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MATERIAL REQUIREMENT PLANNING FOR BUILD-TO-SEQUENCE SUPPLY: A MULTI-LEVEL OPTIMISATION APPROACH

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Abstract: *Material requirement planning (MRP) plays an important role in the life of production companies, because it has a great impact on the efficiency of manufacturing operations and it influences the total cost. Just-in-time and just-in-sequence supply offer new solutions to improve the cost-efficiency from inventory holding point of view. Within the frame of this article the author focuses on the build-to-sequence strategy of just-in-sequence supply and demonstrate an integrated approach of material requirement planning. The suggested methodology includes the determination of build-to-sequence orders, the optimisation of material requirement from lead time and cost point of view and determine the optimal sequence of operations to fulfil build-to-sequence demands. The computational results show, that the integrated optimisation leads to an increased cost efficiency, while the required manufacturing operations are performed with a decreased lead time.*
Key words: *inventory control, optimization, just-in-sequence supply, lead time.*

Planiranje potreba za materijalom za snabdevanje po redosledu izgradnje: Pristup optimizacije na više nivoa. *Planiranje materijalnih potreba (MRP) igra važnu ulogu u životu proizvodnih preduzeća, jer ima veliki uticaj na efikasnost proizvodnih operacija i utiče na ukupne troškove. Snabdevanje tačno na vreme i tačno u nizu nude nova rešenja za poboljšanje troškovne efikasnosti sa stanovišta držanja zaliha. U okviru ovog članka autor se fokusira na strategiju snabdevanje po redosledu izgradnje i demonstrira integrisani pristup planiranju materijalnih potreba. Predložena metodologija uključuje određivanje* snabdevanje po redosledu izgradnje, *optimizaciju zahteva za materijalom sa stanovišta vremena isporuke i troškova i određivanje optimalnog redosleda operacija za ispunjavanje zahteva* snabdevanje po redosledu izgradnje. *Rezultati proračuna pokazuju da integrisana optimizacija dovodi do povećanja troškovne efikasnosti, dok se potrebne proizvodne operacije izvode sa skraćenim vremenom isporuke.*
Ključne reči: *Kontrola zaliha, optimizacija, snabdevanje u skladu sa redosledom, vreme isporuke.*

1. INTRODUCTION

Nowadays, optimisation of production processes has a great importance in order to achieve the right market position, as cost-efficient production is a fundamental prerequisite for attracting a broader range of customers. The conditions for cost-efficient operation cannot be achieved by optimising production processes alone, but also by a significant transformation of logistics processes. One of the most significant cost savings can be achieved through the optimisation of procurement and supply processes. Just-in-time solutions are becoming increasingly important in supply chains, and just-in-sequence supply solutions are becoming more widespread, where the order or sequence of parts supplied is becoming more important than just time. There are three major just-in-sequence supply chain solutions in practice [1]: ship-to-sequence, build-to-sequence and build-to-sequence. In build-to-sequence solutions, the parts needed for the operations to meet customer needs are usually produced in the production company. In the conventional case, a build-to-sequence demand is determined on the basis of master production schedule and a material requirement plan is defined on the basis of this demand. If these two planning steps are implemented sequentially, an optimal solution is not ensured, since by parallelising the planning steps and using integrated objective functions and constraints, an optimal solution can be defined that provides a more cost-effective supply process than the system implemented as a result of the two sequential planning steps. However, there is a wide range of solutions in different ERP systems focusing on the solution of MRP-related optimisation tasks, but the integrated operation of more logistics-related tasks are not available, therefore the mentioned methodology offers new potentials to save costs.

In this paper, the author proposes an integrated optimization algorithm whereby the determination of build-to-sequence demands and the computation of the corresponding material requirement plan can be achieved by integrated optimization.

This paper is organized as follows. Section 2 presents a systematic literature review, which summarizes the research background of just-in-sequence supply. Section 3 describes the just-in-sequence supply solutions. Section 4 presents an integrated optimization model including the optimisation of build-to-sequence demands, material requirement plan and the sequencing of the production operations required to fulfil build-to-sequence demands. Section 5 shows the computational results, which validate the model and the methodology of optimisation. Conclusions and future research directions are discussed in Section 6.

2. LITERATURE REVIEW

The research of just-in-sequence supply resulted a wide range of literature sources, because JIS approach can lead to an efficient management of variety-driven costs and it can help to reduce sourcing risk [2], especially in the automotive industry and electronics sector [3].

