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INTEGRATED ANALYSIS METHOD: VISUAL MODELLING, SIMULATION, DIAGNOSIS AND REDUCTION FOR BOTTLENECK PROCESSES OF PRODUCTION LINES[*]

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Abstract– An integrated analysis methodology composed of four components: visual modelling, simulation, diagnosis and reduction of bottleneck processes of production lines has been presented in this paper. Various components are integrated to analyze the bottleneck process of production lines including process parameters and production planning. In this method, 3D dynamic modelling, which includes hysical and logical modelling, is the basis to define the entire layout, the visual simulation and the diagnosis of the production line. Simulation is the most crucial part for acquiring many data to quickly diagnose the bottleneck processes in the production line. The reducing method of bottleneck processes, which includes two anti-bottleneck ways, local expansion and bypass reducing, is the premise to redesign the production line. Because the result of each following steps can be fed back to the previous steps, the bottleneck processes of the production line can be quickly diagnosed and reduced. With this method, an existing production line is virtually modelled in a computer, simulated and analyzed. Based on the simulation results, the bottleneck processes are quickly diagnosed. Some ways for reducing bottleneck processes are proposed and their simulation results are quickly achieved in the simulation environment. Results reveal that the integrated analysis method can integrate the following functions: modelling, simulation, bottleneck diagnosis and reduction of production lines, and as a result quickly diagnose the bottleneck processes, redesign the production line, and provide a preanalysis tool for the production plan.

Keywords– Visual modelling, simulation, diagnosis, redesign, integrated design, production line

1. INTRODUCTION

With the increasing competition in the world, design and analysis of a production line, especially in conditions of changeable production assortment and customer demand, requires the assistance of computer simulation and modelling technologies. With those tools, the performance of the production line can be predicted before it is implemented to shave time off production cycles, ramp up production, and speed time to market [1, 2].

Unless facilities have infinite capacity, or the process flow is matched perfectly at each step for a production line, it has at least one bottleneck process. Because bottleneck processes influence the throughput of the production line, it is important to quickly diagnose those bottleneck processes before taking correct measures for the rational production plan and optimal selection of equipment resources, as well as reduction workpiece-in-process (WIP). Meanwhile, the in-time diagnoses are extremely helpful to improve the throughput, lower consumption, and economize the cost.

Analysis of bottleneck processes relies on designer experiences in the early design of production lines [3]. This method can still be found in some small–scale factories today. From 1960, many algebra

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methods have been studied to analyze and relieve bottleneck processes of production lines under some assumptions and conditions [4-7]. Now, many ways such as designer experiences, algebra modelling and system analysis acting together have become major methods to analyze and diagnose bottlenecks in different trades [7-10]. However, these methods have great risks and are apt to waste resources and hardly can be known as dynamic modeling and analysis.

Visual and dynamic modelling of the production line is a new method using simulation technologies which are based on computer simulation, modelling, computer graphics, artificial intelligence, concurrent engineering, and multimedia technologies. Compared with the traditional diagnosis methods, this new method can describe practical manufacturing processes and simulate the dynamic running state of the production line at the outset of production planning in a visual environment [11]. It is beneficial to reduce the consumption of production.

In this paper, an integrated analysis method for bottleneck processes of production lines has been presented based on simulation technologies. With the proposed method, an existing production line case has been diagnosed based on simulation results. It is easy to view those bottleneck processes in an integrated analysis environment, and some bottleneck reducing schemes can be quickly simulated, and it can also be easy to get new relieved effects.

2. METHODOLOGY OF INTEGRATED ANALYSIS

a) The framework of integrated analysis method

The framework of integrated analysis method is shown in Fig. 1. It is composed of five modules: Input, Constrains, Support technology, integrated design and Output.

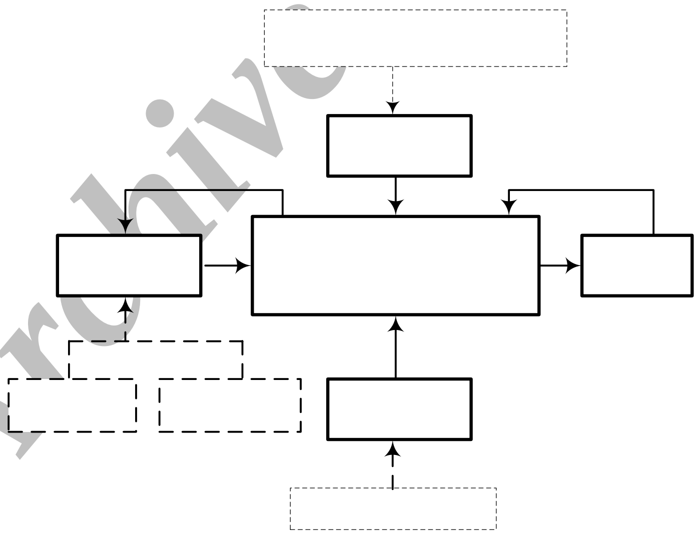


Fig. 1. Framework of integrated analysis method

1. Input. This module provides the data of production planning and process design, such as the manufacturing method (push or pull), job order, tools and equipment resources, as well as cycle and process parameters.
2. Constrains. These Constrains parameters contain the following aspects: quality, cost, efficiency and timeless. The practical resource conditions and evaluation criterions of the production line are also included. Practical resource conditions include equipment capacity, economic capability etc. Evaluation criterions include balance deviation of production, productive capacity, cost, quality, precision, efficiency, lead-time, reliability, responding speed and reconfigurable ability and so on.

