Vibration Damping Optimization algorithm for supplier selection in make-to-order manufacturer

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Abstract

Procurement planning and production planning are challenging problems in manufacturing companies particulary in make-to-order (MTO) companies where production is triggered when the demand is received from the customer. In detail, selecting the best suppliers between potential suppliers and finding sequence of products with optimal cost and the least delivery time are some of decisions that must be made. For this purpose, a new Mixed-Integer Non Linear Programming (MINLP) model of the described problem is presented. Since such problems categorized in *NP* hard class, a Vibration-Damping Optimization (*VDO*) algorithm as a novel and fast metaheuristic method with useful neighborhood search mechanism applied. Parameters of algorithms are calibrated by means of Taguchi design of experiment. Obtained results compared to LINGO 8.0 software in different size of test problems. Numerical result illustrates the great efficiency of algorithm against exact solver, in two quality criterions, solution quality and computation run time. Also, results show a high quality performance in robustness of algorithm.

Keywords: Supply chain, Sequencing, Vibration-Damping Optimization.

1. Introduction

A supply chain (SC) is considered as an integrated process in which a group of different organizations, such as suppliers, manufacturer, distributors and retailers (customers), work together to acquire raw materials in order to convert them into finished products and then distribute them to retailers [1]. Decisions along SC regarding time horizon is divided into strategic, tactical and operational levels. Location or opening of manufacturing/distribution centers is kind of strategic decision while production planning and production scheduling in manufacturing centers are tactical and operational decisions consecutively. This echelon of chain covers four main, diverse and highly priced processes which included procurement of raw material (supply), production of products, distribution of the finished products to retailers and finally covering customer's demands. Integration between these different types of decisions in SC would be highly effective. For instance purchasing plan has influence on both production costs and on-time delivery. In fact, a supplier that is able to provide raw material sooner will charge the manufacturer with higher purchasing cost. It is clear that in a production center with proper purchasing plan, better selection of suppliers will lead to optimum release time regarding finished products due dates while can maintain product costs as low as possible. This integration will make a supply chain both responsive and efficient.

Among the researches which focused on tactical and operational level of the supply chain, Ryu et al. [2] suggested a bi-level model includes two LP models, one for production planning and one for distribution planning, Then they considered uncertainty in some parameters of the model like demand, resources and capacities and next reformulated them by multi-parametric linear programming. Comparison between centralized and decentralized production and transportation planning was proposed by Jung et al. [3] while Park [4] suggested an integrated transport and production planning

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via MILP model in a multi-site, multi-product, multi-retailer and multi-period circumstance. Ref [5] presented a unified transport and production planning model in a multi-period, multi-site, mono-product situation as a graph network. Ref [6] developed a MILP model for midterm planning which follows by coordination between the different stages of a supply chain. Ref [7] suggested a MILP model for production and distribution planning in a production environment which contains a single production plant but several distribution centers. For more detail about supply chain production and transportation planning the reader is directed to [8]. Ref [9] studied a production scheduling problem combined with a capacity planning problem to integrate tactical an operational decisions in flow shop environment. Ref [10] considered economic lot and delivery scheduling problem for a multi-stage supply chain comprising multiple concerning on synchronization of sequence of production and replenishment cycle time. Ref [11] proposed a multi-mode resource-constrained project scheduling problem for concurrently optimizing trade-off between sourcing and planning decisions in MTO environment without concern on sequencing.

The literature in which the integration between different level of decisions is rather vast but studies in which integration of tactical and operational decisions in flowshop manufacturer is rare especially where it considers supplier selection as tactical level decision and sequencing as operational level decision. To fill this research gap, this paper proposed an integrated model which focused on tactical and operational level decisions in the SC in discussed problem. Minimization of total purchasing costs and total weighted tardiness are considered simultaneously in an integrated novel Mixed-Integer Non Linear Programming (MINLP) model in order to fine a trade-off between both contradictory decisions. The two-machine flow-shop problem with total tardiness as the scheduling criterion is proven as *NP* complete [12] so the extension of this also will be *NP*-hard; this means that the discussed problem has considerable degree of complexity. Hence a novel and fast metaheuristic method, i.e. Vibration-Damping Optimization (*VDO*) with useful neighborhood search mechanism is used to solve the problem in acceptable running time and acceptable quality. Then parameters of the *VDO* algorithm are calibrated by means of Taguchi design of experiment. Obtained results compared through LINGO 8.0 software in different size of problems to express efficiency of proposed metaheuristic algorithm. Numerical results illustrate the great efficiency of algorithm against exact solver, in two quality criterions, solution quality and computational run time.