The fourth industrial revolution lead to hyperconnected systems, where the supply solutions plays an important role for all suppliers at all levels. The just-in-sequence supply researches are focusing on the synchronous manufacturing. In the case of TIER1 suppliers, intervention approaches can improve efficiency, because through analyses of suppliers and deliveries optimal supply operations and decision making processes can be performed [4].

Research works show, that an up-to-date IT system can support and control the production and logistics processes of suppliers and the flexibility of just-in-sequence supply is based on the performance of these IT solutions and tools, including optimisation softwares, data base and expert systems [5]. However, just-in-time and just-in-sequence supply solutions seems to have the same root, but applying just-in-sequence approach it is possible to reduce the disadvantages of conventional just-in-time supply solutions [6].

The optimisation methods of just-in-sequence solutions includes a wide range of approaches, form analytical methods to heuristic and metaheuristic solutions, but simulation techniques also plays an important role in the design of just-in-sequence solutions. Oscillators can be used to model the repetitive characteristics of customers' demands and describe the dynamic behaviour of supply chains [7]. In the literature we can find some research results focusing on the integrated optimisation of just-in-sequence supply solutions, where not only the manufacturer's operations are optimised according to just-in-sequence requirements, but also the demands and operations of TIER1 suppliers are involved into the same optimisation process to reduce the total cost of the supply processes [8]. The just-in-sequence supply is integrated into ERP systems, where just-in-sequence or just-in-time practices, total quality management tools and supply chain management paradigms have a joint impact on the performance of production systems [9]. In the Industry 4.0 era, the just-in-time and just-in-sequence solutions must be optimised as an integrated approach for suppliers and manufacturers, to find the optimal schedule and sequence [10]. The material requirement planning solutions play an important role in the design of just-in-sequence solutions, but add-on tools and methods (Wagner-Whitin algorithm, Silver-Meal heuristics) can improve the performance of MRP methods [11]. Using these analytical and heuristic approaches it is possible to improve the performance of both the production and the logistics processes, while the dynamic demands of customers are fulfilled [12]. The just-in-sequence related research results are generally focusing on both the ship-to-sequence and build-to-sequence solutions [13]. The build-to-sequence supply is especially important in the case of manufacturing companies, where the outsourcing potentials are restricted, therefore the required components must be manufactures in-house [14].

3. JUST-IN-SEQUENCE SUPPLY STRATEGIES

One of the main reasons for the application of the just-in-sequence concept is the significant cost reduction. This is primarily due to the large reduction in inventory and the shortening of lead times. Inventories have a balancing and safety function in companies to bridge fluctuating market demands and capacity imbalances. Inventory reduction measures include the decrease of lot sizes, decrease of required steps for dispatching operations, improve forecasts and the quality of dispatches, better spare parts supply, decrease the number of storage stages, decrease the production stages and supply synchronised with production.

