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特定 KPI に基づくサプライチェーン中のボトルネックの発見

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あらまし　デジタルトランスフォーメーション (DX) の到来を迎え，サプライチェーン (SC) ネットワークの現場から様々な情報をセンシングし，シミュレーションなどにより SC のボトルネック (BN) を見つけ出すことが可能となりつつある．SC ネットワークにおいては，各製造工場間の処理能力のアンバランスが BN を発生させ市場への製品の供給能力不足による売上機会損失リスクを SC 全体として発生させる大きな問題となる．そこで，本研究ではサプライチェーンマップと各ノードのシンプルな製造 KPI のみを用いたシミュレーションにより，最終的な生産量や各工場の稼働率などを予測することが可能なシミュレータを開発した．また，需要が SC 全体の供給能力を上回り供給不足が発生している状況において，滞留した在庫量を基に SC 中の BN を検知する手法を提案する．さらにもう一つの検知手法として，シミュレーションを生かし顧客からの需要を仮想的に下げることで得られたノードごとの稼働率を基にボトルネック度を読み取る手法を提案する．想定されるシナリオにおけるシミュレーションと BN 検知能力の評価を実験結果を基に行った．
キーワード　サプライチェーンマネジメント，シミュレータ，ボトルネック検知

Detection of the bottleneck within the supply chain from the specific KPI

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Abstract　It is now possible to obtain digital data on the shop floor with the arrival of the Digital Transformation (DX) era. Data will enable us to find the bottleneck of the supply chain (SC) network by using simulations. It would be a serious issue if there was an unbalance of the processing capacities of the factories that caused a bottleneck leading to an opportunity loss in product sales. We created a simulator to estimate the total amount of production and rate of utilization of each factory, by using the SC node relation map and simple Key Performance Indicators (KPIs) of production. This paper discusses and proposes approaches to identify the bottleneck from the remaining quantities of work in processes (WIP) between the nodes. Also, this paper proposes a methodology to detect how close each node is to being a bottleneck, based on the rate of utilization from the simulator.
Key words　Supply Chain Management, Simulator, Bottleneck Detection

1. Background

It is required to deliver the product by JIT to avoid the opportunity loss for the supply chain (SC) network participants [1]. However the the demand in the real world always fluctuates. It might be difficult to increase the production capacity flexibility for each factory or work stations (nodes) in accordance with the demand fluctuations [2]. It is because the flexibility of each node is different from each other. If there was a node that could not catch up with the demand increase, that would become the bottleneck (BN), and brings the opportunity losses of the sales to all participants of the SC network. That causes damages to the balance sheet by producing the goods without orders to prepare for the future [3]. In the case that the owner of the SC network hoped to send a special team of industrial engineers, it might not be possible to find the right BN. If it was possible to increase the capacity at the non-BN, the result brings redundant work in processes (WIP). Those WIP do not contribute to the SC network to improve the quantity of delivery to the customers. All the activities to non-BN are just a waste. Therefore, it would be a critical issue for the all stakeholders of the SC network to find the right BN. Meanwhile, the arrival of the digital transformation (DX) enables us to sense the information on the shop floors among the SC network [4]. It might be possible to improve the efficiency of the total SC by scrutinizing the obtained data, and estimate by the simulations [5]. Not only the manufacturing industry but also others are trying to visualize the status of the SC network at a glance such as with dashboards [6].

This paper develops the method to detect the real BN within SC network, and we create the simulator to estimate the total production capacity and the rate of utilization. We propose the methods to detect the BN with using this simulator. Concretely, simulator detects the BN by the stacked quantity of the WIPs between the nodes at the time that the demand exceeds the total production capacity of the SC. Additionally, we show that the rate of utilization can be characterized as the degree of the bottleneck (BN degree) that is the ascending order of the throughput of each node at the lowest demand made by this simulator.

