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Using Simulation-Based Optimization to Improve Performance At a Tire Manufacturing Company

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ABSTRACT
In this paper, a simulation optimization-based decision support tool has been developed to study the capacity enhancement scenarios in a tire manufacturing company located in Iran. This company is experiencing challenges in synchronizing production output with customer demand causing an unbalanced work-in-process (WIP) inventory distribution throughout the tire manufacturing process. However, a new opportunity to increase the supplying of raw materials by fifty percent and increase the expected growth in market demand, necessitate this study of the current company situation. This research supported by the company, is to analyze whether the ongoing production logistics system can respond to the increased market demand, considering the raw material expansion. Implementation of a proposed hybrid push/pull production control strategy, together with the facility capacity enhancement options in bottleneck stations and/or heterogeneous lines within the plant, are investigated by the proposed simulation optimization methodology.

Keywords: System simulation, Tire manufacturing Multi-criteria decision analysis

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1. INTRODUCTION

One of the most important tire manufacturing companies in Iran commands a critical share in supplying the tire needs of the country's automotive industries. However, this company is experiencing challenges in synchronizing production output with customer demand, causing an unbalanced work-in-process (WIP) inventory distribution throughout the tire manufacturing process. This lack of synchronization and resulting unbalanced WIP inventory distribution, causes unexpected machine idle time, in particular at the bottleneck workstation. This is due to the lack of downstream work-in-process (WIP) inventory in the intermediate buffer locations. In addition, this lack of synchronization causes finite intermediate storage spaces to remain at-capacity, causing expected machine blockage, preventing the downstream flow of WIP inventory.

Furthermore, the opportunity to increase the supply of raw materials by fifty percent and increase the expected growth in market demand necessitate this study. This research, supported by the company, is to analyze whether the ongoing production logistics system can respond to the increased market demand, considering the raw material expansion. The interactive nature of the effective factors in such a complex production logistics system, for example stochastic parameters, such as process times, market demand and resource failure, make it difficult to study the problem analytically. Trial and error methods, with a real system, is an expensive, destructive way and inapplicable. So, simulation modeling methodology lets a what-if analysis study of the current system, be pursued without disruptions on the real case. Finding the bottlenecks and improving scenarios are proposed and studied through a verified and validated simulation model of the system. A combination of the following approaches are pursued for developing improving scenarios:

- These problems may be effectively addressed using a well-designed integrated production and inventory control policy, based on Lean manufacturing principles. In this paper, a proposed hybrid pull/push production control strategy, that uses a Kanban and (r, R)-based inventory replenishment approach is explored, in order to analyze space enhancement necessities, to alleviate the deficiencies caused by finite intermediate storage spaces.
- The lack of synchronization and resulting unbalanced WIP inventory may be alleviated by harmonizing production lines, reaching the tire manufacturing station (Figure 1). Finding bottleneck stations and improving the capacity of the facilities by replacing/new technologies, may be another way to prepare the company to handle the market growth considering the opportunity to supply more raw materials.

Problems related to the production logistics and/or operational issues studied using simulation modeling and analysis methodology are the most important researches we focus in our review. Baykoc and Erol[1] studied the performance of a multi-item, multi-line, multi-stage just in time (JIT) system, to show how this system reacts under different factor settings in a stochastic environment, using DES modeling as a 'what if' analysis tool. Using simulation modeling, Huang et al.[2] compared the CONWIP system and the original control system for the four situations in a cold rolling plant. They concluded that the CONWIP production control system is very efficient for the production and inventory control of semi-continuous manufacturing.

Simulation modeling has been widely and successfully used to explore and evaluate the performance of various production philosophies and inventory control policies. For instance, Lee and Farahmand[3] use simulation modeling to study implementation of (r, R) inventory replenishment management system, integrated with transportation scheduling strategies in the context of logistic network management. Brito et al.[4] developed a decision support tool using discrete event simulation integrated with multi-criteria decision analysis, to study the strategic decisions regarding the planning and sizing of the logistics and production elements of a steel plant. Sharda and Bury[5] analyze the bottleneck at a chemical plant using discrete event simulation. Bernard and Tseng[6] and Schroer and Tseng[7] represent a new approach in simulating complex manufacturing systems that is based on developing several general-purpose generators for an assembly station, a manufacturing cell and an inventory transfer function that are linked to create a complex manufacturing system. Hao and Shen[8] propose a hybrid simulation approach, using both discrete event and agent-based simulation modeling technologies, to study a Kanban-based material handling system in an assembly line. The efficiency of using simulation modeling tools to visualize, analyze and optimize complex production systems with a reasonable amount of time and investment is critical. This has the potential satisfactory outcome using simulation to analyze the implementation of different production philosophies.[9,10]