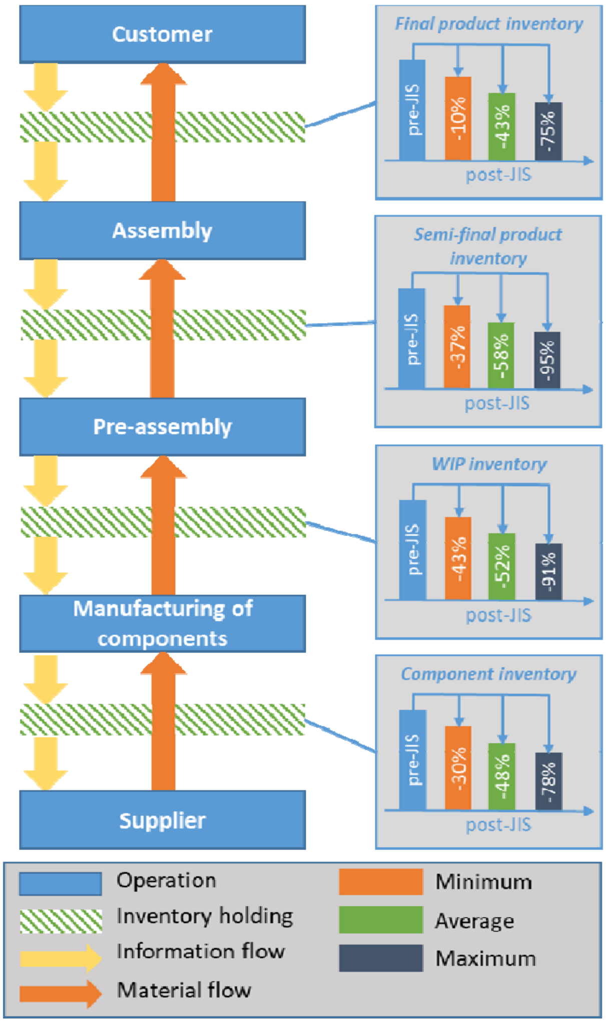

Fig. 1. Expected cost savings caused by just-in-sequence supply

The application of these measures only very rarely leads to an ideal production at zero stock levels, as stock reduction is influenced by technical and economic factors on the other side. However, in many application cases, inventory reductions of up to 70% have been achieved by the introduction of JIT-based production. The main influence of the just-in-sequence concept is on the inventory structure and the sequence of supplied lots and batches, since the aim is to increase the inventory turnover rate by means of production close to the customer. The inventory reduction that can be achieved by introducing the just-in-sequence concept is shown in Figure 1.

The typical just-in-sequence solutions are based on three different just-in-sequence strategies a follows:

- **ship-to-sequence supply:** In this case, the required demands of manufacturing or assembly operations are shipped from an external supplier. Sequencing operations can be performed either by the supplier, or by an intermediate third party logistics provider, for example in a cross-docking facility.
- **pick-to-sequence supply:** In this case, the required demands are supplied to the manufacturing or assembly company either in a conventional way or just-in-time, and the required components are sequenced in the place or request.
- **build-to-sequence supply:** In this case, the required demands are produced or assembled by the same company. The manufacturing and assembly operation must be suitable for build-to-sequence production or assembly and the related logistics facilities (warehouses, storages and material handling equipment) must have enough capacity to support the fulfilment of build-to-sequence demands.

4. MODEL OF MULTI-LEVEL OPTIMIZATION FOR BUILD-TO-SEQUENCE SUPPLY

In the case of conventional build-to-sequence supply models, the material requirements are usually determined on the basis of available component requirements. The component requirements are determined based on the master production schedule for the finished product and since these two planning activities are performed independently and sequentially, the two sequential material requirements planning tasks do not result an optimal solution. In this chapter, a mathematical model is presented for the integrated planning of the build-to-sequence supply, where the component requirements of the finished product are determined based on the master production schedule, from which the production schedule for each time window can be generated. From this master production plan, the appropriate production sequence can be determined, taking into account technological and logistics parameters, and the optimal schedule for the production of components can be determined for this production sequence. Since the two optimisation tasks are not performed sequentially but in parallel, a better MRP in terms of lead time can be achieved than in the case of sequential planning, as shown by the computational results presented in the next section. The main phases of the optimization process are shown in Figure 2.

The input data for the optimization is the build-to-sequence demand for each time windows. The first phase of the optimization is the computation of gross demands, net demands and schedule the required assembly, production and purchasing operations depending on stocks, moving stock, safety stocks, times and demands.

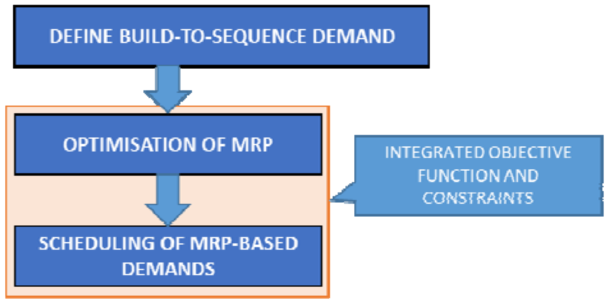

Fig. 2. The main phases of the integrated design of build-to-sequence supply

- **Determination of gross demand.** Gross demand for finished products is based on the production master plan or sales plan. At the hierarchical levels below the finished product, where raw materials, parts, assemblies or sub-assemblies are incorporated into a finished product, assembly or sub-assembly at a higher hierarchical level, the gross requirement can be determined as a function of the quantity scheduled at the start of assembly, production or ordering and the number of units incorporated, as follows