This paper uses one scenario with a certain set of performance figures (KPI) of the nodes. We detect the BN first in this scenario by directly affecting the total throughput of whole SC network by improving the KPI of the node one by one as the preliminary experiment. The first method to detect the BN as the experiment is by detecting the WIP quantity at the input side of each node. And we compare that result against the preliminary experiment. We also propose the second method to detect the BN by descending order of the utilization rates of the nodes under the low demand simulation where the utilization rate reflects the throughput. And we validate this second method as well whether the result fit to the preliminary experiment. As the second method will produce the magnitude of each node, we admit them as the BN degree, and the SC owners will be able to refer it as the priority to work for multiple Kaizen activities at multiple nodes[1].

Below we show the structure of this paper. First is the background issue for this paper. Second is the related past various researches about SC networks, and we propose two methods to detect the BN. Third, we show that the proposed methods correctly detected the BN. Last, we show the conclusion and the future targets.

2. Literature review

There are famous methods in the field of Industrial Engineering.

（1） The method to compare the needed production time from the product mix, the cycle times and the quantity etc, against the capacity that the owner has [7].

（2） The method to guess the BN from the stacked WIPs between the nodes [2].

（3） The method to guess the BN from the rate of the utilization.

（4） Value stream analysis(VSA)： The method to draw the diagram of the material flow and the information as the fig.1, and utilized for the operation transformation for the future mainly among manufacturing industry [8].

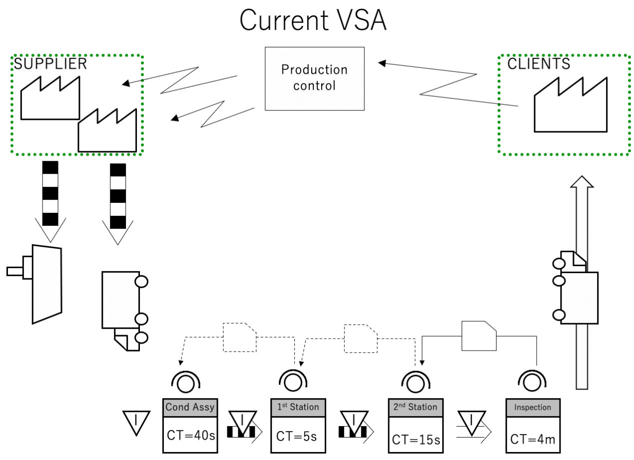

Fig. 1 VSA 例

However those methods above are not perfect, and (1) is inaccurate sometimes without coping with the rate fluctuations of the product mix. (2) can't detect the BN if it is located at the most upstream of the SC because it does not see the throughput directly but does see the WIP quantity that is the result. (3) is inaccurate if it was misunderstood as a good throughput when there were WIP stack ups after the node that are not ordered from the market. Also the snapshot data of the WIP quantity might be an exceptional case if considering it statistically. The work orders without the market's order, makes high rate of the utilization with creating the redundant WIPs that is the cash waste jeopardizing the balance sheet. The WIP inventories can't be reliable depending on the production system whether push or pull. (4) is not good at showing the BN at a glance. Unless the simple flow case, the widely branched Amazon river kind of the flow is not easy to draw in this diagram to find the BN and difficult to create without skills and time. Automation of drawing is also not easy.

Recently, the researches about the smart manufacturing is popular. IoT introduction might be beneficial to utilize the production status information, the analysis, into the different level of the stakeholders such as the levels of the machine, the factory, and the ERP. Also "Industry 4.0" may bring us networking, visualization and automation to monitor the resources, administrate the lines, and help to auto-set ups [5]. The inventory is the eternal issue for the manufacturing industry and the method to prevent the bull-whip effect is researched [9]. As the researches on the AI goes on, machine learning and simulations are applied to the manufacturing industry

(注1)：In the real world, the growth of the throughput will stop even after your Kaizen activities at the BN. It is because the first BN is not anymore BN now and another node became the top BN now. Therefore SC owners need to seek for the top BN always for the growth [2] with aiming for the efficiency [10]. Especially the batch size, due dates, production capacity, and utilization rate of the machines, WIP quantity etc are organically combined in this research [11].