The rest of the paper is organized as follows. In section 2, the problem definition and model formulation is presented. Solution approaches based on *VDO* algorithm, neighborhood search mechanism and parameters tuning using Taguchi method, described in section 3. Computational results are indicated in section 4 and finally, directions for future research come in section 5.

2. Problem Configuration

In this problem the production center is considered as medial link in supply chain. Our supply chain includes three echelons, i.e. supplier, manufacturer and customers. Each customer has a fixed demand (π_i) for one specific product in a specific due date (d_i). On the other hand different suppliers are able to supply each raw material not necessarily with same purchasing cost or same delivery date. In fact if a supplier is able to supply a product sooner it will charge the producer with higher cost and vice versa. Due to the fact that setup time and cost of the product is very high, the same products should be accumulated and then the process in the first stage on this product should be done. As a result, release time of each product is set equal to maximum delivery date of this product from different suppliers that are selected to supply the product.

Some other main assumptions are as below:

- There is one-to-one relation between each raw material and finished product due to unique specification of each final product. Hence for the sake of simplicity, in the rest of article the term “product” is used instead of “raw material”, “under processed product” and “finished product”.
- Each supplier has limited capacity for providing specific product so it is probable that different suppliers are selected to supply the specific product.
- m-stage flowshop is considered in manufacturing centers where in each stage one machine is installed.

- All the products have the same production process and must undergo all flowshop stages and bypass is not allowed.
- The sequence of products is same in all stages
- for each day of tardiness the manufacturer would pay penalty regarding importance of each product.

2.1. Model formulation

The following notation is used in presented mathematical formulation of model:

Indices:

i	index of products	$i = 1, \ldots, N$
k	index of priorities	$k = 1, \ldots, N$
j	index of stages	$j = 1, \ldots, M$
s	index of suppliers	$s = 1, \ldots, S$

Parameters:

p_{ij}	Process time of product i in stage j
d_i	Lower bound of due date of product i
u_i	Upper bound of due date of product i
w_i	Cost coefficients of product i
c_{is}	Purchasing cost of product i from supplier s
r_{is}	Release time of product i from supplier s
π_i	Demand for product i
cp_{is}	Available quantity of product i in hand of supplier s
M	Large number

***Decision Variable*:**

X_{ik}	1 If product i is situated in priority k and 0 otherwise
Y_{is}	1 If product i is purchased from supplier s and 0 otherwise
φ_{is}	Number of products i being purchased from supplier s
RT_i	Release time of product i
CT_i	Completion time of product i in the last stage
T_i	Tardiness of product i
q_{jk}	Completion time of product in priority k of stage j

The MINLP model of the discussed problem is depicted as below:

$$Min \qquad \sum_i w_i \pi_i T_i + \sum_i \sum_s \varphi_{is} c_{is} \tag{1}$$

s.t:

$$\sum_s \varphi_{is} \geq \pi_i \quad \forall i \tag{2}$$

$$\varphi_{is} \leq Y_{is} \times cp_{is} \quad \forall i, s \tag{3}$$

$$RT_i = \max_s \left\{ r_{is} Y_{is} \right\} \quad \forall i \tag{4}$$

$$\sum_i X_{ik} = 1 \quad \forall k \tag{5}$$

$$\sum_k X_{ik} = 1 \quad \forall i \tag{6}$$

$$q_{j0} = 0 \quad \forall j \tag{7}$$

$$q_{1k} = \max\{q_{1(k-1)}, \sum_i RT_i X_{ik}\} + \sum_i X_{ik} p_{i1} \pi_i \quad \forall k \tag{8}$$

$$q_{jk} = \max\{q_{j(k-1)}, q_{(j-1)k}\} + \sum_i X_{ik} p_{ij} \pi_i \quad \forall j, k \tag{9}$$

$$CT_i = \sum_k q_{mk} X_{ik} \quad \forall i \tag{10}$$

$$T_i = \min\left\{\max\left\{0, CT_i - d_i\right\}, u_i\right\} \quad \forall i \tag{11}$$

$$Y_{is} \in \{0,1\}; \quad X_{ik} \in \{0,1\}; \quad \varphi_{is} : Integer \tag{12}$$