3. Support technologies. This module offers the solution of the key technological problems such as describing and management of models, virtual modelling, scheduling, layout and components reconfiguring of algorithms. It includes the following advanced technologies: Virtual Manufacturing Technologies (VMT), Database management (DBM) and Objected-Oriented Modelling (OOM). VMT offers the visual design and analysis environments. DBM is used for saving models into databases. OOM is applied to model the performances of the production line.
4. Integrated analysis, functions such as modelling, simulation, bottlenecks diagnosis and reducing of production line are provided in this module.
5. Output, This module gives optimal design schemes of the production line.

b) Contents of integrated analysis

Integrated analysis is the center of this framework, which shares the data to integrate the following function: modelling, simulation, bottlenecks diagnosis and reducing based on the same production line model. When a new production line is brought up or a new product is introduced on an existing line, it is helpful to reduce those bottlenecks and improve the throughput of the production line through learning some lessons. Based on integrated analysis, bottlenecks and inefficiencies can be quickly identified and corrective action for bottleneck reducing can be developed.

Integrated analysis includes four parts: dynamic modelling, simulation management, diagnosis and reducing bottleneck processes. It is shown in Fig. 2.

Part 1: Dynamic modelling

This step is the basis of visualization for integrated analysis. It includes physical modelling and logical modelling.

1. Physical modelling: Physical modelling establishes the 3D geometry models of those elements such as machine tools, sources, buffers, sinks, automated guided vehicles (AGV), labors, robots, and so on. Those elements are units of the production line. Using this type of sorting, physical modelling can be divided into three steps.

Step 1.3D Elements modelling

Based on accurate 3D geometries of the actual production line, 3D elements models, which are used to visually describe the actual production line, can be developed in integrated analysis environments or can be read from an elements database. If there is no element model in a database, it needs to be developed. The 3D elements model development includes static and dynamic 3D prototypal modelling of the production line. Static 3D prototypal modelling establishes the 3D geometric models which are assembled by some 3D prototypal components. The dynamic 3D prototypal modelling defines the scripts of some component joints. Figure 3 shows a 3D labor model which is composed of some serial pictures. It is shown that the 3D elements model not only depicts its figuration, but also displays its various working status.

Step 2. Operation position modelling

In this paper, operation position points can be classified into three parts: transport way, part stacking and labor operation points. Transport way points are used for setting the starting and ending points of the transport paths among elements. The proper starting and ending points of elements can shorten the conveyance distances. Part stacking point is the precision coordinate values indicating where the parts are placed on the element. Labor operation point is a place where the labor operates the equipment. The proper labor operation points can improve the operation relationship between labor and equipment. Meanwhile, it can release the intensity of the labor. Figure 4 is the operation position of a buffer. It is shown that the operation position points are comprised by one labor position point, two transport way points and twenty four part stacking points.