3. The SC simulator to detect the BN

The set up of node relationship

The simulator connects the nodes imitating the SC network. There are no limitations on the number of the nodes as long as the computing capability allows. There are no limitations on the kinds of the input parts and each quantities as well. If the quantity of the output product at one batch are multiple, shipping destinations can be multiple if the quantity are enough. All nodes are linked like the tree and the last node finishes the production, the end product will be shipped to the customer and the order will be filled.

The flow of the orders and the product

The simulator handles the steps between the different layers of the nodes by handling the parts. The production system is pull on this simulator to eliminate the works without the orders from the customer. The customer places the orders with certain intervals. The manufacturer will places the orders to the upstream tiers with the needed quantity to satisfy the order. The sub-tier nodes will place the order to the more upstream tiers once they received the orders from the downstream. All nodes will start the productions once all needed input parts arrived, but if not arrived yet, the nodes will stand by with waiting for the arrival of the parts.

Step procedures

Once ordered, the node will calculate the needed lead time randomly with Gaussian distribution from the pre-set average lead time （*mu*: the number of needed steps to finish the production at that node） and the standard deviation(*std*). That node will finish its production after the calculated steps and the product will be shipped to the downstream immediately. All the next nodes follows after receiving all needed parts from all up-streams. The simulator will produce all the data such as the received number of the finished goods, and all WIP traces, after finishing all the pre-set steps. One step includes the sub-steps of renewing the latest order, production, shipping the finished goods if done and check whether the next production should be started or not.

Below are the inputs into this simulator.

- The relationships between all nodes
- The quantity of both each input parts and output in one batch
- The average lead time for production on each node （*mu*）
- The standard deviation of each node （*std*）

4. The proposal of BN detection method

This paper proposes two methods to detect the BN.

4.1 Method1: The quantity of WIP at the input side of the node

We propose this method first to detect the BN from the node that has biggest quantity of the WIP at the end of the steps. The criteria are as below.

- The node that has the biggest quantity of the WIP at he input side including manufacturer.
- All quantities at the input side are not zero. It's because the node is not the BN with the low capacity if the reason of the production delays are due to the input parts shortages.
- Exclude the most upstream tiers because the inventories at the input side of this tier is not because of the lack of the production capacity.

4.2 Method 2: The rate of the utilization at low demand

This experiment uses the simulator and it's possible to change only the demand virtually even without changing the node performances that are *mu* and *std*. There is the prerequisite that the supply side does not run to produce the redundant WIPs and stays idle if there is no demand. We compare the utilization rate of each nodes by imitating the recession or bad sales status. We suppose that those rate of the utilization represents the throughput quantities of the nodes, and we admit the higher utilization rates are higher BN degrees.

5. Experiments

5.1 Scenario of the experiment

We set up to produce only one kind of the end product in this experiment. All the nodes are led to the manufacturer finally. All the quantities of inputs are one and assembled to one finished goods in this SC chain. Each nodes does not keep the finished goods inventory and the finished goods will be shipped to the downstream immediately. The rate of the defects are zero at all nodes. All nodes order the parts only the quantities that are needed for the ordered finished goods. Therefore all WIPs among this SC network are tied to the orders. The customer does not receive the goods immediately in placing the orders, and need to wait for the parts till they flow down the stream from the origin. Therefore, all the nodes will not run without the orders.

Fig.2 is the diagram of this scenario with the node relationships and the KPI figures. Facotory_00 is the manufacturer. Factory_01~04 is the the Tier1. Factory_05~10 is the Tier2. Factory11~18 is the Tier3. The most upstream Tier4 is Factory_19~29 and There are enough inventories at the input side of the Tier4. We put the names of the nodes at the top center of the node boxes. （*mu*）と（*std*） are the KPIs of node to finish the production for one batch. The names of the products are at the side of the arrow right side of the boxes. The quantity of the finished goods on one batch is at the right bottom. The quantity of each inputs are at the bottom left. We run the experiment 100 times to eliminate the statistical fluctuations. One simulation consists of 10,000 times of the steps.