The objective function (1) minimizes the sum of total weighted tardiness of the finished products and purchasing costs of the raw materials. Equation (2) guarantees that all the demand be satisfied. Equation (3) ensures that quantity of raw material purchased from each supplier would not exceed its available capacity. Release time of the raw materials is computed via (4). Equations (5) and (6) guarantee that each product is assigned to one priority and each priority is dedicated just to one product. Completion time of jobs in 0*th* priority in each stage is equal to 0 that is shown is (7). Equation (8) calculates the completion time of the product in k_{th} priority of the first stages. Since all the products will be processed together as a batch, the process time in each stage is multiplied by parameter π_i. In (9) the completion time of product in priority k of stage j excluding first stage is calculated. The final completion time of the product i is computed in (10). The late work criterion is shown in (11) and type of the variables is defined in (12).

3. Solving approach

Solving the proposed *NP* model in medium and large scale problems with exact methods is very time consuming, so in this research a simple and fast metaheuristics algorithm, i.e *SA* based on random key encoding are developed to solve the problem in reasonable time and with reasonable quality. Then parameters of algorithms are calibrated by means of Taguchi design of experiment.

3.1. Vibration-Damping Optimization

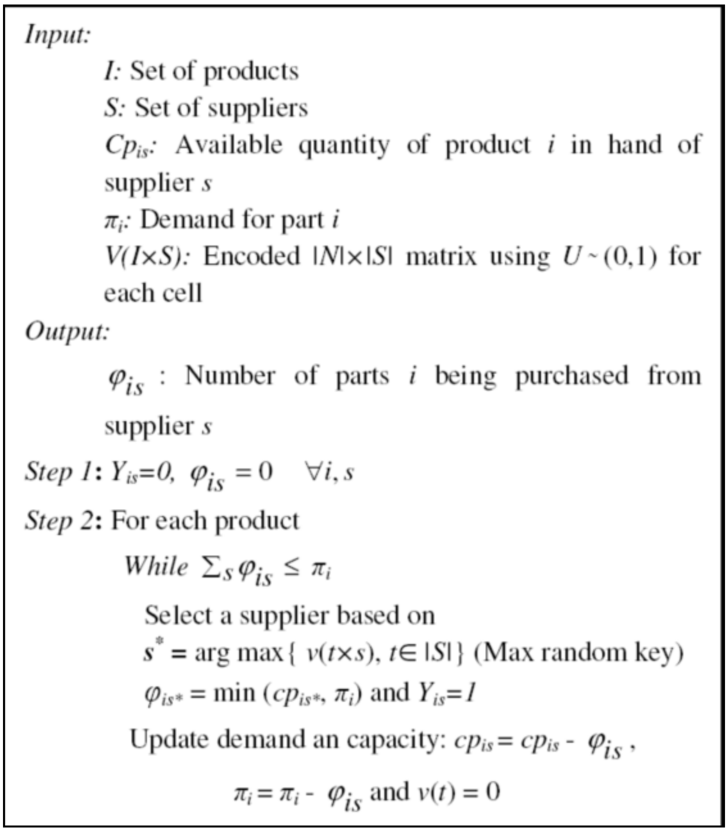
VDO algorithm was first introduced by Mehdizadeh and Tavakkoli-moghaddam [13] and then applied some other problems [14-16]. Similar to Simulated Annealing (*SA*), this algorithm is a stochastic search method but based on the vibration damping in mechanical vibration. VDO begins with an initial solution (*X*), initial amplitude (*A*) and an iteration number (*L*). Amplitude controls the possibility of the acceptance of a worse solution while iteration number sets number of repetitions until reaching stable state under specific amplitude (number of Inner Loop). Like *SA* in the first step of algorithm the possibility of acceptance of deteriorated solution is high but it decreases by term of iteration and finally converges to zero which forces the algorithm to hill climbing in final iterations. This fact causes *VDO* to have high diversification alongside high intensification. The major and key difference of *VDO* and *SA* is its probability function for accepting worse solutions (13):

$$\frac{A}{\theta^2} e^{\frac{-A^2}{2\theta^2}} \tag{13}$$

in which θ is the Rayleigh distribution constant and A is amplitude which updates in terms of iteration and decrease the probability of acceptance of worse solution. Reader is directed to Mousavi et. al [14] for detailed discussions.