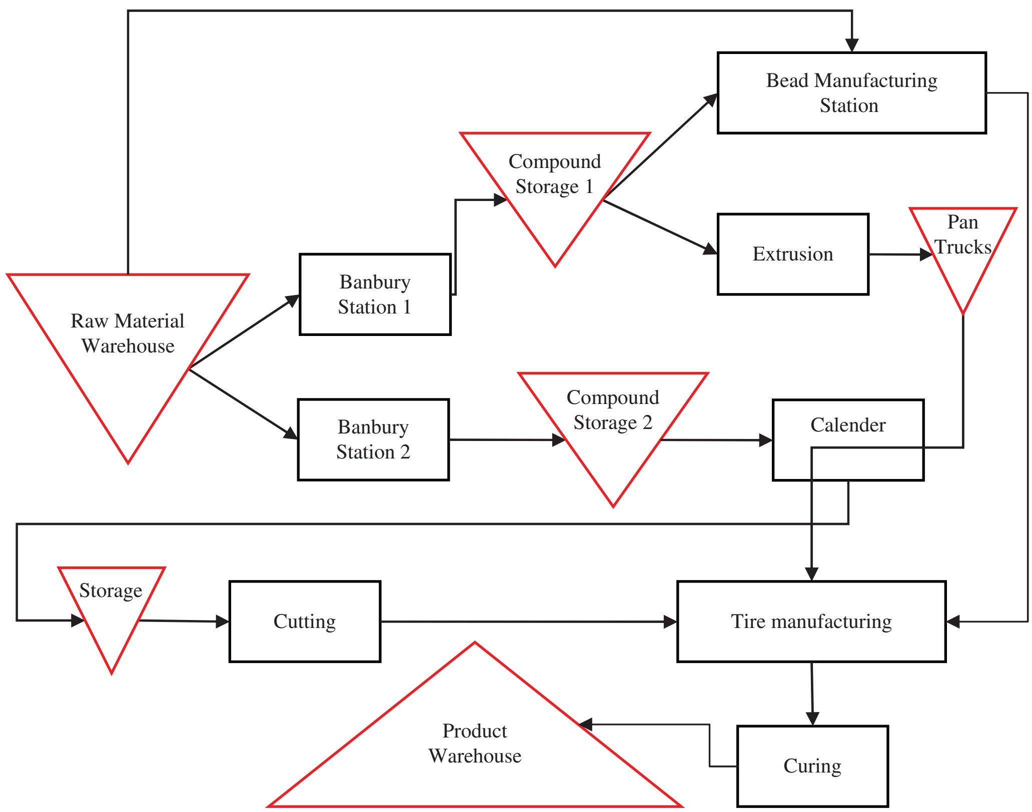

Figure 1. The process of tire manufacturing, under the current push production control strategy.

The Smith[11] and Sun et al.[12] surveys include the use of simulation for manufacturing system design and operation. Unlike the literature studies in manufacturing logistics problems, the mixed discrete/continuous nature of the tire manufacturing processes differentiates such a system simulation modeling study. The modeling approach of such continuous processes in the context of a discrete event simulation model is itself a creative use of tools embedded in Arena software.

Complexity of the tire manufacturing procedure comes from the interactive decision variables and the stochasticity in procedure time, demands and failure. This makes it difficult to study this problem mathematically. The discrete and continuous nature of the tire manufacturing procedure needs an inventive modeling approach to mimic the system under study. More specifically, developing a step-by-step simulation optimization methodology, customized with company problems, together with the inventive simulation modeling approach is a duple, which defines the contribution of this work through the literature. In this paper, a simulation-based optimization tool is developed, to support decisions about capacity enhancement and challenges in synchronizing production output with customer demand. Studying the causes of inefficiencies, the developed simulation-based optimization decision support tool is used to analyze improving scenarios and propose alternatives to the decision makers. The empirical nature of the work, together with the proposed research methodology, is a new opportunity for the use of simulation optimization methodology in the context of decision models, in tire manufacturing decisions.

This paper is organized as follows; Section 2, the tire manufacturing process and the current push production mechanism is described; Section 3, the simulation optimization decision support tool, which is used to implement and analyze the proposed control strategy for intermediate storage space enhancement decisions, is presented; Section 4, looks at simulation modeling and analysis; Section 5 consists of improving scenarios; Section 6, the results of the proposed scenarios are shown; Section 7, the conclusions and recommendations are provided.

2. PROBLEM DESCRIPTION

2.1. The tire manufacturing process

The tire manufacturing process under study is at one of the most important tire manufacturing companies in Iran. This company produces approximately 30,000 tons per year, and is the primary supplier of the nation's automotive industry. As such, the company is capacity constrained and not market constrained. As shown in Figure 1, additive chemical materials, textile, wire and caoutchouc (i.e., rubber) are the main raw materials used to manufacture tires in the company. The rubber-based mixture is fed into a Banbury internal batch mixer. The output from the Banbury mixer is rubber layers, called a receiving compound, which is sent to the Extrusion station, Bead Manufacturing station and Calender station.

