log Normal and Truncated Normal process times on a hypothetical assembly line with one kanban.

The preceding studies highlight the importance of dynamic behavior of production systems with respect to JIT design. In addition, variation in production times (at each stage) has the potential of creating idle time for machines and increasing overtime costs to meet production schedules. This is why design and implementation of a JIT system may last up to several years.

It is concluded that conventional (theoretical) JIT does not fit most dynamic systems and is more applicable to static systems. Furthermore, design and implementation of theoretical JIT philosophy may not be possible for most dynamic systems due to their unique limitations and constraints. Therefore, a more applicable JIT design approach compatible with the limitations of dynamic systems is required. The preceding pros and cons of JIT demands powerful tools for design and assessment of the dynamic systems into JIT before actual deployment. In fact, there are certain difficulties in design and implementation of JIT that could be overcome by integration of computer simulation and analysis of variance (ANOVA). Consequently, a practical optimum JIT design for dynamic systems may be developed by incorporating systems limitations and integration of simulation and ANOVA. Section 2 presents the integrated framework for development of practical optimum JIT design for dynamic production systems. The proposed framework is then designed and tested for two actual dynamic production systems.

2. The integrated framework

A conventional (theoretical) JIT approach seeks zero defects, set ups, inventories, breakdowns, transportation time, and lead-time. It is argued that the above objectives are idealistic and thus not achievable for most dynamic systems. Furthermore, design and deployment of the conventional JIT systems is almost impossible for most dynamic systems due to their limitations, constraints, and dynamic behavior. This study introduces a framework for development of practical optimum JIT design for dynamic systems.

To achieve the objective of this study first, the system under study must be *totally* modeled and simulated. Furthermore, all detailed operations and activities including maintenance, repairs, inspection, and interacting system should be modeled and simulated. This would cover the dynamic behavior modeling of the system under study. Analysis of variance (ANOVA) must be used (Azadeh and Jalali Farahani, 1998; Azadeh, Jalali Farahani, & Sakkaki, 1999; Hicks, 1982; Montgomery, 1984) to test the validity of simulation model (H_o: $\mu_1=\mu_2$). This is accomplished by identifying critical performance measures in the dynamic system being studied and conducting independent *t*-test or *F*-test with respect to each of the performance measures. It should be noted a test on ratio variances ($F_o=S_1^2/S_2^2$) should be conducted prior to ANOVA. The test on variances or $H_o:\ \sigma_1^2=\sigma_2^2$ would reveal the degrees of freedom for the independent *t*-test. Next, the results of simulation model are presented and accredited by experts of the actual system. At this point, system limitations including constraints on human operators, machines, production, and layouts should be addressed. How many additional operators and machines are permitted by the system? How flexible is the present layout toward the new JIT design? Then, verified, validated, and accredited integrated simulation model is used to develop kanban-based production model if the system being studied is not a JIT system. Otherwise, line balancing and bottleneck analysis are to be used for JIT or near JIT systems. In utilizing, the kanban-based modeling techniques all system limitations and constraints must be considered. Therefore, the practical optimum JIT design is developed by transforming validated and accredited integrated simulation model into practical kanban-based production model of the system being studied given system constraints and limitations. The general kanban-based production model of a JIT system for a hypothetical assembly line with three serial stations is discussed in the next paragraph. In addition, the Visual SLAM model of the hypothetical JIT system is presented. Fig. 1 presents general steps required to develop the practical optimum JIT design for dynamic systems.

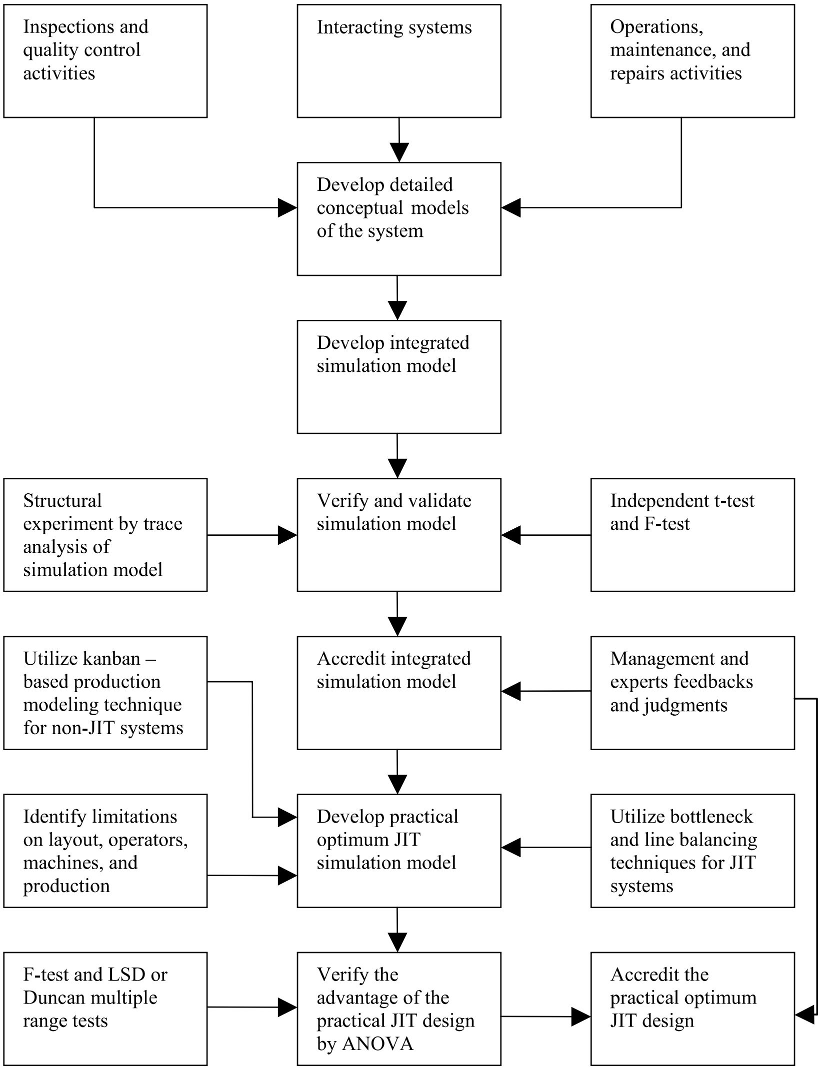

Fig. 1. The general steps required to develop practical optimum JIT design.