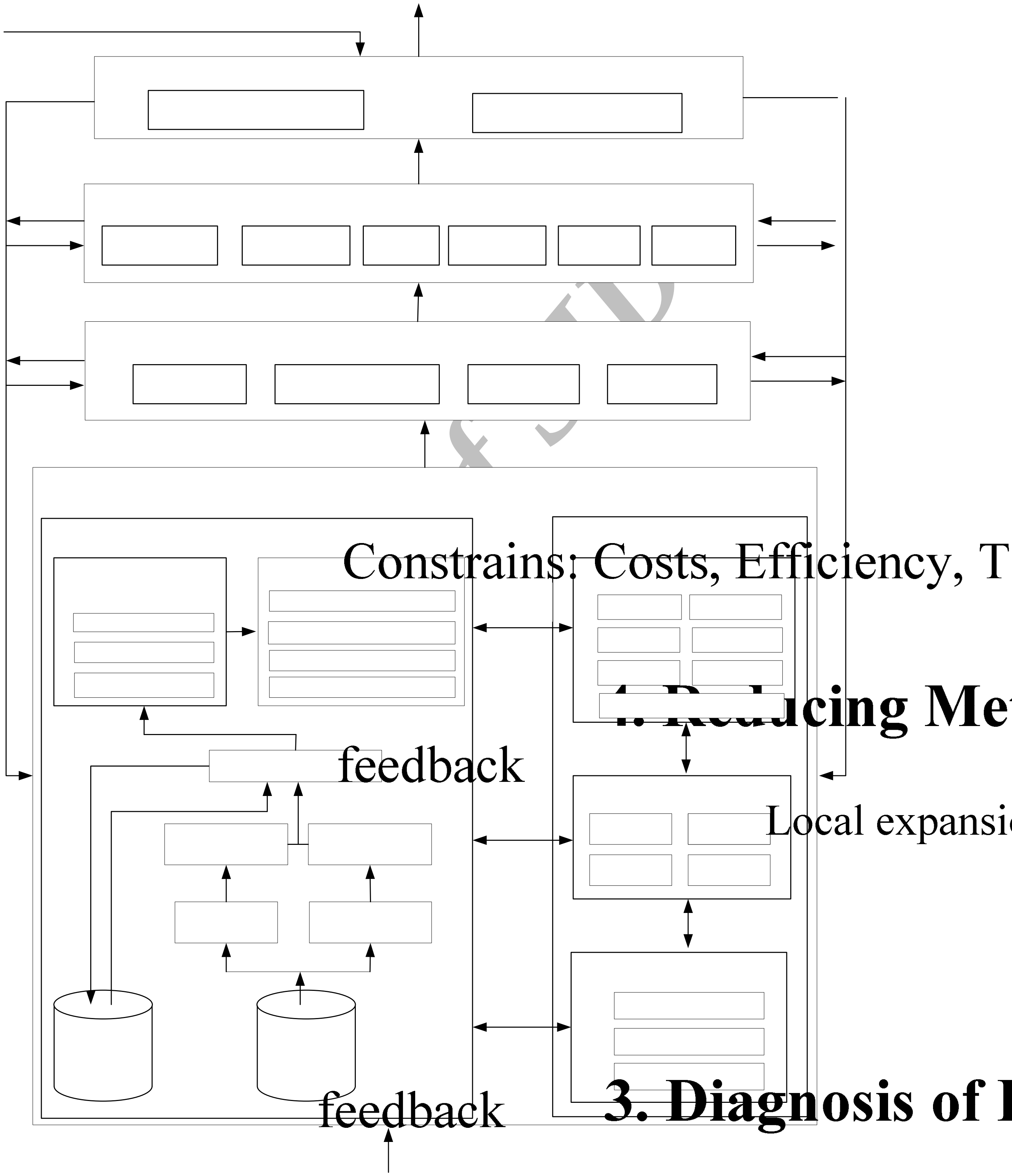


Fig. 2. Integrated design

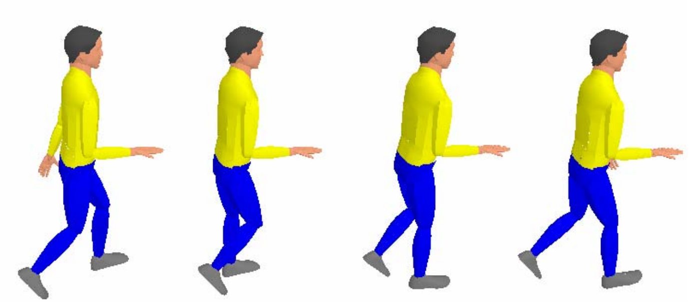


Fig. 3. A 3D labor model and its working status

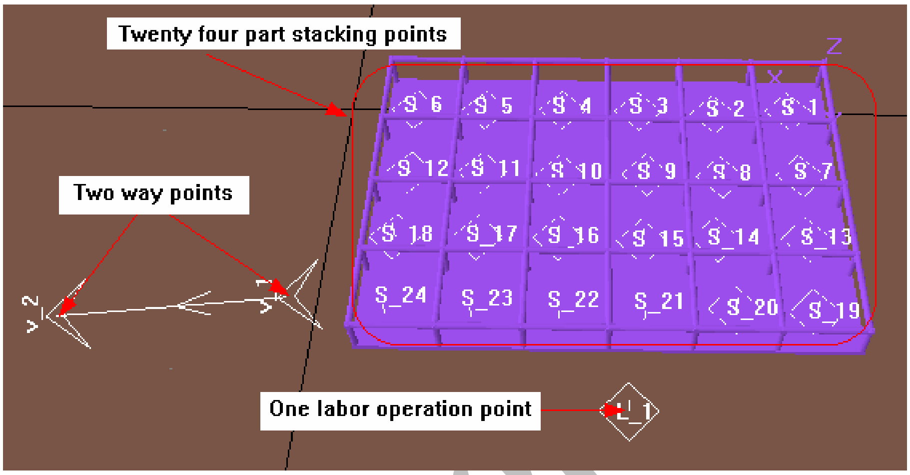


Fig. 4. The operation positions model of a buffer

Step 3. Layout modelling

When finished the 3D elements modelling and operation position modelling, the layout of the entire production line can be accomplished by defining the absolute and relative coordinate system of those elements contained in this production line. Figure 5 is the layout of a production line.