Wires in the Bead Manufacturing station are covered with the receiving compounds and sent to the Tire Manufacturing station. Textile raw materials at the Calender station are covered with compound layers and sent to the Cutting station. The most important role of the produced compound is its use in the Extrusion station to produce the tire layer, called the 'tread'. The materials in the Extrusion station, Bead Manufacturing station and Cutting station, are used in the Tire Manufacturing station to produce the raw tire, called the 'grain tire'. The produced grain tires are baked under pressure, and heated in the Curing station. The final products are called 'radial' or 'bias' tires, depending upon the desired product customization.

2.2. Current Production System

The current production control strategy in the manufacturing plant is a pure push approach. Under this pure push strategy, the tire final products are primarily manufactured to stock. Raw material, work-in-process inventory availability and finite intermediate storage capacity create starvation and blocking conditions at individual workstations. It is worth mentioning that, among the raw materials used in the subject process, the availability of the caoutchouc rubber material is relatively unpredictable. As shown in Figure 1, the Banbury mixer stations begin processing if there is sufficient caoutchouc available in the warehouse, and it stops processing when there is no space available in the compound storage buffer. The inverted triangles, in Figure 1, represent inventory storage locations. The Extrusion station begins processing if the available materials at the intermediate Compound Storage 1 location can support its production, and stops processing when there are no Pan trucks available to store its output. The Calender station begins processing if there is Compound Storage 2 inventory available, and stops processing when there is no space in the intermediate storage location between the Calender and Cutting stations. Finally, the Tire Manufacturing station requires a smooth flow of materials from the Cutting, Extrusion and Bead Manufacturing stations to allow for the desired synchronized flow of WIP inventory. Most importantly, tire production may stop at a station if there is no buffer space available between that and the next station to accommodate the output of that station. In the manufacturing process at the subject company, these finite buffer restrictions are as follows:

- Compound Storage 1 can accommodate at most 200 pallets of compounds from Banbury Mixer Station 1.
- Compound Storage 2 can accommodate at most 150 pallets of compounds from Banbury Mixer Station 2.
- There are, at most, 50 Pan trucks available that can accommodate the tire treads produced at the Extrusion station.
- The intermediate buffer space between the Calender and Cutting stations can accommodate, at most, 50 rolls produced by the Calender station.

A new opportunity to increase the supply of raw materials by fifty percent, that was a problem in the past, and an expected growth in market demand that is not constrained, necessitate this study. Supported by the company, this research aims to analyze whether the ongoing production logistics system, considering the increase in raw material supplies, can respond to the increased market demand. In fact, the methodology, studied in Section 3, proposes to find out whether the current logistics production strategies and facilities at the company meet expectations, considering the opportunities made by the fifty percent increase in raw material availability.

3. THE PROPOSED METHODOLOGY

Our aim is to develop a methodology to implement the proposed hybrid Kanban and (r, R) production control and inventory replenishment strategy, together with facility capacity enhancement options in bottleneck stations and/or heterogeneous lines. Due to the sheer complexity of the problem and stochastic nature of the manufacturing processes, a simulation optimization methodology is used to evaluate the expected performance of hybrid production improvement strategy. First, a discrete event simulation model of the tire manufacturing process is constructed using Arena software.[13,14] Simulating the tire manufacturing company, the current system is studied in order to find potential causes of bottlenecks and unbalances. Then, improving hybrid scenarios are pursued and the results are listed, considering cost, throughput, sales, cycle time, customer waiting time and customer reneging, due to the unavailability of product. In the proposed simulation based optimization decision support tool, OptQuest optimization software is used to find the best values for the set of decision variables of the proposed hybrid strategy, i.e., x_1, x_2, x_3, and x_4. These represent enhancement decisions on intermediate storage spaces in order to facilitate the flow of material and eliminate waste caused by starvation, and R and r, which are the product warehouse inventory control parameters.

3.1. The simulation model

The complexities and uncertainties in real-world systems are the main reason that simulation is often used as a basis for handling decision problems associated with those systems. Simulation can be used to study system processes that are too complex to permit analytical model formulation and/or evaluation. Complexity of the problem and stochastic nature of the manufacturing processes satisfy the use of simulation modeling as a what-if analysis tool. To simulate the tire manufacturing company procedures, the following steps are used:[15]

(a) Conceptualization: defining the system, its objectives, constructing and validating the conceptual model of the system;
(b) Model development: constructing, verifying and validating the computer simulation model; and
(c) Analysis: setting the simulation run parameters, performing simulation production runs under different scenarios, and analyzing the simulation output results.

A discrete event simulation modeling approach is used to model the tire manufacturing processes, shown in Figure 1. Historical production data, obtained from the company, is used to validate the baseline model of its current pure push production control strategy. The most important performance measures such as production rate, customer satisfaction level, inventory related factors and cycle time were pursued to study the validation of the developed model. The model is run for one simulated year with 27 hours warm-up period.