F-test is used to compare the behavior of actual system, simulation model, and JIT simulation model. If null hypothesis is accepted, then it is concluded that the practical optimum JIT is not superior and therefore has the same performance as simulation and the existing system. Therefore, the deployment of the practical optimum JIT is not recommended. If the null hypothesis is rejected (H_o: $\mu_1 = \mu_2 = \mu_3$), all pairs of treatment means are compared to assess the advantage of the JIT design. It is recommended to use the least significant differences (LSD) method or Duncan's multiple range test since they are very effective in detecting true differences in means (Montgomery, 1984). The preceding tests would reveal if the practical optimum JIT were superior to existing system and simulation model with respect to the selected performance measures. Finally, the structure and results of the practical optimum JIT design may be presented to experts of the actual system to insure its applicability and ease of deployment.

In the two-card kanban production system, information flow always takes place with two cards named withdrawal kanban (WK) and production kanban (PK). Each station has two input and output inventories. The input of each station is the output of previous station. WK and PK are attached to the input and output inventories, respectively. If there is demand for final product given, demand is met, PK will be detached, product will be departed from the system and detached kanbans will be placed in PK post. Otherwise, demand has to wait until it is satisfied. If there is any kanban in the PK post, a new unit of product will be produced. Required amount of input products will be picked up from input inventory, WK will be detached and placed in the WK post and by detaching a PK from PK post, production will be initiated (Huang et al., 1983, 1985; Monden, 1993; Price et al., 1994; Pritsker et al., 1989).

A general kanban-based production model of Visual SLAM (Pritsker, O'Reilly, & LaVal, 1997) has been developed for a hypothetical assembly line with three serial stations (Fig. 2). The model considers defectives generated at each stage. The production time in each is defined as 'P_i' for $i=1,\ldots,3$. The time between arrivals of the demand for final product is 'D'. The reader should note that P_i and D could be deterministic or random. The transportation time between any two neighboring stations is assumed zero. The lot size (inventory) for the production and transportation is one unit. Therefore, each kanban indicates production or transfer of one unit of inventory in the system. If an order is received and there is no inventory to satisfy that demand, the order should wait. At the beginning of the work in this system, a one-unit inventory in some of the QUEUE nodes is considered to prevent instability. The percent defectives at each station is defined as 'Si' for $i=1,2,3$ which could be either deterministic or stochastic where it is generated by a pseudo-random number to model stochastic process of defective items.