3.2. Solution Representation

The problem is consisting of two parts: product-supplier and production sequence of products. The first part could be shown by $|N| \times |S|$ matrix, each row represents a product and each column represents a supplier. The strategy is to generate a feasible solution from the starting point rather than apply penalties on function in future. A solution is feasible if each cell of the supplier-product matrix be limited to the capacity of supplier and sum of each row be equal to demand of product and finally, the sequence vector must be a permutation of products. In order to make feasible matrix, the random key method is used. First give each cell of matrix a random number. Then in each row the cell with the most random number is selected and the capacity of supplier is dedicated to product. If demand of the product is not fully satisfied, the next supplier with the largest random number is selected. This procedure is used until the demand of this product is fully responded. For all the products this process will apply until all the demand for all the products be satisfied. Despite its simple representation of solution, the implementation of this method requires developing special operators and using huge memory space. Pseudocode of the encoding and decoding algorithm is illustrated in Fig 1.



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Input:
        $I$: Set of products
        $S$: Set of suppliers
        $Cp_{is}$: Available quantity of product $i$ in hand of supplier $s$
        $\pi_i$: Demand for part $i$
        $V(I \times S)$: Encoded $|N| \times |S|$ matrix using $U \sim (0,1)$ for each cell
Output:
        $\varphi_{is}$ : Number of parts $i$ being purchased from supplier $s$
Step 1: $Y_{is}=0,\ \varphi_{is}=0 \quad \forall i, s$
Step 2: For each product
            While $\sum_s \varphi_{is} \leq \pi_i$
                Select a supplier based on
                $s^* = \arg\max\{ v(t \times s),\ t \in |S| \}$ (Max random key)
                $\varphi_{is^*} = \min(cp_{is^*}, \pi_i)$ and $Y_{is}=1$
              Update demand an capacity: $cp_{is} = cp_{is} - \varphi_{is}$ ,
                    $\pi_i = \pi_i - \varphi_{is}$ and $v(t) = 0$
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Figure 1. Pseudocode of the encoding and decoding algorithm

3.3. Neighborhood search

In *VDO* algorithm, in order to find a neighborhood of a solution two change must be made first on the matrix and second on the sequencing priorities. For the first a product will be randomly selected and random numbers are generated for a row related to this product. Then using abovementioned procedure new suppliers are selected for the product. For the sequence of products two changes will happen with equal probability which are inversion and 2-opt.

3.4. Parameter Tuning

The selection of parameters usually has considerable influence on the efficiency of a metaheuristic. In this sub section, the effects of different parameter settings on the performance of *VDO* investigated.

One of the most important techniques to explore the effects of some factors on a response is a full factorial experiment [17]. Due to this fact that this method is time consuming especially when number of factors and their relative levels increase, an alternative method was introduces by [18] which is known as fractional factorial experiment (FFE). Taguchi is considered as a family of FFE matrixes that using quite smaller number of experiments, still provides sufficient information [19].

In this method, controllable factors (parameters) are situated in the inner orthogonal array and noise factors in the outer orthogonal array. The noise factors are those over which the experimenter has no direct and exact control. Because the elimination of the noise factors is rather impossible, the Taguchi method searches to minimize the effect of noise and using concept of robustness determines the optimal level of the important controllable factors [20]. Taguchi proposed a signal-to-noise (S/N) ratio that is why this type of parameter design is called robust [20]. Here, the term ‘signal’ denotes the desirable value (mean response variable) and ‘noise’ denotes the undesirable value (standard deviation). This method classifies objective functions into three groups: the smaller the-better type, nominal is-best type, the larger-the-better type. The S/N ratio considered for smaller-the-better type is as below:

$$S/N = -10\log_{10}(Objective \quad function)^2 \tag{14}$$

Different level of factors for *VDO* is shown in Tables 1.