3.2. Simulation-based optimization approach

The optimization of simulation models, often deals with the situation in which the interest is to find which, of a large number of sets of model specifications, lead to optimal output performance.[16] One popular method, to optimize simulated systems, uses metaheuristics. In this mechanism, a simulation model is treated as a black-box, i.e. only the inputs and outputs of the simulation model are observed. At each iteration, the metaheuristic optimizer chooses a set of values for input decision variables and uses the output (response) values, generated by the simulation model, to make decisions regarding the selection of the next set of decision variable values. The goal is to find the best values for the decision variables. In this study, OptQuest optimization software is used to find the optimal or near-optimal set of decision variables. OptQuest combines the metaheuristics of Tabu search, Scatter search and Neural networks into a single, composite search algorithm to identify new decision variable values.[16,17] It is important to note that simulation-based optimization approaches, which employ metaheuristic algorithms, do not guarantee finding the optimal solution.

The simulation-based optimization methodology used in this study is shown conceptually in Figure 2. Evaluation of the proposed improving scenarios, consisting of hybrid production control philosophy,

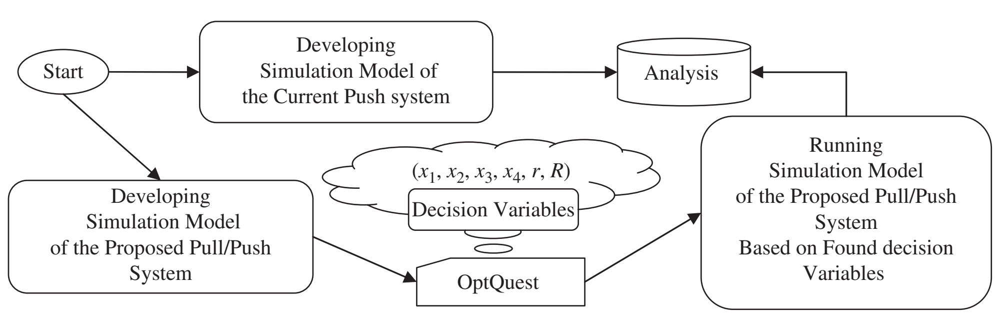

Figure 2. Proposed simulation optimization based decision support tool.

based on pull/push system using Kanban and (r, R) inventory replenishment strategy, and capacity enhancement decisions for production facilities, requires the defining of the model's decision variables x_1, x_2, x_3, and x_4. These represent enhancement decisions on intermediate storage spaces in order to facilitate the flow of material and eliminate wastes caused by starvation and (r, R), while considering the throughput of the company as an objective, and the company space limitations as constrained.

4. SYSTEM SIMULATION ANALYSIS

4.1. Simulation modeling

The conceptual model, which is planned (Figure 1) and validated by interactive discussions with experts at the company, is the basis of computer simulation model development in Arena software. The snapshot of the Arena modeling blocks is depicted in Figure 4. The next step is to input data to the model. Then, it is important to have pilot runs for checking the validity and verifiability of the developed computer simulation model. Finally, simulation run parameters, such as length of each run, length of the warm-up period and number of independent simulation runs, is set.

4.2. Input data

Historical data acquisition is crucial because the results and findings of a simulation study, in the best case, are as good as the input information. The nature of the problem necessitates using both historical data and interview techniques for the input data. The stochastic nature of the receiving demands, process times, failure occurrence in facilities, even minor variation in raw material delivery, are considered in this study.

4.3. Verification and validation

Verification is the task of answering the question, "did we build the model right?" Verification is concerned with building the model correctly, according to the conceptual model and its assumptions. In fact, the logic of the proposed model is examined through the conceptual model, depicted in Figure 1. Validation is the task of answering the question, "did we build the right model?" Absolute validation is usually impossible because the simulation is, at best, an approximation of the real system. The most definitive method is to compare the output data from the simulation, with the actual data from the existing system, using formal statistical analyses, such as confidence intervals. In the validation procedure, important performance measures, such as cycle time and throughput, are used as the bases for comparing the computer simulation results with the historical data of the company. In all cases there were no significant differences between results at a 95% confidence level.[18] We calculated the confidence intervals of the simulation outputs at 95% confidence level and compared them to the actual values, 30% of the data was retained for validation of the model. The comparison is summarized in Table 1. In these cases, the simulation result intervals (Avg. ± Half With) encompass the results of real system, with a little slip for average cycle time.

Table 1. Average cycle time and throughput in simulation model versus historical data of the real system.