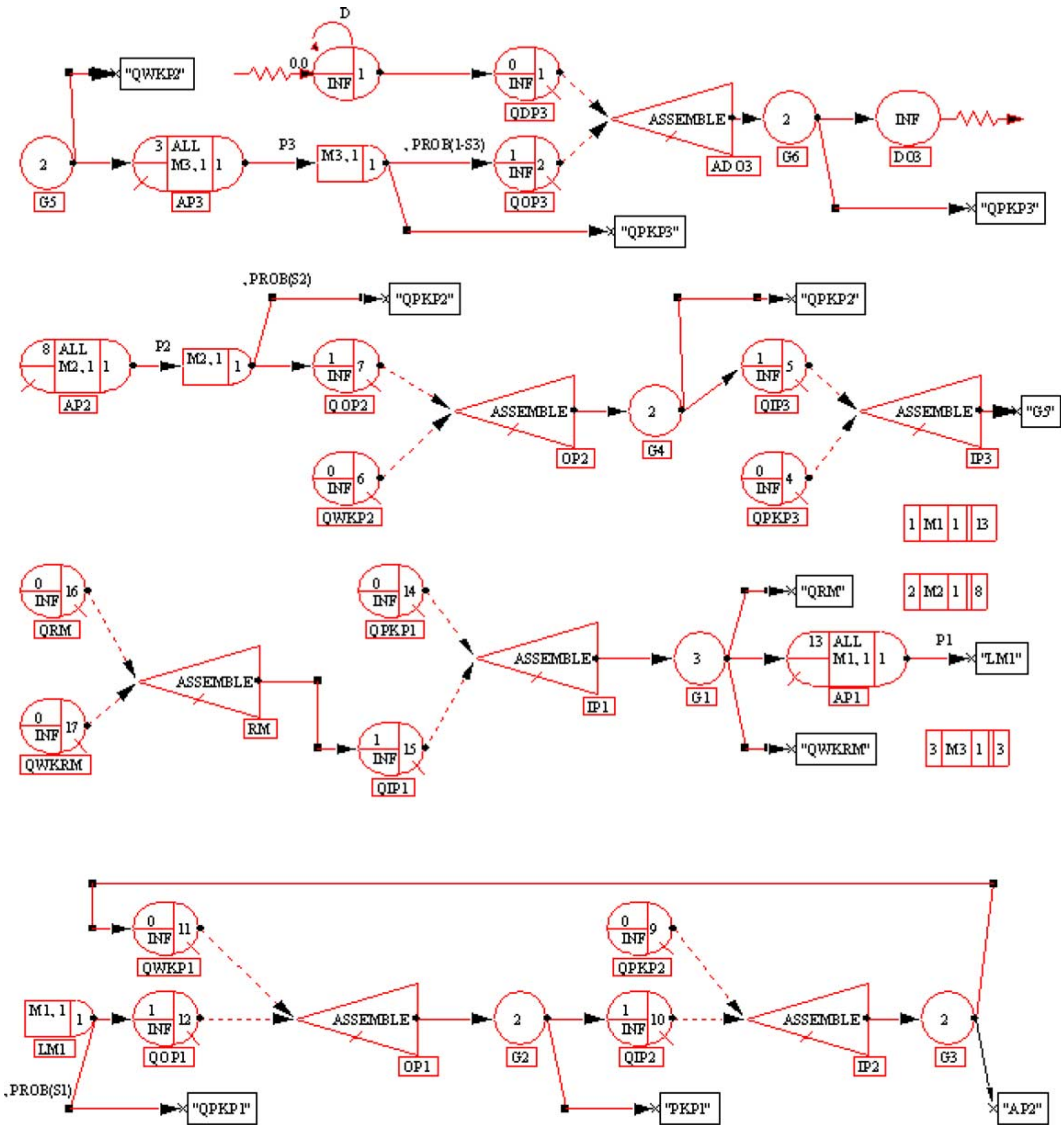

Fig. 2. Visual SLAM model of a JIT system with three serial stations.

The main structure of this model is composed of ASSEMBLY (SELECT), QUEUE, and GOON nodes. The role of the QUEUE node is to store the final product or a product waiting for the process. The GOON node branches the flow of entity. On the other hand, the ASSEMBLY node combines the received kanban (WK or PK) with the needed inventory and then gives the authority for the production or transfer of processed product to the next station.

The information flow for the production orders and receiving materials are shown as the connections between GOON and QUEUE nodes. The first entity that starts production takes place by receiving the first order at the CREATE node. The order takes place in CREATE node and is transferred to the QUEUE node.

The received order in QDP3 node and the inventory in QOP3 node are combined in the ASSEMBLY node ADO3 and the assembled entity leaves the system. At the same time, the GOON node inserts an entity to the QUEUE node QPKP3 to authorize the production of another product in the last station. The entity at QPKP3 node is assembled with one unit inventory in QIP3 node by the assembly node IP3. The assembled entity is then duplicated by GOON node. One of the duplicated entities will wait in the await node AP3 to be processed by P3 operation and the other one will authorize the transfer of one unit of semi-finished product from the previous station to this station. This is accomplished by the entity waiting in QWPK2 node to receive the semi-finished product and assembling it with one unit inventory in QOP2 node by the assemble node OP2. The assembled entity is then transferred to the main process.

A unique feature of the practical optimum JIT design is modeling of defects generated by the actual process. This is an important feature as the generation of defects is almost inevitable in dynamic environments. After operation P3 on the waiting entity in the await node AP3, the FREE node will release resource named M3. The output entity would be routed to the QUEUE node QOP3 with the probability of 1-S3, which could be deterministic or generated by a pseudo-random number to model stochastic process of defective items. Otherwise, the emanated entity would go to QPKP3 node with the probability of S3. Furthermore, the product is identified as defective with the probability of S3. Consequently, the PK of the defective product is detached from it and is left on the PK post such that the production of another unit of product would satisfy its demand. This process will prevent the entrance of the defective semi-finished products to the next station. The process will be continued up to the beginning of the network representing the arrival of raw material to the system.

3. An automotive production line

The system being studied is the production line of the lateral doors in a large auto industry. The production of lateral doors depending on front or rear is performed separately. The front and rear lateral doors are assembled and completed in six and five stations, respectively. In addition, some operators service more than one station (multitask operators). The operation of all stations was stop watched randomly several times to obtain their distribution functions and parameters. The data was analyzed by Kolmogorov–Smirnov goodness of fit test for each station. A technical identification form was developed for each station. The breakdowns caused by repairs and maintenance, quality problems and lack of parts and raw materials are considered in the simulation model. The mean time between failures (MTBF) for the production line was identified as 8200 s. Total effective work in the line for two daily shifts is 52,200 s. Percent defective for each station was evaluated by referring to the existing data and documentations. In addition, the limitations and constraints were identified as defectives and random breakdowns. The defects generated by the system could not be dismissed and a practical JIT design must consider this phenomenon. Random breakdowns are a part of the production line and it therefore should be a feature of the practical optimum JIT design. The conceptual models were developed by logical charts, operation process chart (OPC) and flow process chart (FPC) to reflect the material flows of front and rear doors. Fig. 3 shows the overview of the production line.

3.1. Integrated simulation

The integrated simulation model in context of Visual SLAM was developed by referring to the data and the detailed conceptual models of the production line. The network models are composed of 135 nodes representing the complete assembly operations of lateral front and rear doors. Also, it was verified whether the production line has the same behavior as the computer model or not. With respect to verification process, the following observations

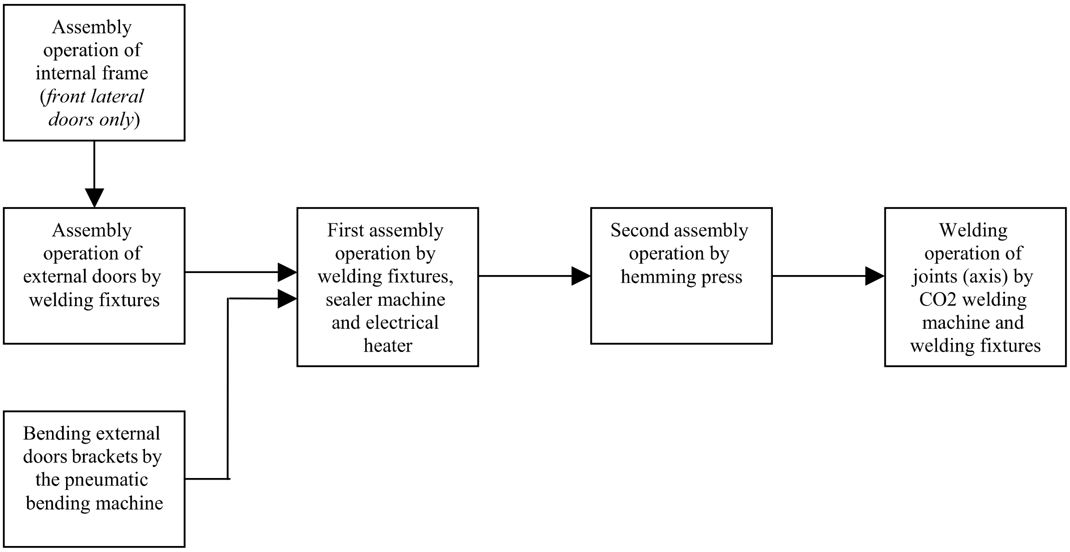

Fig. 3. The overview of the automotive production line.