$$\forall \alpha_1 > 1, i, j: q^B_{\alpha_1 ij} = \sum_{\alpha=\alpha_1}^{1} \sum_{k=1}^{i_\alpha^{max}} \vartheta^{pre}_{\alpha_1 i\alpha k} \cdot q^{N*}_{\alpha ij} \tag{1}$$

where $q^B_{\alpha_1 ij}$ is the gross demand of final product, assembly, sub-assembly or component i in time window j at the hierarchical level α_1 of the bill of materials; $q^{N*}_{\alpha ij}$ is the net demand of final product, assembly, sub-assembly or component i in time window j at the hierarchical level α_1 of the bill of materials to be produced or ordered; $\vartheta^{pre}_{\alpha_1 i\alpha k}$ is the specific incorporated amount of assembly, sub-assembly or component i at the hierarchical level α_1 of the bill of materials into the final product, assembly or sub-assembly k at the hierarchical level α of the bill of materials.

- **Determining net demand**. From the gross demand, the net demand is calculated by taking into account the stock and the safety stock:

$$q^B_{\alpha_1 ij} \geq k^{*b}_{\alpha_1 ij} \rightarrow q^N_{\alpha_1 ij} = q^B_{\alpha_1 ij} - k^{*b}_{\alpha_1 ij} + b_{\alpha_1 i} \tag{2}$$

$$q^B_{\alpha_1 ij} < k^{*b}_{\alpha_1 ij} \rightarrow q^N_{\alpha_1 ij} = 0 \tag{3}$$

where $q^N_{\alpha_1 ij}$ is the net demand of final product, assembly, sub-assembly or component i in time window j at the hierarchical level α_1 of the bill of materials; $k^{*b}_{\alpha_1 ij}$ is the beginning inventory of final product, assembly, sub-assembly or component i in time window j at the hierarchical level α_1 of the bill of materials; $b_{\alpha_1 i}$ is the safety stock of final product, assembly, sub-assembly or component i. The $k^{*b}_{\alpha_1 ij}$ beginning inventory is the sum of the previous week's ending inventory and the arriving moving inventory. The safety stock must be taken into consideration.

- **Computing inventory after fulfilling demands**. Since the net demand is the difference between the gross demand and the stock taking into account the safety stock, the stock should be reduced by the difference between the gross demand and the net demand after the net demand has been determined:

$$k^{*e}_{\alpha_1 ij} = k^{*b}_{\alpha_1 ij} - (q^B_{\alpha_1 ij} - q^N_{\alpha_1 ij}) \tag{4}$$

where $k^{*e}_{\alpha_1 ij}$ is the ending inventory of final product, assembly, sub-assembly or component i in time window j at the hierarchical level α_1 of the bill of materials, after the gross demand was fulfilled from the $k^{*b}_{\alpha_1 ij}$ beginning inventory. If the stock decreased by the safety stock is greater than the gross demand, the net demand is zero, i.e. no manufacturing or assembly activity is required, as the total gross requirement can be met from the stock:

$$k^{*b}_{\alpha_1 ij} - b_{\alpha_1 i} \geq q^B_{\alpha_1 ij} \rightarrow q^N_{\alpha_1 ij} = 0 \tag{5}$$

- **Computing moving stocks.** If a moving stock is expected to be received in a given time window, the stock for that time window should be increased by the value of the moving stock before the gross demand is fulfilled:

$$k^{*e}_{\alpha_1 ij} = k^{*b}_{\alpha_1 ij} + \rho_{\alpha_1 ij} \tag{6}$$

where $\rho_{\alpha_1 ij}$ is the amount of moving inventory of final product, assembly, sub-assembly or component i at the hierarchical level α_1 of the bill of materials expected to be received in time window j. Of course, if there is also a gross demand to be fulfilled in a given time window, the expected amount should also be taken into account in (2-3) as follows:

$$q^N_{\alpha_1 ij} = q^B_{\alpha_1 ij} - k^{*b}_{\alpha_1 ij} + b_{\alpha_1 i} + \rho_{\alpha_1 ij} \tag{7}$$

- **Computation of time periods for operations.** An operation can be determined as production, assembly or placing of an order. The start date of an operation can be determined as a function of the net demand date and the lead time of the operation as follows:

$$\tau_{\alpha_1 ij} = j - t_{\alpha_1 i}(q^N_{\alpha_1 ij}) \tag{8}$$

where $t_{\alpha_1 i}(q^N_{\alpha_1 ij})$ is the required time to produce or purchase assembly, sub-assembly or component i in time window j at the hierarchical level α_1 of the bill of materials, which can be influenced by the moving stock scheduled for the net demand of time window j.