Simulation model Avg. ± Half-with	Real system	Performance measure
7.55 ± 0.02	7.33	Avg. Cycle time (hour)
285,944 ± 1,557	286,831	Avg. Throughput (Tire Unit)

4.4. Run parameters

The model is run for one simulated year, 24-hour working day, with 27 hours warm-up period. This is because the overall scope of the real system for financial, technical and production logistics decisions is one year, and the plotted work in process of materials in the company over time shows that the initial variations are stabilized after 27 hours from the starting point (Figure 3). The number of independent simulation runs adjusted to 20, since the average of important performance measures do not change significantly after 20 replications.

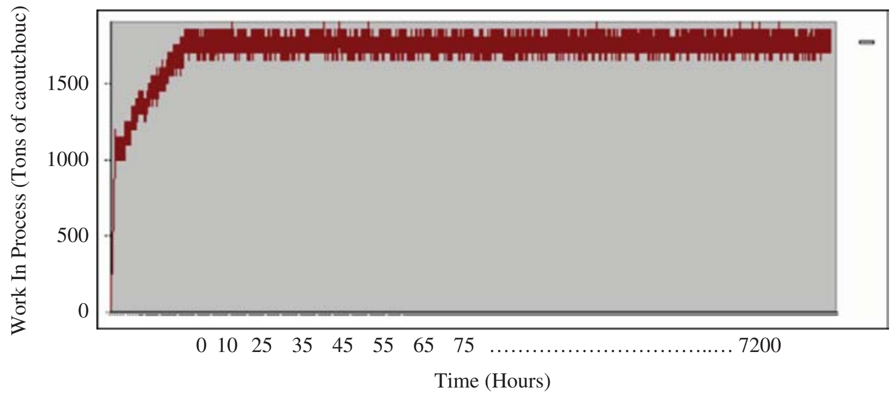

Figure 3. Determining the length of warm-up period tracing work in process in the plant.

4.5 Results analysis

The current system is studied through the developed simulation model. The capacity of the existing system, with the new opportunity to increase supply of raw materials by fifty percent and expected growth in market demand, is evaluated (Table 2).

Table 2. Simulation model results of the current system (significance level $\alpha = 0.05$).

			Customer satisfaction factors		
System	Avg. Throughput (#) ± Half-with	Avg. Sales (#) ± Half-with	Avg. Cycle time(hour) ± Half-with	Avg. waiting time (hour) ± Half-with	Avg. Percent of reneging
Current	285944.50 ± 1557.24	266800.00 ± 6211.81	7.55 ± 0.02	540.87 ± 34.77	12%
New*	285841.00 ± 2145.26	2665200.00 ± 6084.31	7.56 ± 0.02	427.75 ± 42.73	43%

* New: Fifty percent increase in supply of raw materials and provisional fifty percent increase in customer arrival frequency

Bottleneck stations and causes of unbalances are studied through the simulation model. Two approaches are followed to propose improving scenarios:

- In order to analyze space enhancement necessities to alleviate the deficiencies caused by finite intermediate storage spaces, a hybrid pull/push production control strategy that uses a Kanban and (r, R)-based inventory replenishment approach is explored.
- The lack of synchronization and resulting unbalanced WIP inventory may be alleviated by harmonizing production lines to the tire manufacturing station (Figure 1). Finding bottleneck stations and improving the capacity of the facilities by replacing/new technologies may be another way to prepare the company to handle the market growth, considering the opportunity to supply more raw materials. Output analysis identify Cutting, Calender and Extrusion as bottleneck stations, in the case of new opportunities causing a fifty percent increase in the supply of raw materials and a provisional fifty percent increase in customer arrival frequency (Table 3).

Table 3. Sources of the long lead time.

Avg. waiting time (hour)	Resource's queue/ Middle storage	Utilization	Resource
0.19	Banbury station 1	47%	Banbury 1
0.22	Banbury station 2	44%	Banbury 2
1.56	Bead station	37%	Bead Manufacturing
2.78	Compound storage 1_Extrude station	83%	Extrusion
1.22	Compound storage 2_Calender station_	88%	Calender
2.03	Storage_Cutting station_	87%	Cutter
0.87	Pan truck_Tire station	63%	Tire manufacturer
0.2	Curing station	55%	Curing