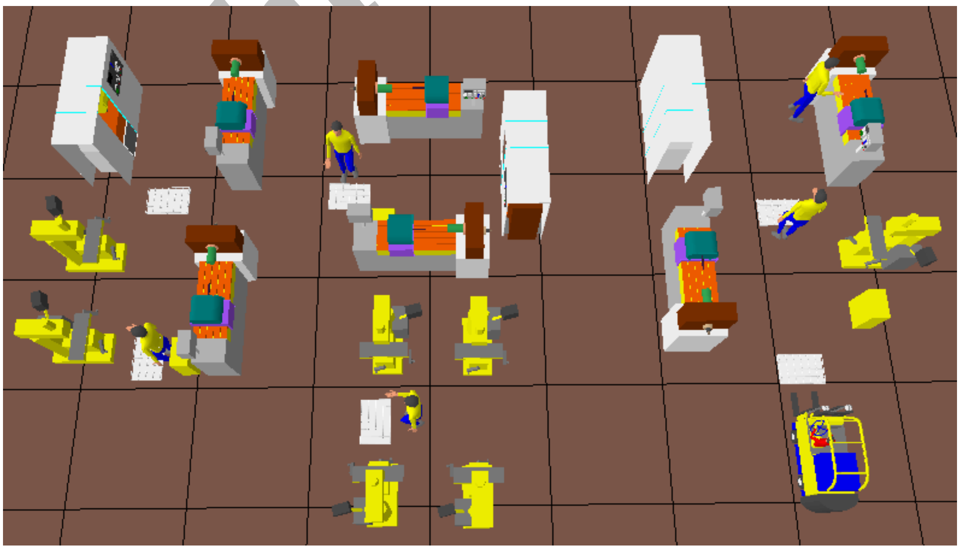
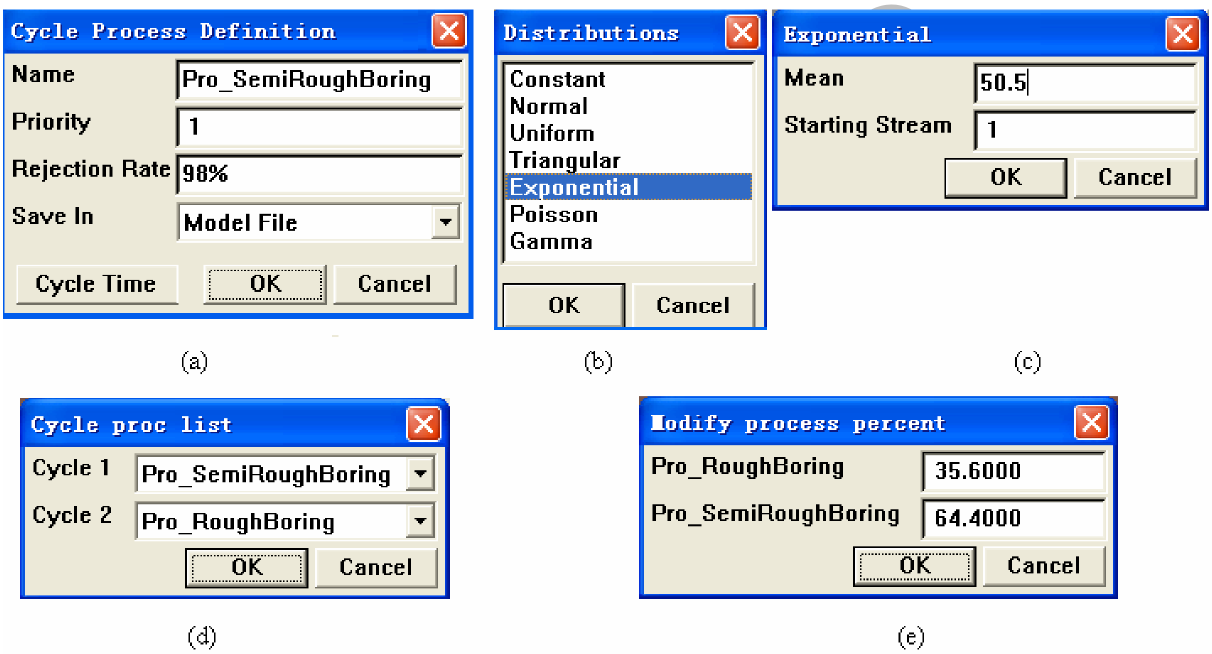


Fig. 5. The layout of a production line

2. Logical modelling: 3D elements modelling only shows the figure and layout of the production line, because it lacks machining processes. Those models can not be used to simulate, except for assigning some logical models. A logical model is used to model the processes, schedule and some algebraic rules.

Process modelling can define the following processes such as cycle, initial running, setup, repair, load and unload processes, as well as routing processes.

Algebraic rules modelling is used to select production resources, the precedence of part processing, and plan the entire layout as well as allocate the number and capacity of buffers. Scheduling modelling concludes shift break, daily and multi-day schedule modelling. Processes, algebraic rules and schedule can be assigned to each element. Figures 6 and 7 are the steps of cycle processes modelling and how to assign processes to a machine. Figure 6a is the attributes of a process which includes name, priority, rejection rate and the path of the saved model files. Figure 6b is the distribution of the cycle time and its value is shown in Fig. 6c. Multi-processes modelling are shown in Figs. 6d and e. Figure 7 shows that the pro_semiroughboring process is assigned to semi-rough boring machine, and its multi-day schedule is set with week_1.



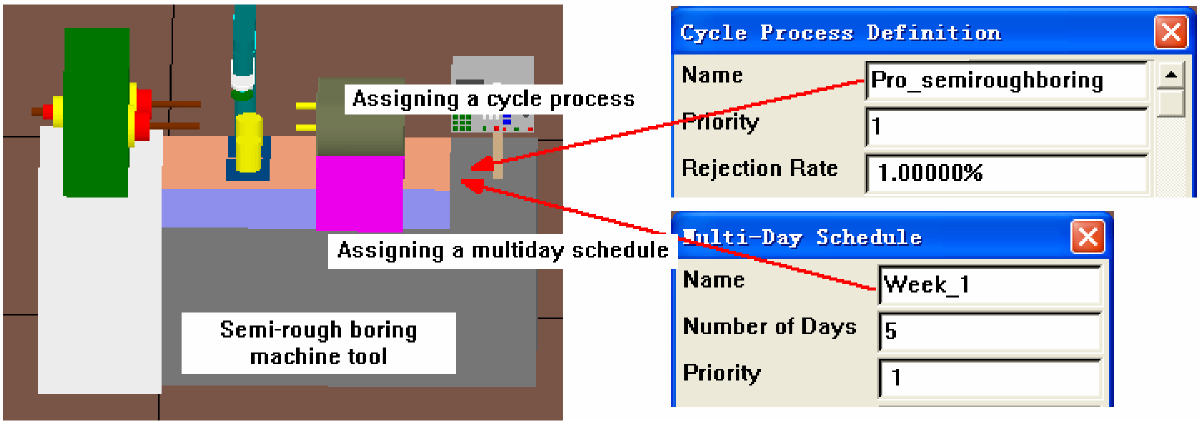
Name Pro_SemiRoughBoring
Priority 1
Rejection Rate 98%
Save In Model File