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- **Managing production, assembly and order batch sizes and limits.** If a batch size can be linked to a manufacturing, assembly or purchasing operation as a condition, then

$$q^{N*}_{\alpha_1 ij} = \left[q^N_{\alpha_1 ij}\right]^{LOT} \tag{9}$$

where $\left[q^{N*}_{\alpha_1 ij}\right]^{LOT}$ is the amount of required assembly, sub-assembly or component i in time window j at the hierarchical level α_1 of the bill of materials rounded up to the next batch size. If a lower limit (minimum production, assembly or ordering batch size) is set for the manufacturing, assembly or ordering activity, then

$$q^{N*}_{\alpha_1 ij} = \begin{cases} q^N_{\alpha_1 ij} < s_{\alpha_1 i} \rightarrow q^{N*}_{\alpha_1 ij} = s_{\alpha_1 i} \\ q^N_{\alpha_1 ij} \geq s_{\alpha_1 i} \rightarrow q^{N*}_{\alpha_1 ij} = q^N_{\alpha_1 ij} \end{cases}, \tag{10}$$

where $s_{\alpha_1 i}$ is the upper r lower limit of assembly, sub-assembly or component i in time window j at the hierarchical level α_1 of the bill of materials.

If a quantity greater than the net demand has to be produced due to the minimum batch size, part of this quantity produced is added to the stock:

$$q^N_{\alpha_1 ij} < s_{\alpha_1 i} \rightarrow q^{N*}_{\alpha_1 ij} = s_{\alpha_1 i} \tag{11}$$

$$q^N_{\alpha_1 ij} < s_{\alpha_1 i} \rightarrow k^{*z}_{\alpha_1 ij} = q^{N*}_{\alpha_1 ij} - q^N_{\alpha_1 ij}. \tag{12}$$

If an upper limit (maximum production, assembly or ordering batch size) is defined for the manufacturing, assembly or ordering operation, then

$$q^{N*}_{\alpha_1 ij} = \begin{cases} q^N_{\alpha_1 ij} > s_{\alpha_1 i} \rightarrow q^{N*}_{\alpha_1 ij} = s_{\alpha_1 i} \\ q^N_{\alpha_1 ij} \leq s_{\alpha_1 i} \rightarrow q^{N*}_{\alpha_1 ij} = q^N_{\alpha_1 ij} \end{cases}. \tag{13}$$

The second phase of the optimisation is to define the optimal permutation for the required assembly, manufacturing or purchasing operations within each time windows. We can transform the optimised net demands for a more transparent representation in the following way for each time windows:

$$q^{N*}_{\alpha_1 ij} \rightarrow q_{j\zeta}, \tag{14}$$

where $q_{j\zeta}$ represents operation ζ to be perfomed in time windows j. Within the frame of this transformation the net demand for assembly, sub-assembly or component i in time window j at the hierarchical level α_1 of the bill of material is transformed to a simple demand for the same time windows.

The objective function of this scheduling within each time window is the minimisation of the lead time, which can be defined as the minimisation of changeover time, because assembly, production or order time are constant values:

$$C_{\alpha_1 i} = \sum_{j=1}^{j_{max}} \sum_{r_1=1}^{\zeta_{j_{max}}-1} h_{p_{jr_1} p_{jr_1+1}} \rightarrow min. \tag{15}$$

where $\zeta_{j_{max}}$ is the total number of assembly, production or purchasing operation of time window j, p_{jr_1} is the assembly, production or order operation assigned as operation r_1 to time windows j, $h_{p_{jr_1} p_{jr_1+1}}$ is the changeover time between operation r_1 and its subsequent operation $r_1 + 1$, and $C_{\alpha_1 i}$ is the objective function, which defines the minimization of lead times for all time windows of assembly, sub-assembly or component i at the hierarchical level α_1 of the bill of materials.

The third phase is to define the objective function for all hierarchical levels of the bill of materials based on (14) and find the minimal value of the integrated objective function, which can be defined as follows:

$$C = \sum_{\alpha_1=1}^{\alpha_{1max}} \sum_{i=1}^{i_{max\alpha_1}} C_{\alpha_1 i} \rightarrow min. \tag{16}$$

where α_{1max} is the number of hierarchical levels of the bill of materials, $i_{max\alpha_1}$ is the total number of assembly, production or purchasing operation at the hierarchical level α_1 of the bill of materials.