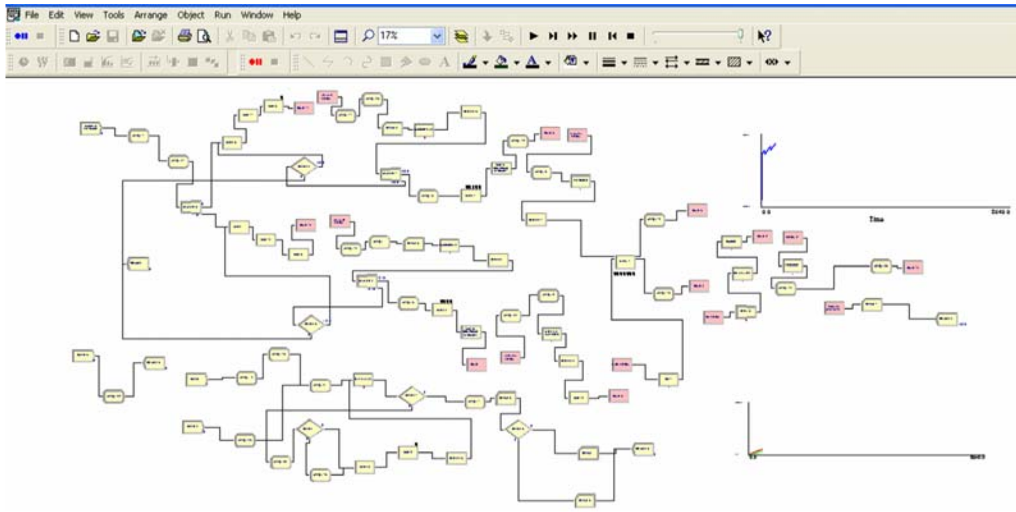

Figure 4. Snapshot of the Arena modeling blocks.

5. IMPROVING SCENARIOS

Taiichi Ohno, an engineer working for Toyota, theorized the Lean production philosophy as a method to avoid, eliminate or reduce waste, which is time, space or material used in an activity that does not directly contribute value to the finished product.[19] Koskela[20] outlines the key principles of Lean production as follows:

- Reduce the share of non value-adding activities;
- Increase output value through a systematic consideration of customer requirements;
- Reduce variability;
- Reduce lead/cycle time;
- Increase output flexibility;
- Balance flow improvement with conversion improvement; and
- Reduce inventory.

Long cycle times and unbalanced production rates relative to customer demands often occur. In addition, the push-based manufacture-to-stock production strategy, with finite intermediate storage space, causes unplanned stoppages in production due to the occurrence of machine starvation and blocking conditions. Implementing a hybrid pull/push production strategy using Kanban and (r, R) inventory replenishment moving towards a Lean-based production approach, should ameliorate the production performance at the company and act as a decision support tool for managers to readjust the intermediate storage spaces at the plant.

Figure 5 shows the proposed hybrid Kanban-based production control strategy. According to the proposed strategy, the Banbury Station 1 works if there is sufficient caoutchouc rubber material available at the Raw Material warehouse, compound quantity at the Compound Storage 1 (CS_1) is lower than or equal to x_1, and the station stop processing when CS_1 is greater than x_1. Banbury Station 2 stops processing when Compound Storage 2 (CS_2) is greater than x_2. The Extrusion station requests material to work only if the Pan truck stock is equal or lower than x_3. Finally, the Calender station stops work if the intermediate buffer is greater than x_4. These processing stop and start conditions are signaled using Kanban cards. More importantly, the cards are sent to signal the stop situation. In Figure 5, PT denotes the number of Pan trucks that are at capacity. The current number of rolls produced in the Calender station in the middle storage is denoted by S. An (r, R) inventory replenishment policy for the final product warehouse is used to signal the start and stop conditions at the Cutting and Bead manufacturing stations.

The final product inventory level is updated whenever a demand is sent to a customer. In fact, in the proposed strategy, new maximum levels for the intermediate storage locations are imposed to regulate the WIP inventory flow through the manufacturing facility. It is worth mentioning that the applicability of the proposed hybrid pull/push system in the company has been well received by key experts who are members of Production Planning and Manufacturing Engineering Departments at the subject company.