were noted about the integrated simulation model. MONTR statement and other tools available in Visual SLAM facilitate the verification process:

- Material flow along the simulation model is the same as actual production system. This is achieved by MONTR statement in conjunction with TRACE option of Visual SLAM.
- All detailed as well as major operations are integrated and modeled in the simulation. There are 29, 61 and 45 nodes for joint rear and front doors, front doors and rear doors sub-networks, respectively. These sub-networks are composed of CREATE, UNBATCH, ACTIVITY, ASSIGN, GOON, BATCH, AWAIT, RESOURCE BLOCK, FREE, ALTER, QUEUE, SELECT, COLCT and TERMINATE nodes to model major an detailed operations of the assembly line. In addition, ATRIB [1], LTRIB [1], XX [1], and XX [2] are used as attributes and variables to collect entity arrival times, door types and file storage for internal frames.
- Behavior of all operators including multitask operators in the simulation is the same as actual system. It is achieved by MONTR statement in conjunction with FILES, ENTITY and RESOURCE options of Visual SLAM.
- Repair, maintenance, quality control, and inspections are considered in the simulation model. The daily mean time between failures due to repairs, improper quality of parts and shortage of material is 8200 s which is modeled in modeled in the CREATE node of the Visual SLAM network.

3.2. Analysis of variance

The behavior of the production line was examined against the simulation model by analysis of variance (ANOVA). Daily production rate was considered as the main performance measure since it is the most important criteria to the production managers. By using COLCT node at the end of the network and replicating the model 50 days ($n=50$), the production rates for lateral front and rear doors were automatically reported. Also for the actual system, throughputs (production rate) of 50 working days were selected randomly from the existing documentations. The data for simulation was collected in steady state by the method of replication.[1] Furthermore, the transient state was deleted from further considerations and simulation analysis. In addition, required number of observations for t-test and F-test was evaluated by method of operating characteristics curve.

[1] $\bar{x}(i) \pm t_{1-\alpha/2,i-1}(S(i)/\sqrt{i})$ where $\bar{x}(i)$ and $S(i)$ are the mean and standard deviation of production rate for $i=1,2,3,\ldots$ representing 15, 30, 45, … min cycles, respectively.

Table 1
The analysis of variance for the auto production line

Assembly type	Treatment	$\bar{X}(n)$	Two-sided P value	t-Value	H_0: $\mu_1 = \mu_2$
Lateral rear doors	Simulation Actual system	371.78 366.04	0.466	−0.734	Accept at $\alpha = 0.05$
Lateral front doors	Simulation Actual system	395.96 394.48	0.880	−0.1512	Accept at $\alpha = 0.05$

An independent t-test was conducted to test the equality of means (H_o: $\mu_1 = \mu_2$). The equality of variance of $H_o : \sigma_1^2 = \sigma_2^2$ was tested by F-test prior to the t-test. The results of ANOVA for the lateral front and rear doors assembly operations are shown in Table 1. It is concluded that there is no difference between the simulation model and actual system with respect to daily production rate at $\alpha = 0.05$.

The outputs of the simulation model revealed that there are considerable inventories and waiting times in all stations (Table 2). Noting that the theoretical JIT system is impossible for the production line, the framework of this study was used to design and test a unique practical optimum JIT system.

3.3. JIT design

The following modifications are recommended for the actual production system in order to achieve a practical optimum JIT design because of system's constraints and limitations. The reader should note that these modifications are only a small portion of the theoretical or conventional JIT philosophy. Moreover, deployment of all theoretical JIT design demands major changes and significant cost in the workshop, which is practically impossible:

- Because hemming press is not transferable, all machines and equipment related to rear or front doors should be as close as possible to the hemming press. This would decrease the transportation time and operational costs.
- Machines should be close to each other in order to nullify the transportation time. On the other hand, multitask operators are only allowed to perform required services according to the sequence of the related kanbans.
- A withdrawal kanban and a production kanban must be designed next to each station.
- Each station starts production or transfers production to next station if there is no production or withdrawal kanban. Therefore, the existing production policy, which demands some stations to transfer their productions in pallets of 10 or 20, is no longer valid.

The daily production plan is 234 and 210 front and rear doors, respectively. The daily available time and down time are 44,000 and 8200 s, respectively. Because each pallet contains 10 doors, one pallet of front and rear doors is departed from the system every 1880 and 2095 s, respectively.

The above features together with system limitations were modeled for rear and front doors assembly operations. The JIT modeling approach depicted in Figs. 1 and 2 were used to develop the practical optimum JIT design for the production line. Moreover, the integrated simulation model discussed in the previous section was transformed to integrated kanban-based simulation model. The Visual SLAM network of the proposed JIT system is composed of 218 nodes. A CREATE node was added to represent the time between demand. An UNBATCH node was added to represent the split of the pallet into10 units (semi-finished products). The order is received at the QUEUE node and is waited until the assembly operation in SELECT node. A BATCH node was used to represent a pallet by accumulating 10 finished products. In parallel to each entity received by the BATCH node, a cloned entity is also received to the QUEUE node representing the kanban post (Beydokhti, 2000). The effects of the JIT design in the production line are discussed in Section 3.4.