5.2 The BN of this scenario

We improved the KPIs of *mu* and*std* at only one nodes for 20% to find the right BN on this scenario for 30 times for each nodes. If the improvement were on the non-BN, the total throughput should not

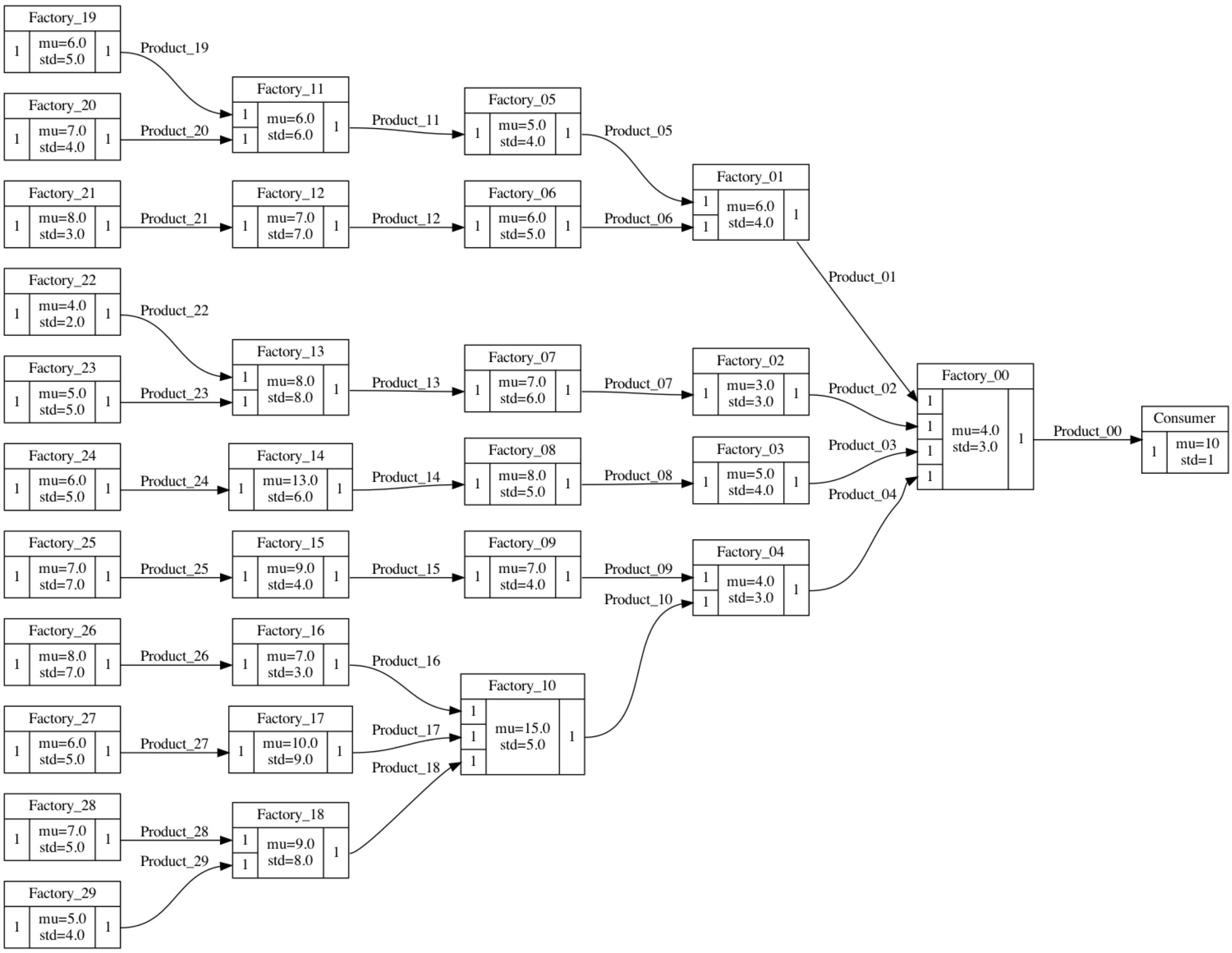

Fig. 2 The structure of the SC network for this experiment

(Figures at the bottom left are the needed quantities for inputs, and figures at the bottom right are the quantities of outputs)

Table 1 The rate of the right answers on method 1 and 2

Method	rate
Method1: WIP qty before the node	99%
Method2: Utilization rate	100%

change. On the other hand, if we improved the right BN, the total throughput should be improved.