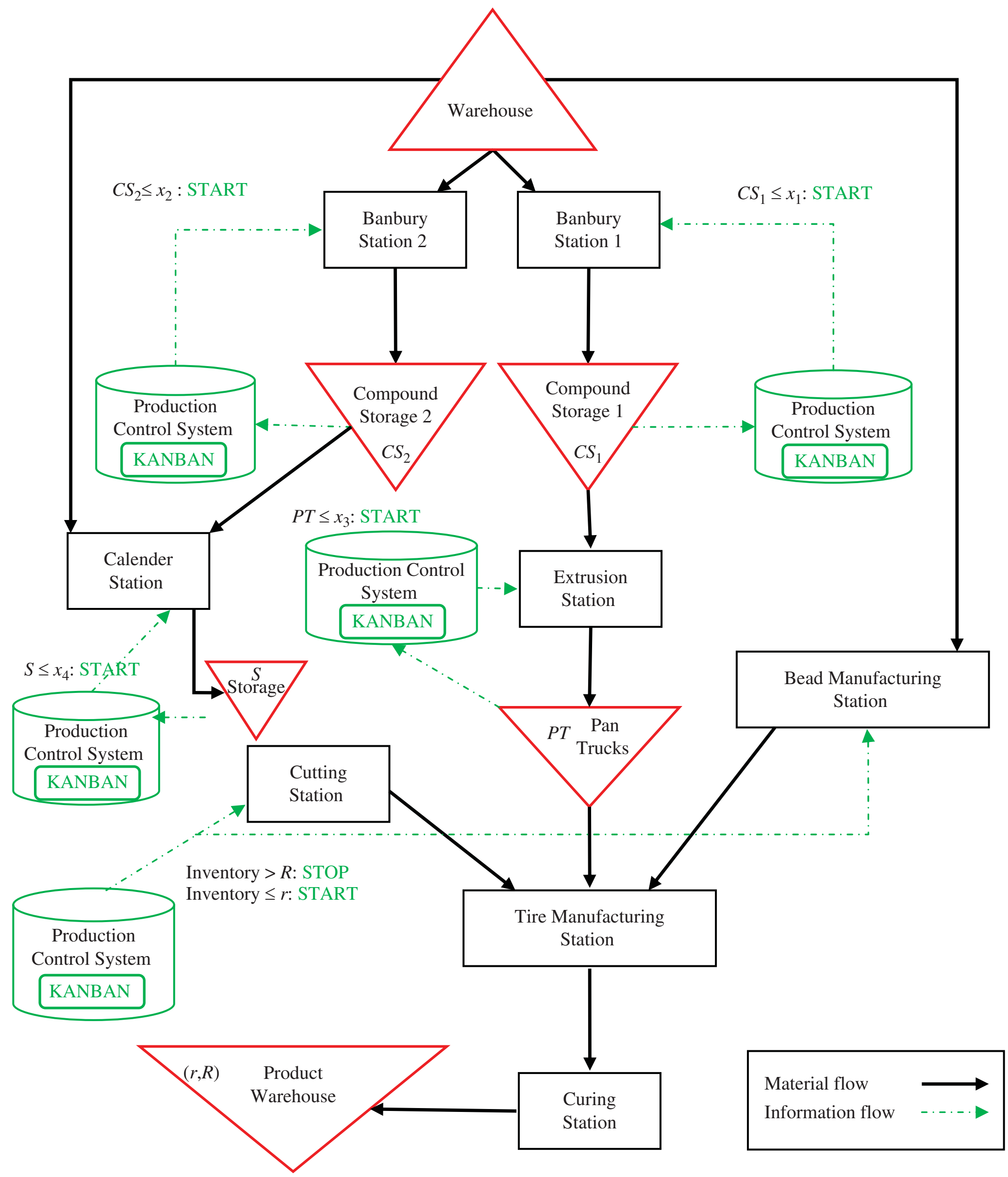

Figure 5. Proposed hybrid Kanban and (*r*, *R*) production control strategy.

The proposed improving scenarios are as follows:

Scenario 1: Options for extension of intermediate storage spaces in the context of the proposed hybrid Kanban and (*r*, *R*) production control strategy are analyzed through the developed simulation based optimization decision support tool considering the throughput of the company as an objective, and the company space limitations as constrain (Figure 2).
Scenario 2: Update the Extrusion station technologies, which will double the capacity of this station in comparison with the current situation.
Scenario 3: Update the Cutting station technologies, which increases the capacity of the cutter by three times in comparison with the current facility.
Scenario 4: Update the Calender station technologies, which doubles the capacity of this station in comparison with the current situation.
Scenario 5: Implementing a hybrid scenario by pursuing Scenario 1, in the case of executing scenario 2.
Scenario 6: Implementing a hybrid scenario by pursuing Scenario 1, in the case of executing scenario 3 and Scenario 2.

Scenario 7: Implementing a hybrid scenario by pursuing Scenario 1, in the case of executing Scenario 2 and Scenario 4.
Scenario 8: Implementing a hybrid scenario by pursuing Scenario 1, in the case of executing Scenario 2, Scenario 3 and Scenario 4.

It is worth mentioning that the initial analysis shows that Scenario 2 and Scenario 3 cannot improve the system performance, because unbalances occurred in the production lines and reach the Tire Manufacturing Station.

Performance measures average waiting time and percentage of reneging customers, translated to the average sales of the company. This company, generally, deals with demands in big batches that normal lead times should be 20-23 days. However, there are some uncertain behaviors in customer parts that lead to reneging, which is simulated with different probabilities in waiting limits for some customers. Furthermore, average cycle time, as a remark for smoothness of the production system and productivity of the resources, is used in our comparisons.

6. RESULTS AND DISCUSSION

Fixing the input data of the system, such as fifty percent incensement in raw material, around fifty percent growth in the frequency of the market demand, process times, failure rates and transportation times, the results of the plant, in cases of implemented scenarios, is analyzed. Finding the decision variables x_1, x_2, x_3, x_4 and (r, R) with the support of developed decision making methodology, the proposed push/pull production based control strategy using Kanban and (r, R) inventory replenishment, has been implemented using discrete event system simulation model in order to investigate the implementation of the Scenario 1 considering the company space limitation.