Mean 50.5
Starting Stream 1

Cycle 1 Pro_SemiRoughBoring
Cycle 2 Pro_RoughBoring

Pro_RoughBoring 35.6000
Pro_SemiRoughBoring 64.4000

Fig. 6. The steps of processes modelling



Name Pro_semiroughboring
Priority 1
Rejection Rate 1.00000%

Name Week_1
Number of Days 5
Priority 1

Fig. 7. The semirough boring machine tool model and its assignment model

Part 2: Simulation management

When the dynamic model of the production line is finished, it contains the following information:

1. The 3D elements models, operation points models and layout models of entire production line.
2. The process of each machine tool, i.e. cycle process and its values, setup process and its value.

3. Some algebraic rule models, i.e. production resource optimal selection, processing precedence of each part.

4. Schedule models, i.e. shift break, daily schedules and multi-day schedules.

A dynamic model of the production line can simulate the running states under constrained conditions. Based on those simulation results, some data can be acquired such as machine utilization, AGV utilization, labor utilization, part outputs, process time, machining cost, etc.

During a model simulation course, simulation clock management, event scheduling and activity scanning, and random number management, simulation data statistics should be extremely focused on. A simulation clock pushes the time from one event to another event. For reducing the running time, the simulation time is proportional to the actual time through setting the time steps.

Event scheduling and activity scanning modelling adopts the OOD method to deal with the order of serial events happened add in time. It records the time of each event which changes the state of the system. The changeovers of those states have accomplished the dynamic simulation of the entire production line.

Because some random events, such as the arriving of part, AGV and labor, as well as the distribute time of cycle process, have happened, the distribution time of the cycle process and random number management are greatly essential. Before dynamic simulation, the model of random variables needs to be developed first. After running the dynamic simulation, the results should be statistically analyzed in order to produce the confidence intervals.

Part 3: Diagnosis of Bottleneck Processes

Before designing and redesigning a production, some objects must be set based on input parameters and constraint conditions. Those objects include output, productivity, number and cost of elements, number of WIP in each buffer, utilization of each element, walking distance of each labor, and equilibrium of each cycle process time.

Figure 8 shows the WIP in each buffer. WIP in B5 is the most sever and exceeds 50 per day, if the design goal which defines the WIP in each buffer is not more than 50, the bottleneck process after B5 has been found in the production line. Meanwhile, with the change of the design goal, some other bottleneck processes can also be found in this production line, Actions need to be taken to reduce those bottlenecks.

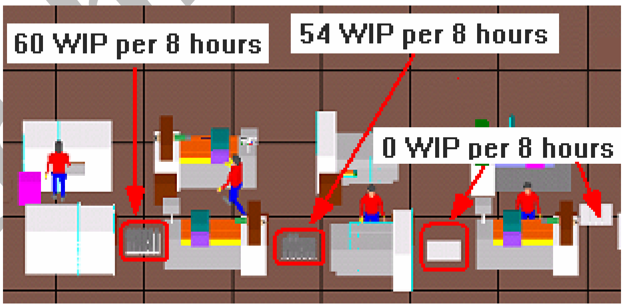


Fig. 8. WIP in each buffer

Part 4: Reducing Methods for Bottlenecks Processes

Two methods are taken to reduce those bottleneck points: local expansion for bottlenecks and bypass reducing bottlenecks.

Figure 9 shows the bottlenecks and two reducing methods. The working abilities of three processes: P_1, P_2, P_3 are A_1, A_2, A_3, respectively, shown in Fig. 9a. If $A_2<A_1<A_3$, P_2 is the bottleneck process. The local expansion reducing method is shown in Fig. 9b. For reducing the bottleneck processes, this method enlarges the working ability of the bottleneck point through the following ways: increasing the feed speed, improving labor skill, reselecting a machine tool which has great machining capabilities, or using a new

machining way. When actions with this reducing method are taken, the bottleneck process can improve its working ability to reduce or eliminate the bottleneck point. It is used:

1. Because of unsuitable parameters in the bottleneck process, its optimal ability has not played an important role in machining process. If parameters are correctly redesigned, the bottleneck point can be reduced or eliminated.
2. The machine tool in the bottleneck point can be replaced by new machine tools with better machining abilities.
3. The machining process in the bottleneck point can be changed with some new technologies which improve the machining capability.

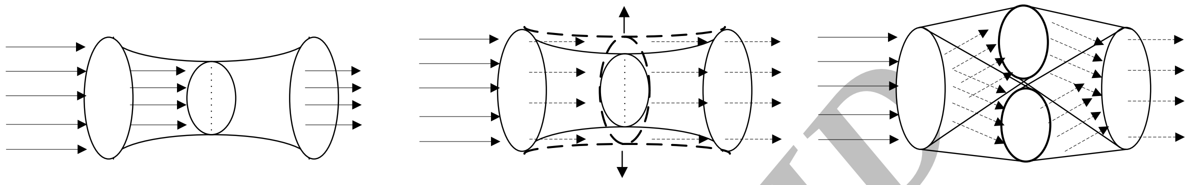


Fig. 9. Bottlenecks and its reducing methods

Figure 9c shows the bypass reducing bottlenecks method. It is accomplished by adding the same process, shifts or equipment in order to enlarge the machining ability of the bottleneck to reduce the bottleneck point. It is used on occasions when it is difficult to increase the machining ability for the bottleneck process by changing process parameters, replacing new machine tools or adopting new technologies.