We can define other objective function, which focuses on the total cost model based on the economic order quantity method and dynamic lot sizing problems, where the following cost parameters can be taken into consideration:

- setup cost of assembly, production or purchasing, which does not depends on the amount assembled, produced or purchased: $\boldsymbol{c^{setup}_{\alpha_1 i}}$,
- specific assembly, production or purchasing cost: $\boldsymbol{c^{spec}_{\alpha_1 i}}$,
- specific inventory holding cost: $\boldsymbol{c^{inv}_{\alpha_1 i}}$.

Figure 3 shows the above mentioned computational process to determine the optimal build-to-sequence supply for all final products, assemblies, sub-assemblies and components. The computational method makes it possible to integrate the following optimisation tasks of build-to-sequence supply design from material requirement planning and scheduling point of view: determination of the optimal sequences for build-to-sequence supply, computation of the optimal MRP solution for all hierarchical levels of BOM, define the optimal production schedule to fulfil build-to-sequence demands.

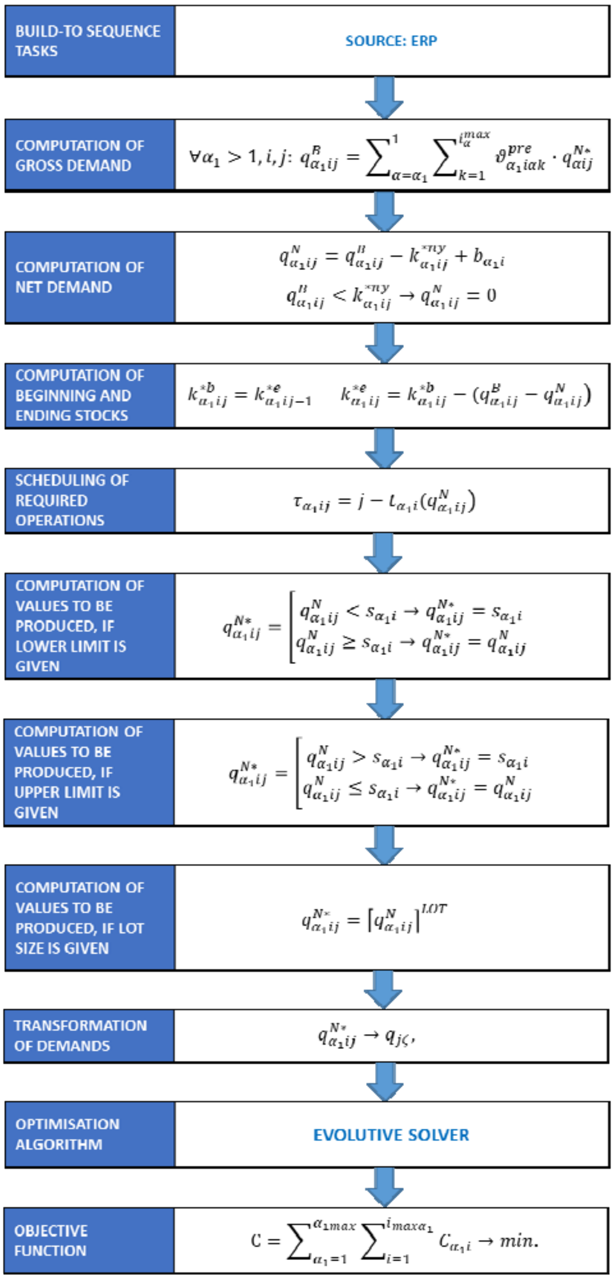

Fig. 3. The computational process to determine the optimal build-to-sequence supply using an integrated optimisation approach, where the determination of sequences is handled as an integrated approach

Within the frame of the next chapter, a scenario analysis will demonstrate the computational results of the mentioned model and validate the performance improvement potential.