Table 4 shows that implementing the proposed hybrid pull/push system, together with the scenarios related to the line balancing and bottleneck eliminations such as Scenario 2, helps the company to improve the throughput, decrease customer reneging and, consequently, decrease the sales of the company.

Though the results documented in Table 4 signal the use of multi criteria decision making models to rank the scenarios in order to be implemented in the company, the executive managers, due to budget constraint, insist on implementing the improving scenario which costs between 100 to 150 monetary units and has the most sales, which is the scenario 1. They argued that implementing scenario 1, in comparison with scenarios 2, 3 and 4, is the priority becuase it could be the base of more effective scenarios, such as Scenario 5, Scenario 6, Scenario 7, and Scenario 8, in the case of future budget availability.

7. CONCLUSIONS

In this research, the current production logistics activities at a tire manufacturing company in Iran are studied. A new opportunity to increase the supply of raw materials by fifty percent and an expected growth in market demand necessitate the study of the current situation of the company. This research is supported by the company, and aims to analyze whether the ongoing production logistics system can respond to the increased market demand, considering the raw material expansion. The complexity and discrete-continuous nature of the system under study needs an inventive simulation modeling approach and a homogenous simulation-optimization platform to study the company problems.

Analysis of the current system, with the new opportunities in providing more raw materials and having market demand expansions, prove the system inefficiencies to handle new situation. A combination of the following approaches are pursued for developing improving scenarios:

- The proposed hybrid pull/push production control strategy, that uses a Kanban and (r, R)-based inventory replenishment approach, is explored in order to analyze space enhancement necessities to alleviate the deficiencies caused by finite intermediate storage spaces.
- Finding bottleneck stations and improving the capacity of the facilities by replacing/new technologies may be another way to prepare the company to handle the market growth, considering the opportunity to supply more raw materials.

Scenario analysis in Section 6 shows that options, including the intermediate storage space enhancement together with the updating technologies at Calendar and Extrusion stations, can be a real scenario for the improvement of the company. The ranking of the improving scenarios needs

Table 4. Analysis results of the proposed scenarios (significance level $\alpha = 0.05$).

Scenarios for the New situation	Avg. Throughput (#) ± Half-with	Avg. Sales (#) ± Half-with	Avg. Cycle time (hour) ± Half-with	Customer satisfaction factors: Avg. waiting time (hour) Half-with	Customer satisfaction factors: Avg. Percent of reneging	OptQuest The extension of intermediate storage (St. Unite in the plant**)	Expenditure (Cost Unit)
Scen. 1	316285.00 ± 2159.76	297900.00 ± 5333.75	7.291 ± 0.08	500.69 ± 32.75	20%	x1=100, x2 = 0, x3 = 10, x4 = 35, r = 45000, R = 90000	130
Scen. 2	292539.00 ± 1758.58	271300.00 ± 4568.15	5.47 ± 0.02	459.90 ± 38.57	24%	–	70
Scen. 3	286757.50 ± 1865.69	270600.00 ± 5036.95	5.55 ± 0.02	454.01 ± 44.99	27%	–	50
Scen. 4	286180.00 ± 1928.79	266100.00 ± 5022.05	5.56 ± 0.02	452.44 ± 33.40	25%	–	90
Scen. 5	339403.50 ± 2683.76	318300.00 ± 5732.12	6.07 ± 0.08	518.31 ± 29.48	16%	x1=0, x2 = 100, x3 = 40, x4 = 20, r = 40000, R = 90000	200
Scen. 6	344582.00 ± 2477.04	323100.00 ± 5789.75	4.82 ± 0.02	538.54 ± 30.81	18%	x1=00, x2 = 100, x3 = 10, x4 = 40, r = 40000, R = 70000	250
Scen. 7	366279.50 ± 2026.23	347700.00 ± 5366.50	2.89 ± 0.01	571.71 ± 21.95	11%	x1=140, x2 = 0, x3 = 0, x4 = 40, r = 45000, R = 90000	290
Scen. 8	358913.00 ± 2463.28	331400.00 ± 4916.50	4.62 ± 0.02	505.14 ± 26.64	17%	x1=100, x2 = 0,x3 = 0, x4 = 10, r = 40000, R = 90000	340

** St. Unite in the plant: The unit for expansion of space for each intermediate storage is a standard defined in the company.

implementation of MCDA techniques. However, in this study, due to the budget constraint, scenario 1 will be used in the plant. A new avenue to be followed is to do a sensitivity analysis of the system performance towards important variables, and finally define a set of vulnerability aspects of the system. In a practical view point, the computer simulation model developed in this research provides a potential platform for system analysts in this company to study the possibility to manufacture other kinds of products in the tire families, since it has been shown that there are idle times which can be covered by new products, in the case of adding machines in bottlenecks or other practical devises.

BIBLIOGRAPHICAL NOTES

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