Table 1. Factors and their levels for *VDO*

Factors	Quantity	Level
Amplitude (A)	{A(1) – 6, A(2) – 8, A(3) – 10}	3
Damping Coefficient (λ)	{λ(1) – 0.005, λ(2) – 0.05, λ(3) – 0.5}	3
Standard deviation (σ)	{ σ(1) – 1, σ(2) – 1.5, σ(3) – 2}	3
Outer loop (t)	{t(1) – 200, t(2) – 300, t(3) – 400}	3
Inner loop (L)	{L(1) –200, L(2) – 300, L(3) – 400}	3

For the above parameter levels of *VDO*, the L_{27} orthogonal array is selected as the fittest design to fulfill all the minimum [17].

In order to tune the parameters of algorithm, three different-sized problem classes (small and medium) are generated which Table 2 shows source of parameters. Then, each problem is solved 10 times for each parameter combination. Therefore, for each combination 30 response values are obtained. Using the S/N ratio in Minitab 14.0 software the proper levels of parameters for *VDO* is determined which are depicted in Fig 2.

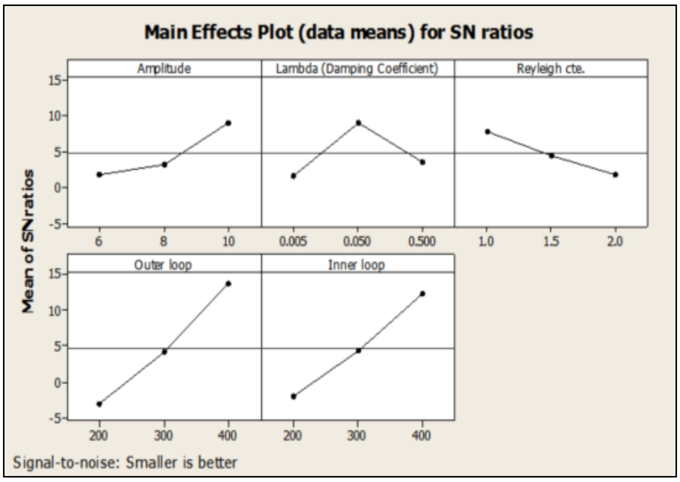

Figure 2. The S/N for factors of *VDO*

Table 2. The value of the parameters

Parameters	Source
w_i	~Uniform (0,1)
p_{ij}	~ Uniform (1,50)
c_{is}	~ Uniform (200,600)
cp_{is}	~ Uniform (0,100)
π_i	~[Sum (cp_{is})/2]
d_i	~ Uniform (75,100)×π_i
u_i	~[d_i/5]
r_{is}	~ Uniform (20π_i ,100π_i)

4. Computational Results

Evaluate the performance of the proposed metaheuristic algorithm with tuned parameters, *VDO* are coded in MATLAB 7.9.0 and the results of it are compared to the solutions obtained by LINGO 8.0 optimization software using Laptop with CPU of dual core 2.66 GHz and 4 GB of RAM on 12 problem classes. LINGO solves the problem whit branch-and-bound algorithm and guaranteed to find global optimal solution. Each problem classes are run 20 times and the average of their corresponding results is used to compare the performance of algorithm.

To compare optimal objective value obtained by LINGO with the results of *VDO*, the error of solution is defined as bellow:

$$\%Error=\left(\frac{VDO_{average}-LINGO}{LINGO}\right)\times 100 \tag{15}$$

The performance of *VDO* on objective value under different problem classes is illustrated in Table 3, with respect to the solution error and CPU time.

In Table 3, average of CPU time and optimal objective value of *VDO* is presented. It could be mention that LINGO solves small size problem classes about 0.02 to 6.56 min; for medium problem classes global optimum is not achieved in 13 hours and in large size problem even feasible solution is not found in 13 hours.

As illustrated in Table 3, in small scale problems *VDO* gives global optimum in quite small CPU time. As the size of the problem increases, the quality of results decreases very slightly.