The result of each 30 experiments of the number of the final product that customer received showed the improvement at only the Factory_10 as the fig.3. Thefore the right BN is Factory_10. We deploy evaluations on two methods of the experiments with setting this as the right BN. This calculations to detect the right BN needs enormous calculations with long time, and impossible to calculate manually.

5.3 The result of the simulation

Table1 shows the rate of the right answer for each methods. Method 1 showed 99%, and method 2 showed 100%.

Method1:

Method1 brought us the right answer of Factory_10, 99 times

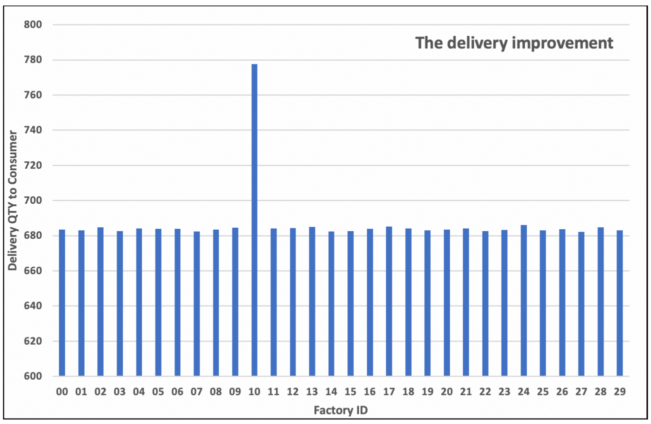

Fig. 3 The number of the total delivery when the nodes are improved 20%

among 100 experiments. The last one showed the BN was Factory_00 and we scrutinized the log of that experiment. Only one input parts among 4 was almost always zero at input side of the Factory_00, so we should not see this node as the BN. This wrong answer was brought by the statistical fluctuation as the exceptional case. Therefore we should improve these criteria of BN on this ex-

行ラベル	30459.csv	30519.csv	30539.csv	30559.csv	30619.csv	30638.csv	30658.csv	30717.csv	30737.csv	30756.csv	30816.csv
Factory_00	0.215	0.2211	0.2231	0.2176	0.2181	0.2281	0.2216	0.2249	0.2237	0.2247	0.2283
Factory_01	0.3256	0.3266	0.3227	0.3287	0.3267	0.3152	0.3159	0.3137	0.3253	0.3163	0.332
Factory_02	0.1903	0.196	0.188	0.1898	0.1976	0.1936	0.1938	0.1945	0.1847	0.1957	0.1947
Factory_03	0.2843	0.3003	0.286	0.3013	0.3021	0.2879	0.2911	0.2919	0.3025	0.2872	0.2863
Factory_04	0.2198	0.2271	0.2328	0.2147	0.2255	0.2258	0.2307	0.2196	0.2253	0.2245	0.2229
Factory_05	0.2942	0.2967	0.2979	0.2831	0.287	0.2858	0.2914	0.2808	0.288	0.3046	0.2836
Factory_06	0.355	0.3637	0.3583	0.3591	0.3609	0.3618	0.3641	0.3421	0.35	0.3598	0.3723
Factory_07	0.4318	0.409	0.414	0.4277	0.4309	0.4304	0.4218	0.4215	0.4302	0.4228	0.4195
Factory_08	0.4383	0.4154	0.4277	0.4353	0.4178	0.4132	0.4217	0.4218	0.414	0.4362	0.4257
Factory_09	0.3661	0.3608	0.3536	0.365	0.3554	0.3629	0.3619	0.3462	0.3653	0.3629	0.3684
Factory_10	0.7528	0.7499	0.7622	0.7593	0.741	0.7317	0.7494	0.7507	0.74	0.7641	0.7435
Factory_11	0.3999	0.385	0.3773	0.3843	0.3765	0.399	0.4057	0.4091	0.408	0.3941	0.3883
Factory_12	0.4743	0.471	0.4416	0.4647	0.4597	0.4575	0.4502	0.48	0.4452	0.4634	0.4675
Factory_13	0.5142	0.5242	0.5088	0.5282	0.5163	0.5612	0.5294	0.5227	0.5399	0.547	0.5189
Factory_14	0.686	0.6563	0.6508	0.6658	0.6454	0.6559	0.6574	0.6246	0.645	0.6774	0.6429
Factory_15	0.4561	0.4447	0.4527	0.4445	0.4593	0.4252	0.4412	0.4516	0.4486	0.4484	0.4482
Factory_16	0.3313	0.3396	0.34	0.3326	0.3436	0.3479	0.3431	0.3393	0.3389	0.3436	0.3446
Factory_17	0.618	0.6369	0.6343	0.6249	0.6355	0.6011	0.6266	0.6457	0.6403	0.6186	0.6436
Factory_18	0.5287	0.5469	0.575	0.5597	0.5537	0.5679	0.5555	0.5563	0.5443	0.5505	0.5647
Factory_19	0.3603	0.3532	0.3659	0.364	0.3474	0.3717	0.3532	0.3676	0.354	0.3697	0.3545