Table 2
Important characteristics of the automotive production line

Door type	Front right	Front left	Rear right	Rear left
Average cycle time (s)	5350.57	5334.26	5446.52	5461.95
Average queue length	27.90	27.53	25.03	26.64
Average daily production rate	193.60	203.20	181.90	179.50

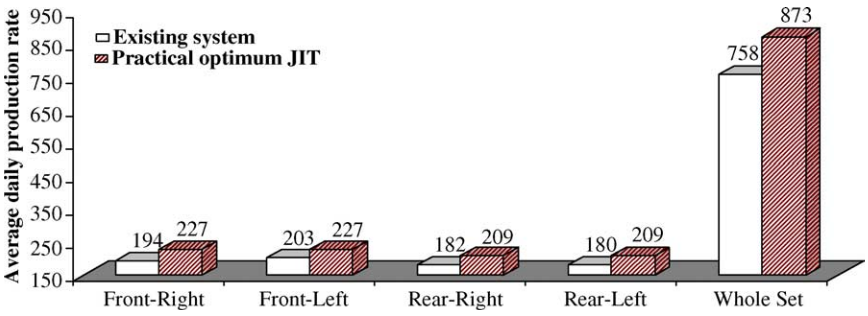

Fig. 4. The comparison of average daily production rates.

3.4. JIT test and validation

At this stage, an ANOVA is conducted to evaluate the effects of the JIT design. Four performance measures are considered to foresee the effects of JIT design. The performance measures are categorized as production rate, cycle time, in-process inventory level and resource utilization. First, it was tested whether daily production rate has the same behavior in actual system (τ_1), simulation model (τ_2) and the JIT design (τ_3). Furthermore, it was tested whether the null hypothesis H_o: $\mu_1=\mu_2=\mu_3$ is accepted. It was concluded that the three treatments differ at $\alpha=0.05$. Furthermore, the least significant difference (LSD) method was used to compare the pairs of treatment means μ_1, μ_2 and μ_3. That is H_o: $\mu_i=\mu_j$ for all $i\neq j$. The results of LSD revealed that at $\alpha=0.05$, $\mu_1=\mu_2$; $\mu_3>\mu_2$; $\mu_3>\mu_1$ and hence treatment 3 (the optimum JIT) produces a significantly greater daily production rate than other treatments. It was also observed that the optimum JIT design is statistically superior to the actual system and simulation model with respect to cycle time and average in-process inventory level. The same findings could not be concluded for resource utilization. Furthermore, the optimum JIT design improves production efficiency by utilizing the same resources. The advantages of the practical optimum JIT are depicted in Figs. 4–6. As shown, it is concluded that the practical optimum JIT design will improve the production rate by about 15%. In addition, cycle time and in-process inventory level for the production of lateral doors are decreased by about 67 and 52%, respectively. Moreover, the practical optimum JIT simulation model identified the optimum quantity of 3 and 1 kanban for the lateral front and rear doors assembly operations, respectively.

4. A heavy rolling mill system

The system being studied is an automated continuous heavy rolling mill line of a large steelmaking factory. The operation of the line is very similar to a JIT production model. One of the main objectives of a JIT system is to reduce the inventory between stations to an optimum amount that is called economic batch. It is not however possible to have

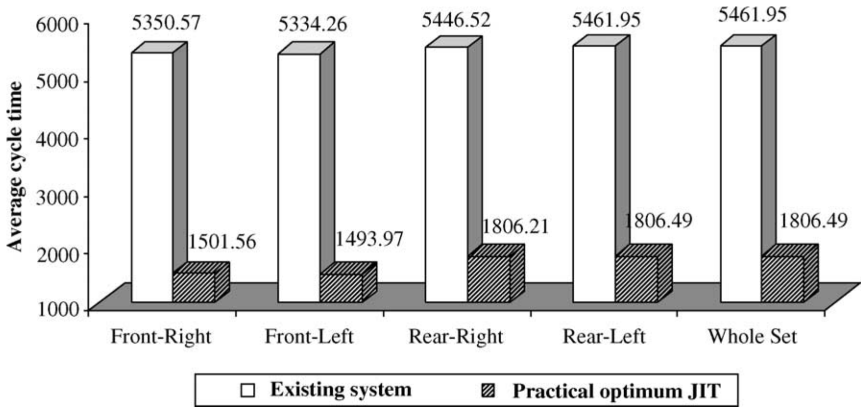

Fig. 5. The comparison of average cycle times (s).

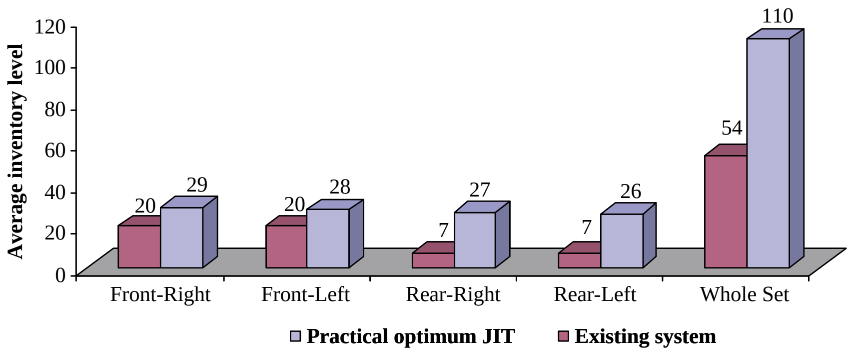

Fig. 6. The comparison of average inventory level.

inventories between stations in the rolling mill line. Therefore, the amount of material between each two stations that is equal to the limited capacity of the queue is similar to the economic batch in a JIT model. Although the workshop is capable of producing various types of profiles, but its major products are profiles 14 and 16. Furthermore, the input of this workshop is steel-bars and the output products are different types of profiles (transferred to final storage). The steel-bars are transferred from the casting workshop to the storage facility in the rolling mill workshop. They are then charged into a furnace with the production rate of 200 ton/h. There is a 400-tons cutter after the furnace station. The cutter is used to divide the bars into smaller parts when the production line is being tested. After the cutter, nine rough mills each composed of two rolls that are used to shape bars. The mills number 1, 3, 5, 7 and 9 are positioned horizontally, and the dies number 2, 4, 6, and 8 can be positioned vertically or horizontally according to the type of profile. After rough mills, a 130-tons cutter cuts off the tip of the bar in a normal condition or divides the bar into the small parts in an abnormal condition. There are seven final mills in the next station for final shaping operation of the bars. After final milling, there is a 63-tons cutter used to divide the bars into three parts. Then, the bars are transferred to a cooling channel and the finishing station with two parallel machines. Bars are transferred to a 630-tone cold cutter that is used to divide bars into 12-m profiles. Then, they are transferred to the inspection section and are weighted, labeled and moved to the storage. The parts that pass the inspection are moved to the packing station composed of two parallel machines. The existence of two parallel finishing and packing machines has created two left and right lines from the beginning of the finishing station. Fig. 7 shows the overview of the rolling mill system.