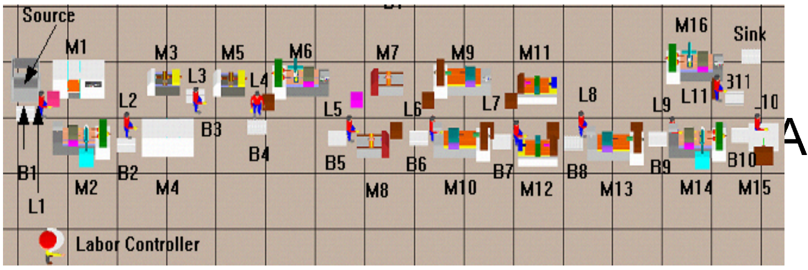
After taking reduction actions, the dynamic model and simulation can be modified again. If the simulation results are unsatisfactory, relative parts and steps should be fed back to adjust the parameters until the optimal design scheme of the production line is achieved.

3. CASE STUDY

a) Dynamic modelling

By using the methodology of integrated analysis, an existing production line is simulated, its running state is visually simulated, and its bottleneck processes are quickly diagnosed and reduced. The evaluation criterions of logistics balance for the production line are that: 1) process cycle time is less than 50 seconds. 2) the numbers of WIP in each buffer are no more than 30 parts. 3) the number of labors is no more than 11, and the number of machines tools is no more than 16.The parameters of each process are shown in Table 1.

The dynamic model of the production line is shown in Fig. 10. It is clear that the production line is composed of one source, one sink, 11 buffers (marked from B1 to B11), 11 laborers (L1 to L11) and 16 machine tools (M1 to M16). The layout of the production line is irregular.



A_2 A_3

Fig. 10. Dynamic model of a production line

Table 1. The parameters of each process

Process	Equipment	Num.	Labor	Machining time	notes
P1	M1	1	L1	36	Shifts: 7:30~8:00: Ready for working 7:30~11:30 ,1:00~4:30: Working time. 4:30~5:00: Ready for off duty. Supposed: Calculated other auxiliary time such as machining tools maintained time, labor rest time, tools change time, etc. Labor speed = 800mm/s
P2	M2	1		36 (two position)	
P3	M3,M4	2	L2	68.8	
P4	M5	1	L3	31.2	
P5	M6	1	L4	29.3	
P6	M7	1	L5	36	
P7	M8	1		36	
P8	M9	1	L6	36	
P9	M10	1		36	
P10	M11, M12	2	L7	61.6	
P11	M13	1	L8	29.25	
P12	M14	1	L9	34.4	
P13	M15	1	L10	14.7	
P 14	M16	1	L11	39	

b) Simulation, diagnosis and reducing for bottlenecks

After finishing the virtual modelling, some output and statistical results can be obtained with different forms such as multimedia, animates, pictures, figures and data. From these results, some ways such as visual simulation results, cycle time, machine utilization and labor utilization are presented to diagnose the bottleneck processes for the production line in this paper.

The visual simulation results are shown in Fig. 11. It is clear that WIP in each buffer are visually displayed, and the numbers of WIP in B5, B6 and B11 are more than that of other buffers. The numbers of WIP are shown in Table 2 under different simulation times. From Fig. 11 and Table 2, bottleneck processes of this production line are quickly diagnosed. The processes after B5, B6, and B11 are the bottlenecks of this production line. If it needs to be redesigned under the objects, the cycle time, labor utilization and machine utilization must be taken into account.

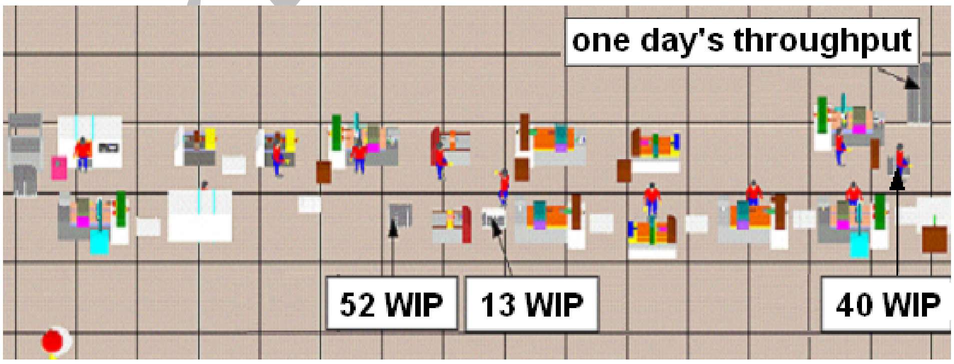


Fig. 11. Simulation results

Table 2. The numbers of in-process parts

Time	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
1 hour	1	0	0	17	6	0	0	13	0	15
1 day	0	0	0	52	13	0	0	0	0	40
1 week	1	0	0	205	48	0	0	0	0	95

Figure 12 shows that output parts have a direct ratio with simulation time, and the cycle time of the production line continuously varies with different running times and finally stabilizes at 45.21s. Figure 13 shows that the process time of each labor has three break-even points at L4, L5, L10, respectively, which is helpful to analyze the severity of bottleneck processes. This indicates three things. First, each buffer after L4, L5, and L10 has stacked many parts. Second, the differences between each process time and process cycle time are distinct, especially for L4, with a lag time up to 4.84 seconds, and thirdly, the differences among each process time are remarkable.