Fig. 4 A part of the results of BN degree from utilization rate
(Pink: Top BN, Yellow: Second BN, Green: Third BN)

Table 2 Worst3 nodes under utilization rate

Position	Name	appearance
Top bottleneck	Factory_10	100%
2nd bottleneck	Factory_14	95%
3rd bottleneck	Factory_17	95%

periment. This method was possible because the WIP are the result of the unbalance between nodes to find the BN. [2]

Method2:

The result of this method showed correctly 100 times among 100 as Factory_10, as the drawing4 if we used the rate of the utilization under the low demand. It showed Factory_14 as second worst BN 95 times among 100 experiments. And it showed Factory_17 as the third worst BN 95 times among 100 experiments as well. From those results, Method2 is easier and brings us more info with the magnitude of the BN degree.

6. Conclusions and Future research

In the real world, industrial engineers many times find the BN from the stacked WIP quantities between nodes. However those are inaccurate many cases. It's because those WIPs might not the inventories linked to the market orders. In that case the node might be judged to be the BN even if the needed parts were produced.

If we need the different quantities for each parts numbers, we can't judge from just the quantities of the WIPs and we need to convert it into the number of the final product using the BOM. But it would require more time to consider the BOM info and the skills as well for the analysis. Also this method will not work if the BN were at the origin of the SC flow.

Therefore we proposed the method to detect the BN by the simulation under the low demand with less orders from the customer. This method does not consider the rate of the product mix, cycle times of each processes, production quantities neither BOM. This method only requires the statistical sampling of the lead-time of the critical path on the node, and it will cover the origin tier of the SC network with the magnitude of the BN degree. The nodes on this SC relation map can be admitted both as the internal processes within one factory and as the factories among the total SC network. Therefore this method would be convenient and applicable to many industries.

The future of this research will require us to consider the double bottleneck cases that there are two BNs at the same level of BN degree. Also the lead-time statistics limit our real-time status displaying, and this point should be improved.

7. Conclusion

This paper developed the simulator from the SC map and the simple KPIs of each node, enabling to estimate the total production delivery and the rate of the utilization. Also proposed the method to detect the BN under the high demand case. Also it evaluated the ability of this simulator to detect the BN, and the proposed methods showed good enough result.

(注2)：It is wrong to evaluate the BN degree directly from the WIP quantities. The magnitude of impact are not equal even you had 3 wheels and one engine at the automobile factory as the WIP. The quantities of WIP need to be converted into the number of the final product.

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