The limitations and constraints were identified as scraps, random breakdowns of machines and equipment and layout. It is impossible to change the layout of the present heavy rolling mill system, because all stations are attached to each other and the cost of detaching is too high. Moreover, no additional resources could be added to the line. Also, the generation of scraps and random breakdowns are inevitable because of the structure of such systems. Interacting systems are casting workshop and final storage.

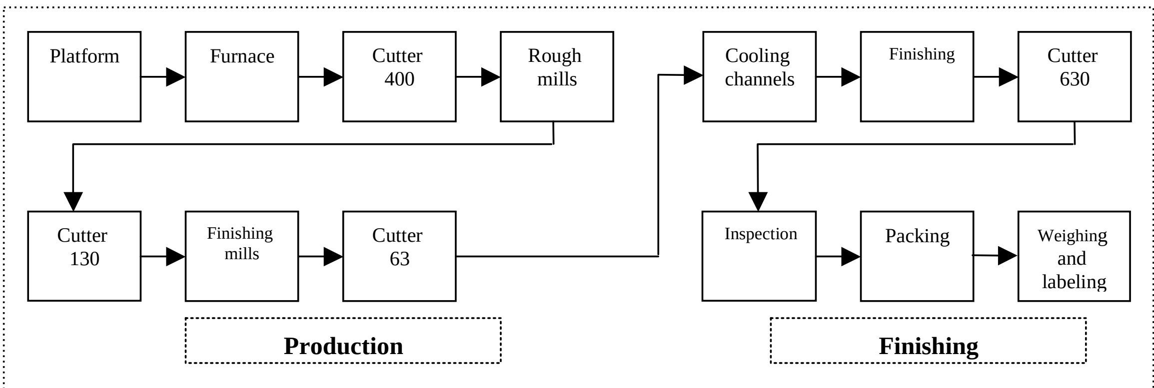

Fig. 7. The overview of the heavy rolling mill system.

Table 3
Network models of the heavy rolling mill workshop

Order	Code	Network definition
1	NAV-N1	From the arrival of steel-bars to the end of finishing station
2	NAV-N2	From the end of the finishing to the end of the right line (profile 14)
3	NAV-N3	From the end of the finishing to the end of the left line (profile 14)
4	NAV-N4	From the end of the finishing to the end of right line (profile 16)
5	NAV-N5	From the end of the finishing to the end of left line (profile 16)
6	N-TP1-M	The mechanism to replace profiles
7	NTAM1	Repair and maintenance of platform, furnace, 130-tons cutter & mills
8	NTAM2	Repair and maintenance of 63-tons cutter
9	NTAM3	Repair and maintenance of the cooling channel & finishing
10	NTAM4	Repair and maintenance of the inspection & 630-tons cutter
11	NTAM5	Repair and maintenance of the packing & weighing & labeling
12	NTAMA	Major maintenance
13	RNAV	Defined resources in the above networks 1 to 12

4.1. Integrated simulation

The operation of the existing rolling mill line is very similar to a JIT production model. Furthermore, if the rolling mill line is divided into storage, furnace, finishing, cutting and inspection departments, the operation of each part will depend on the last and the next parts. Therefore, the integrated simulation model has been built according to the JIT logic of the actual system. However, it seems that the framework of this study may further improve the current JIT operation of the rolling mill.

Visual SLAM language was used to build the integrated simulation model. In order to simplify and integrate the model and increase its flexibility, it is made of 13 different networks, and each network represents an aspect of the production process. The integrated simulation model contains all detailed operations and considers interaction with casting workshop and final storage (interacting systems). The reader should note that the integrated simulation modeling is a pre-requirement for development of the practical optimum JIT design.

Table 3 shows the list of these networks and their functions. Maintenance networks are designed to define the downtimes caused by random failures and preventive maintenance. In each of these networks, an entity is created and the characteristics of the first downtime are assigned to it as attributes. These characteristics include the failure time and its duration. Then, the entity makes the station unavailable randomly, and after the failure period, it makes the station available again. Afterwards, the entity gets next failure characteristics and starts a new loop (Azadeh, 2000; Sakkaki, 2000).

4.2. Analysis of variance

Two performance measures were chosen to examine the validation of the simulation model: (1) the average daily throughput of the furnace, and (2) monthly production rate of the line. Two main reasons support these criteria, which are significance and measurability. Moreover, the production rate of the rolling mill line and furnace are the most important criteria in evaluation of this system. In addition, the above performance measures can be easily measured in both the real system and simulation model.