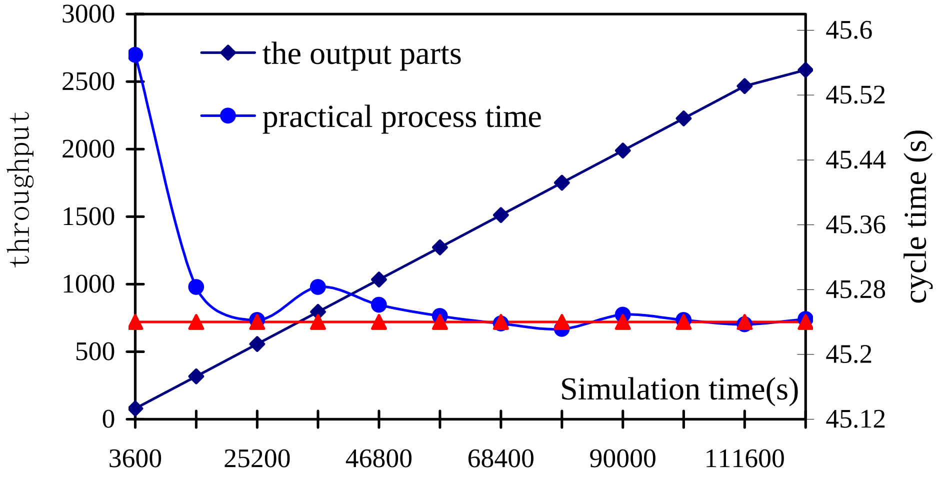


Fig. 12. Throughput and cycle time

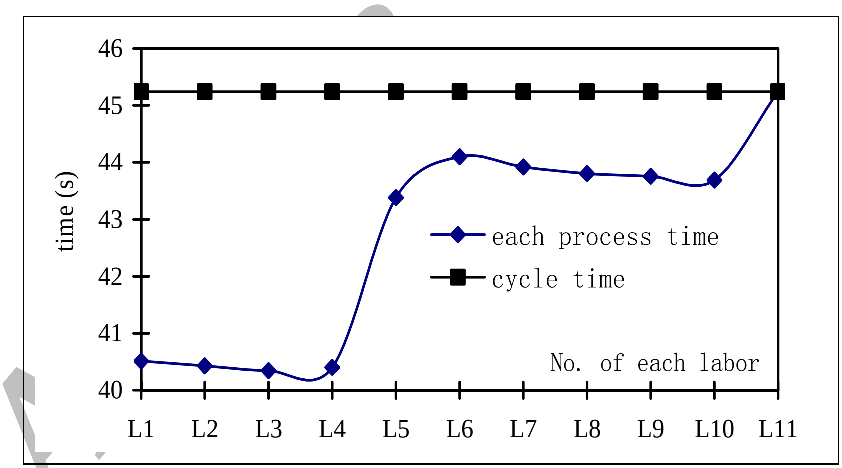


Fig. 13. Each process time and cycle time

The analysis of the utilizations of machines and labor is beneficial in adjusting or redesigning correlative parameters to reduce bottlenecks according to equipment ability. Figures 14 and 15 present the data of machine utilization and labor utilization. The comparison shows that: (a) utilization does not vary with the simulation time when the simulation state tends to be stable. (b) productivity of those machines in the preliminary process, such as from M1 to M4, need to be controlled to reduce WIP in bottlenecks. At the same time, allocate the labors with low utilization to operate other machines, i.e. L1's utilization is only 13.66%, which indicates that L1 has superfluous ability to take charge of other machines. (c) utilizations of M7, M8, L5, M9, M10, and L6 are higher than those of other machines and labors. It is shown that machines and laborers of P6, P7, P8 and P9 are busy. These processes are bottlenecks, and need to be adjusted to release labor intensity. (d) utilizations of M13, L8, M14, L9, M15 and L10 are less, which indicate that P13 can adjust by reconfiguring equipment and labor, that is to say, developing a modular machine tool to fulfil the function of M13, M14 and M15 is necessary.