Table 3. Summary of test result on Obj value and CPU time

Problem Class	$(\lvert S\rvert\times\lvert I\rvert\times\lvert J\rvert)$	LINGO Performance		Algorithm Performance		
				Obj Average		CPU Time (S)
		Obj	CPU Time (S)	*VDO*	Error %	*VDO*
PC1	**2×3×3**	53,475	1	53,475	0.00000	17
PC2	**4×4×4**	107,162	2	107,162	0.00000	19
PC3	**5×6×7**	1,119,376	16	1,119,376	0.00000	37
PC4	**7×7×5**	6,077,492	394	6,077,492	0.00000	62
PC5	**8×10×12**[a]	6,590,912	46,800	6,590,912	0.00000	79
PC6	**10×12×14**[a]	7,062,512	46,800	7,062,512	0.00000	106
PC7	**12×14×18**[a]	15,391,220	46,800	15,391,888	0.00434	180
PC8	**14×18×22**[a]	36,899,200	46,800	36,903,177	0.01078	236
PC9	**16×18×24**[a]	33,802,800	46,800	33,817,511	0.04352	232
PC10	**20×30×40**[b]	-----	-----	146,879,524	-----	637
PC11	**35×45×55**[b]	-----	-----	601,677,960	-----	1,435
PC12	**50×60×70**[b]	-----	-----	1,202,253,603	-----	2,414

[a] Interrupted after 13 hour. [b] Could not find feasible solution after 13 hours

The maximum error for largest problem class is less than 0.04352. The objective value error varies from 0% to 0.04352% for *VDO*. Also, for first six problem classes *VDO* objective values are equal to LINGO. The comparison between LINGO and algorithms indicated that performance of algorithms on producing a closed optimal solution are traffic and for large size problem, i.e. with no answers of LINGO on enough time, algorithm error is acceptable and reliable.

The robustness of solution achieved by algorithms is another important factor. This factor is calculated using Coefficient variation (C.V) index as bellow:

$$CV = Standard\ Deviation\ of\ 20\ run\ /\ Average\ of\ 20\ run \tag{16}$$

Referring to Table 4, *VDO* algorithm gives robust results in all cases while C.V index does not surpass 0.0000604 in the worst cases.

Table 4. The robustness of algorithm

Problem Class	$(\lvert S\rvert\times\lvert I\rvert\times\lvert J\rvert)$	Algorithms Performance
		Coefficient Variation
		VDO
PC1	**3×3×3**	0.0000000
PC2	**4×4×4**	0.0000000
PC3	**5×6×7**	0.0000000
PC4	**7×7×5**	0.0000000
PC5	**8×10×12**	0.0000000
PC6	**10×12×14**	0.0000000
PC7	**12×14×18**	0.0000400
PC8	**14×18×22**	0.0000353
PC9	**16×18×24**	0.0000604
PC10	**20×30×40**	0.0000303
PC11	**35×45×55**	0.0000294
PC12	**50×60×70**	0.0000421

5. Conclusion

This paper designed an integrated MTO model which helps managers to cope with their challenges and threats on this echelone of chain. In other words, concerning different tactical and operational level of decision on the SC in a production center is studied. Minimization of total purchasing costs and total weighted tardiness are considered. The studied problem is m-stage flowshop sequencing problem in which selecting the best supplier and the optimal sequencing was the main goals. In fact the model do the best trade-off between purchasing costs and tardiness costs.

Due to this fact that the model has great degree of complexity and is proven as *NP* hard problem, a novel and fast metaheuristic, i.e. *VDO* is developed to solve the problem. Using Taguchi method the most appropriate level of algorithm's parameters is found. And the results are compared to LINGO 8.0 optimization software. Also, 12 problem classes ranged from small, medium to large size are solved. The results are proven to be sufficiently close to the exact solution obtained by LINGO. The results show that computational time of algorithm is highly better than the CPU time of LINGO. Also the maximum error for largest problem class is very low, less than 0.05%. applied algorithm gives robust results in all cases while C.V index does not surpass 0.0001 in the worst cases.

As the future research the following offers could be given to the reader:

- Subject to increase cost saving, obey the governmental legislation and achieve more customer loyalty, it's a intractive point to covering reverse flow of used products particullary in harmfull products like Battery, etc.
- Investigating the model under uncertainty using fuzzy and robust optimization approach could be a good extension of this research.
- Since the two terms in objective function are completely conflicting, bi-objective approach would be another useful and applicable extension of the work.

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