To evaluate the furnace's throughput, the simulation model was run for 5 days and replicated 12 times. The simulation run time is measured in minutes and therefore, one working day is equivalent as 1440 min. It should be noted that the steady state was evaluated by method of replication by $\bar{x}(i) \pm t_{1-\alpha/2,i-1}(S(i)/\sqrt{i})$ where $\bar{x}(i)$ and $S(i)$ are the mean and standard deviation of production rate for $i=1,2,3,\ldots$ representing 15, 30, 45, … min cycles, respectively. Furthermore, with $i \cong 12$ (180 min), the transient state approximately ends because confidence intervals from then on overlap significantly. Moreover, transient state was deleted from simulation analysis. Performance measures for the two systems were examined by ANOVA. The required sample size was identified by operating characteristics curve method as $n=10$. First, it was examined the equality of variance of $H_o: \sigma_1^2 = \sigma_2^2$ by F-test. Because the variances of the two treatments were proven to be statistically the same at $\alpha=0.05$, the standard t-test was conducted to examine the equality of the means (H_o: $\mu_1 = \mu_2$). The test has proved the statistical similarity

Table 4
The results of ANOVA for the daily throughput of the furnace

	n	Average throughput rate (tons) in 5 days	Standard deviation	95% Confidence interval	t-Test: H_0: $\mu_1=\mu_2$
Rolling mill	11	4348.00	278.17	4158.28, 4537.72	Accept H_0 at $\alpha=0.05$
Simulation	12	4346.67	211.25	4210.80, 4482.54	

Table 5
The results of ANOVA for the monthly production rate of the rolling mill

	n	Average monthly production rate (tons)	Ratio of variances	t-Statistic	t-Test: H_0: $\mu_1=\mu_2$
Rolling Mill	6	79,526.8	0.174	1.138	Accept H_0 at $\alpha=0.05$
Simulation	6	84,593.9			

between the model and the heavy rolling mill system. Furthermore, from the t-test and F-test it is concluded that the throughput of furnace for the rolling mill system and simulation model are statistically equal at $\alpha=0.05$. The same procedure was used for the second performance measure or monthly production rate. Moreover, the transient state has been deleted from simulation analysis by method of replication. The required sample size was identified by operating characteristics curve as $n=5$. The simulation model was replicated six times to evaluate the monthly production rate of the line. Hence, from the t-test and F-test, it is concluded that the average monthly production rates of the rolling mill and simulation model are statistically equal at $\alpha=0.05$. The results of ANOVA with respect to the two performance measures for the actual system and simulation model are shown in Tables 4 and 5.

4.3. JIT design

The production managers verified and accredited the results and outputs of the integrated simulation model discussed in previous section. By referring to Fig. 1 and because the existing system is a typical JIT system, prospective bottlenecks if any must be identified. Therefore, bottleneck analysis and line balancing techniques are used to show how the integrated approach of this study would even improve a typical JIT by shifting it into a practical optimum JIT system. The practical optimum JIT approach identifies an alternative, which optimizes the line without any additional resources. Moreover, due to layout and limitations of the line, no additional resource could be added to it. The simulation model was run for a period of 6 months and the conditions of workstations were monitored by referring to the simulation outputs. The percent of idleness for the most important stations are shown in Table 6. Since it was found that the furnace is the most critical workstation in the workshop, its condition was further analyzed.

The function of furnace station is heating the steal bars to the appropriate temperature. Sine the milling process can only be performed on the heated bars; in the ideal condition, the furnace should always be ready to feed the line. The simulation results showed that in 48.5% of the time, the furnace is not ready to feed the line because it is either cold (shortage of its capacity: 16.8%), faces with various failures (15.6%), waiting for steal-bars (12.6%) or could not feed the line (cooling channel is full: 3.5%). Therefore, it is identified that the furnace cannot feed the line properly mainly because of its capacity. Furthermore, to reach a practical JIT production line the capacity of this station should be increased to an optimum level. Increasing the capacity of the furnace is also practical and allowable by the system because a new one may easily replace it. In order to determine the optimum capacity of the furnace, the simulation model was run with different capacities and the results showed that increasing the furnace capacity up to 250 ton/h would have a positive effect on the production rate. However, after 250 ton/h, the production rate remains almost constant. Therefore, increasing the furnace capacity to more than 250 ton/h does not have logical and economic justification. Table 7 tabulates the line's production rate with different furnace capacities. In fact, with an ideal

Table 6
The comparison of idleness in major workstations of the rolling mill system

Station	Crane for storage	Furnace	Finishing	Cutter	Inspection	Packing	Crane for packing
Idleness (%)	58.00	31.70	52.90	42.990	51.73	37.00	55.00

Table 7
The sensitivity of furnace capacity versus daily production rate of the line

Furnace's capacity (ton/h)	150	180	200	220	250	More than 250
Monthly production rate (ton)	84,593.9	112,936.9	116,261.8	120,603.2	123,100.4	About 123,200

furnace (250 ton/h), the monthly production rate increases to about 123,000 ton or 52% increase in the throughput of the line would be observed.

The practical optimum JIT would even be more improved if next bottlenecks were identified. Furthermore, to identify the next bottleneck, the model was run 5 days and replicated five times and the results were analyzed. In the first attempt, the furnace capacity is supposed to be unlimited. In this case, it was expected that the line would become fully utilized. However, the simulation results showed 17.9% of idle time for the furnace. This idle time is caused by random breakdowns in the line and the capacity of the cooling channels. However, random breakdowns are inevitable and capacity of the cooling channel could not be increased due to layout limitations and several issues within the system. Even if the furnace is assumed heated and ready and there are no breakdowns in the line the packing station would be the next bottleneck. Furthermore, in the similar fashion the cutter and inspection would be the next bottlenecks. However, defusing random breakdowns in the system is impractical and impossible. In addition, the layout of the line would not allow any changes in packing and cutter stations. Therefore, to reach a practical optimum JIT design, the capacity of the furnace should be increased to about 250 ton/h. The management accredited this change and they are in the process of deploying the practical optimum JIT design.