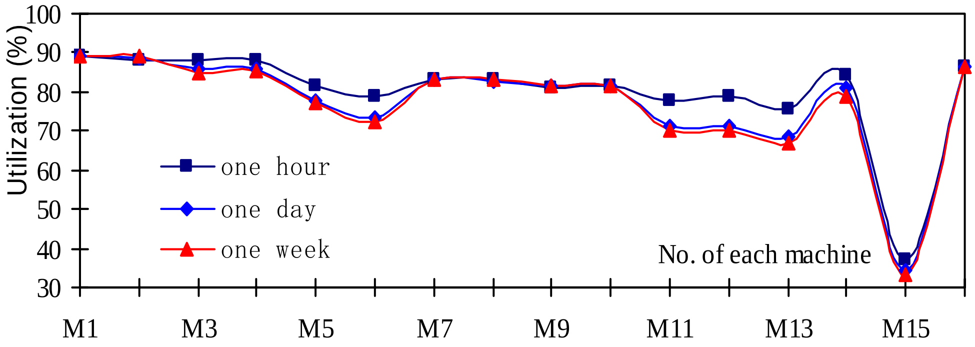


Fig. 14. Machine utilization

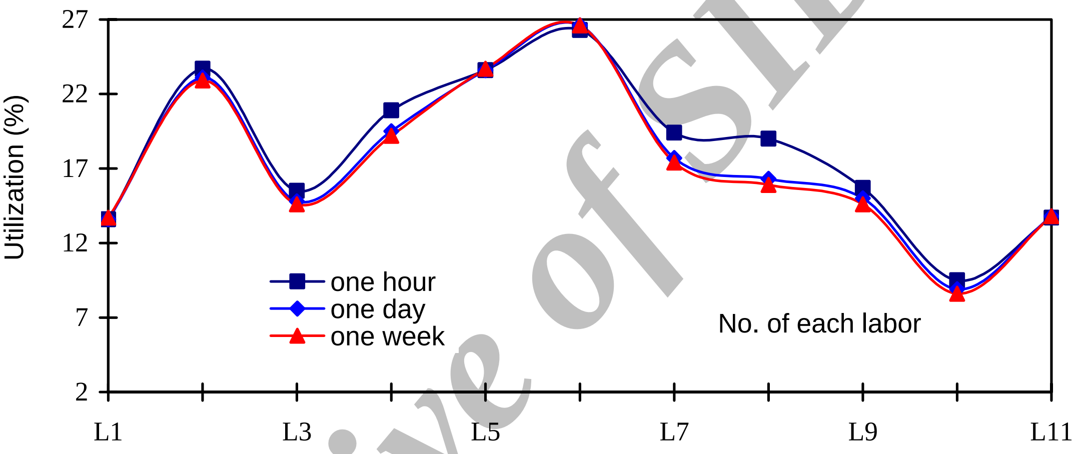


Fig. 15. Labor utilization

In a word, utilizations of L5 and L6 are higher than that of others. Based on utilizations of M7, M8, M9 and M10, it can be concluded that the processes of P6 and P7 are the most serious bottlenecks, and reducing methods must be adopted, firstly, to P6 and P7.

c) Simulation results after taking reducing actions

From the above analysis, for these bottlenecks, some reduction actions of bottlenecks using a local expansion method are adopted to decrease the bottlenecks:

(a) The cutting speeds of bottleneck processes (P6, P7, P8, and P9) are improved. After reduction, the process time of M7, M8, M9, M10, and M16 are decreased to 33.2s, 33.2s, 33.6s, 33.8s and 34.3s, respectively.

(b) M15 and M16 are operated by L10, so L11 and B11 can be removed as well.

(c) The walking velocities of L5, L6 and L11 are increased from 800mm/s to 1000mm/s.

WIP in each buffer after taking reduction actions for this production line are shown in Table 3. It is shown that: WIP in B5 obviously decreases to 12 per day. Visual simulation results shown in Fig. 16 show that (a) the maximum. WIP per 8 hours is no more than 12, (b) throughput is up to 569 parts, the process cycle time is no more than 50 seconds.

Table 3. The numbers of in-process parts after bottleneck reduction

Time	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
1 hour	0	0	0	8	3	0	0	5	0	3
1 day	0	0	0	12	13	0	0	0	0	10
1 week	1	0	0	74	70	0	0	0	0	54

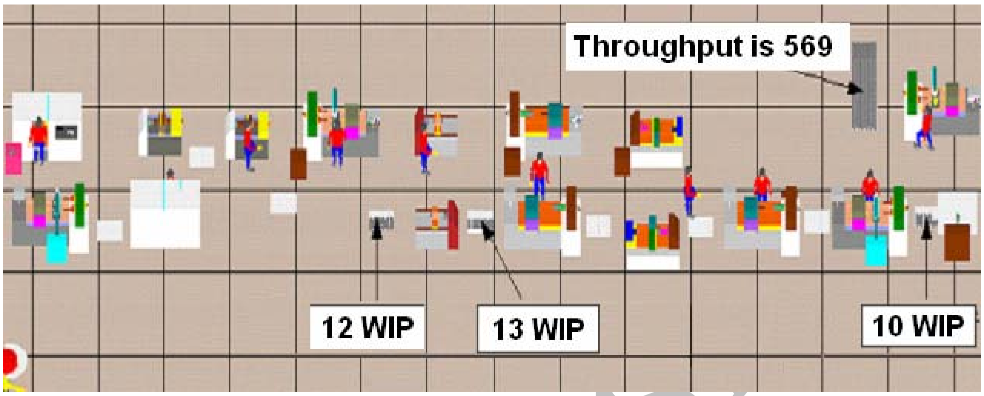


Fig. 16. Simulation results after redesign

Through the above analysis, the reconfigured scheme satisfies the practical demands based on the evaluation criterion. It is shown that, in a virtual simulation environment, the bottleneck processes diagnosis and redesign of the production line process are accomplished rapidly and waste none of the practical resource, which can decrease the production cost and provide a pre-analysis tool to diagnose the bottleneck processes in the early stages of the production plan.

4. CONCLUSIONS

A method of integrated analysis for bottleneck processes of production lines has been presented. The advantages of this method show that:

The entire course including modelling, simulation, diagnosis and reduction of bottlenecks for production lines have been integrated in a simulation environment. It wastes none of the practical resources, and all parts and steps are clear and ocular.

For diagnosis and reduction of bottlenecks of an existing production line, integrated analysis is quicker than traditional methods and can also provide a prospective prediction tool to foresee the dynamic state of a planning production line on the initial stage of the design.

Furthermore, integrated analysis can quickly simulate the results of a production line in which bottlenecks have been reduced after trying some ways of reduction. It can also provide different ways such as the visual simulation results, cycle time and machine and labor utilization to analyze bottleneck processes.

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