5. COMPUTATIONAL RESULTS

Within the frame of this section a short scenario analysis is described to show, how the suggested approach can lead to decreased lead time. The input parameters of the scenario are shown in Figure 4 and 5, including the change over time of a set of final products and a set of required components. The assembly time of the required final products has no impact on the computed total lead time from the optimisation point of view, because the most important constraints of the optimisation defines, that all required demands of customers must be produced on time, therefore only the sum of the changeover time must be minimised.

lead time	A	B	C	D	E	F	G	H
A	0	2	4	6	5	8	5	2
B	5	0	1	4	5	8	5	3
C	3	4	0	4	5	6	6	1
D	6	5	7	0	12	2	1	3
E	3	6	4	5	0	1	1	4
F	9	5	8	6	7	0	2	3
G	4	1	4	7	6	5	0	2
H	8	2	2	4	5	6	5	0

Fig. 4. Changeover time between products A to H for the scenario in [min]

lead time	a	b	c	d	e	f	g	h
a	0	12	15	20	24	12	23	9
b	5	0	11	12	13	15	14	9
c	58	12	0	5	6	8	7	11
d	20	14	22	0	102	21	25	2
e	12	15	12	5	0	9	9	9
f	14	98	13	9	12	0	22	34
g	20	22	25	8	25	55	0	22
h	22	25	52	66	26	66	22	0

Fig. 5. Change over time between components a to h required by products A to H for the scenario in [min]

As Figure 6 shows, four different strategies were analysed to validate the mentioned approach for integrated optimisation. The best strategy is the integrated optimisation, which reduced the lead time with about 71%.

The build-to-sequence demand is predefined by ERP and the build-to-sequence demand is optimised									Lead time
F	1	2	3	4	5	6	7	8	24
C	2	1	6	3	5	7	4	8	55
								Total:	79
The build-to-sequence demand is optimised anf the components' sequences are the same									Lead time
F	5	6	8	4	7	2	3	1	14
C	5	6	8	4	7	2	3	1	225
								Total:	239
The sequences for both final products and the components are optimised									Lead time
F	5	7	2	3	1	8	4	6	14
C	2	1	6	3	5	7	4	8	55
								Total:	69
The build-to-sequence demand is predefined by ERP and the sequence of components is the same									Lead time
F	1	2	3	4	5	6	7	8	24
C	1	2	3	4	5	6	7	8	183
								Total:	207

Fig. 6. Comparison of four different scenarios including different strategies to optimise the sequences for final products and required components (F=final product, C=component)

The following four sequencing strategies were analysed:

- The build-to-sequence demand of customers for final products is predefined using ERP data, which is based on the master production schedule. The build-to-sequence demand for component required to fulfil customers' demands is optimised using the basic schedule for final products.
- The build-to-sequence demand of customers for final products is optimised using the objective function for minimising the total lead time of final products and sequencing of the build-to-sequence demands is the same.
- The sequencing of both final products and required components are optimised taking the build-to-sequence demand into consideration.
- The build-to-sequence demand of customers for final products is predefined using ERP data, which is based on the master production schedule and the sequence of the required components is the same.

6. CONCLUSIONS AND DISCUSSION

Production companies are trying to meet the dynamically changing demands of their customers as cost-effectively as possible. To do this, they are seeking to make improvements in both their technological and logistics processes that will enable them to meet increasingly diversified customer demands more efficiently. An important part of this effort is the optimal material requirements planning, as material requirements have a significant impact on the total cost of production processes, especially in terms of transport, storage and material handling costs. While companies try to operate with low inventory, this stock reduction should not greatly increase the level of supply risk, as unmet customer demand can lead to significant losses for companies in both short and long term. The potential solution for this problem is the just-in-time and just-in-sequence supply.

Within the frame of this article, the author described an integrated approach, which makes it possible to optimise the material requirement planning process for build-to-sequence supply.

As the described model shows, the approach can integrate the following main phases of material requirement planning for build-to-sequence supply: defining build-to-sequence supply demand using ERP data, computation of gross demands, computation of net demand, calculation of beginning and ending inventories, scheduling of required operation, computation of values to be produce while taking lot size-related constraints into consideration, integrated sequencing of demands at the different levels of the bills of materials for all products, assemblies, sub-assemblies and components, computation of the objective function in the case of the optimal solution.

As the described scenario demonstrates, the integrated approach lead to decreased lead time. This approach focuses on the build-to-sequence problem in a deterministic environment, but in future research the stochastic parameters of the build-to-sequence problem can be taken into consideration. Other future research direction is the integration of Industry 4.0 technologies into the logistics processes and transform conventional supply chain solutions into a cyber-physical system, where uncertainties and forecasting options can be taken into consideration.

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