4.4. JIT test and accreditation

ANOVA is used to evaluate the effects of the optimum JIT design. Production rate and the throughput of the furnace are the two performance measures considered to foresee the effects of the new JIT design. First, it is tested whether the main daily production rate has the same behavior in actual system (τ_1), simulation model (τ_2) and the JIT design (τ_3). Furthermore, it is tested whether the null hypothesis H_o: $\mu_1=\mu_2=\mu_3$ is accepted. It is concluded that the three treatments differ at $\alpha=0.05$. Furthermore, the least significant difference (LSD) method is used to compare the pairs of treatment means μ_1, μ_2 and μ_3. That is H_o: $\mu_i=\mu_j$ for all $i\neq j$. The results of LSD revealed that at $\alpha=0.05$ $\mu_1=\mu_2$; $\mu_3>\mu_2$; $\mu_3>\mu_1$ and hence treatment 3 (the JIT design) produces a significantly greater daily production rate than other treatments. The practical optimum JIT design is also superior to the actual system and simulation model with respect to the throughput of the furnace. The advantage of the practical optimum JIT design with respect to throughput of the furnace is shown in Fig. 8.

Another method of increasing the throughput of the line is through development of a JIT between the rolling mill and casting workshops. Feeding the heated steel-bars directly from the casting to the furnace causes improvement of the line's throughput (12.6% improvement in furnace utilization). However, the proposed JIT feature is impractical at this time because of poor design and layout and the management is considering it as one of the future plans. However, to develop a practical optimum JIT between casting and milling workshop the optimum capacity of storage facility of milling line needs to be evaluated. Two different aspects should be considered to review such problems. First, the storage capacity should be large enough to support production changes or demands in the shop. On the other hand, it should not trap a large amount of investment. The simulation was run several times to estimate the average and the standard deviation of the required steel-bars in the storage. According to these values and a $(1-\alpha)$ percentile,

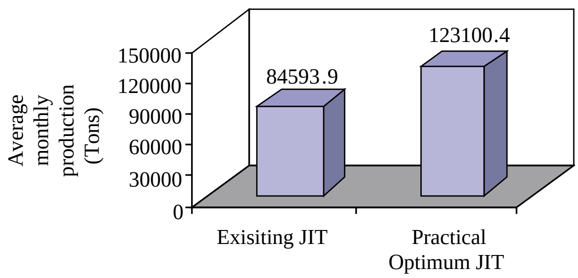

Fig. 8. Average monthly production rate of existing system versus practical optimum JIT system.

the optimum capacity of the steel-bars storage is then estimated. Furthermore, if β, μ, σ, and $\mu_{\max}$ are defined as safety stock, average and standard deviation and maximum monthly demand of the steel-bars in the workshop, respectively, then the optimum capacity of the steel-bars storage ($\tilde{A}$) is estimated as follows:

$$\beta = \mu_{\max} - \mu = Z_{a/2}\sigma \tag{1}$$

$$\tilde{A} = \beta + \mu \tag{2}$$

Therefore, there needs to be an average of $\tilde{A}$ steel-bars in the storage area so that in $(1-\alpha)$ percent of the time the shop would not face a shortage. In the above expression, $Z_{\alpha/2}$ is the normal deviate at α level of significance. Consequently, a practical optimum JIT between the two workshops would be established if there is an average of $\tilde{A}$ steel-bars in the storage facility of milling line.

5. Significance

This study presents an integrated framework for development of the practical optimum JIT design for dynamic production systems. It has been shown that conventional (theoretical) JIT approach is applicable to static rather than dynamic production systems. The distinct feature of this study is accomplished by integration of computer simulation, analysis of variance and dynamic behavior modeling of the actual system. Consequently, the practical optimum JIT design is practical rather than theoretical because it considers dynamic behavior and limitations of the system being studied. In addition, it may be deployed in the actual dynamic system because it is validated and verified by analysis of variance. The practical optimum JIT approach locates the best-fitted JIT design for the dynamic systems by an integrated mechanism. It considers system's limitations and all endogenous and exogenous factors affecting the dynamic systems. Moreover, it is practical and may be implemented in the dynamic system being studied.

6. Conclusion

This study presented an integrated framework for development of the practical optimum JIT design for dynamic production systems. Several factors must be noted to accomplish a practical optimum JIT design through simulation. First, all detailed operations, processes and activities of the system being studied including interacting systems, repairs, maintenance and inspections must be considered and modeled. Second, limitation, constraints, and dynamic behavior of the system being studied must be considered when designing a practical optimum JIT design. Third, an integrated simulation approach to problems of dynamic production systems must be incorporated. The distinct feature of the prescribed approach is accomplished by integration of computer simulation, ANOVA, and dynamic behavior modeling of the actual system. Consequently, the practical optimum JIT design is practical rather than theoretical because it considers dynamic behavior and limitations of the system being studied. In addition, it may be deployed in the actual dynamic system because it is validated and verified through analysis of variance. The advantages of the practical optimum JIT approach is as follows:

- It locates the best-fitted practical JIT design for the dynamic systems by an integrated mechanism.
- It considers system's limitations and constraints.
- It is well suited for dynamic production systems. It is practical and may be implemented in the system being studied.
- It considers all endogenous and exogenous factors affecting system being studied.

In summary, the following steps must be accomplished to develop the practical optimum JIT design for dynamic production systems:

- Develop detailed conceptual models of the system
    - Operations
    - Maintenance and repair
    - Quality control, inspection and defectives
    - Interacting systems

- Develop integrated simulation model
- Verify and validate simulation model by ANOVA
    - Independent *t*-test and *F*-test
- Accredit simulation model
    - Management and experts feedback
- Define system limitations and constraints for practical JIT model
    - Constraints on layout
    - Production capacity
    - Machine and workforce limitations
- Develop the practical optimum JIT simulation model
    - Utilize kanban-based production modeling techniques for non-JIT systems
    - Utilize bottleneck analysis and line balancing techniques for JIT systems
- Verify advantages of the practical JIT design by ANOVA
    - *F*-test
    - Least significant differences method
    - Duncan' s multiple range test
- Accredit the practical optimum JIT design
    - Management and experts feedbacks

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Erratum

Erratum to "Design of practical optimum JIT systems by integration of computer simulation and analysis of variance" [Computers & Industrial Engineering Volume (49/4) 504–519]

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The publisher regrets that when the above paper was published Baharak Beydokhti's name was incorrectly spelt. It has now been reproduced correctly above.

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