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Generation of Planned Orders and their Matching with Customer Orders in Multi-Variant Series Production

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Abstract

Sustainability of production and supply chains can be achieved by efficient planning. However, customers' demand for multi-variant products and short lead times poses a challenge for automobile manufacturers not receiving customer orders in the mid-term planning horizon. To meet this uncertainty, this paper shall introduce an approach for anticipating customer orders by generating planned orders and for matching planned orders with incoming customer orders.
Planned orders enable the integration of sales planning, production planning and material requirements planning in the mid-term and short-term planning horizons. In conclusion, resources can be used more efficiently to fulfill customer needs.

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Keywords: Integrated Planning; Order-Driven Planning; Option-Based Order Generation; Order Matching

1. Introduction

One challenge in multi-variant series production, as it applies for example to the automobile industry, is the utilization of production network capacities that are provided by making investments based on strategic decisions with variable market demands in terms of the quantity demanded of multi-variant products [1]. In catalogue mass customization, customers configure their product from a pre-engineered catalogue of product variants that are produced following a standardized order fulfillment process [2]. Regarding product variety it has to be distinguished between external variety, referring to the derivatives and option choices offered to the customer, and internal variety, meaning the variations of parts [3]. In build-to-order (BTO) (or assemble-to-order) production, the decoupling point between internal variety based on forecast and external variety based on customer orders is at final assembly [3]. Thus, lead times for production determine delivery lead times for customer orders [1]. In contrast, following a build-to-stock (BTS) strategy, products are assembled according to forecasts and thus external variety is not based on customer orders leading to the problem that inventories of finished goods are high and that customer requests that are different from those in stock cannot be fulfilled [3]. In order to combine the advantages of BTO and BTS, automobile original equipment manufacturers (OEMs) follow a hybrid order fulfillment strategy making use of both BTO and BTS [1]. Pursuing such a strategy, there is an "order freeze" being defined as the point in time when the product configurations of orders of a planning period are fixed in order to release them to production plants [1]. The share of capacity that is utilized by customer orders before the "order freeze" is BTO and the rest is BTS [1]. For the share of BTS, customer orders have to be anticipated by generating planned orders that are free to be matched with incoming customer orders later on [1]. The share between BTO and BTS is not the same for different markets as it depends on the behavior of the customers of a market as well as the proximity of a market to the production sites and the respective delivery times [4]. In the US, only 6% of the cars are BTO whereas in Europe 48% and in particular in Germany 62% are BTO [5].

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Planned orders may be generated directly by an OEM's central sales organization or by intermediaries in the distribution chain such as regional sales offices or local dealers [1]. The "order freeze" for order-driven short-term planning and thus the point in time when options of orders have to be specified for calculating the demand for parts, meaning material requirements planning for the precise call-off, is reached about one month before production [6, 7]. The call-off for parts is defined as communicating the need for material to suppliers that ensure short sourcing lead times based on long-term purchase agreements [8]. It follows a purchase-to-order logic in short-term planning if it is coupled with customer orders and thus not based on forecasts [8]. In the mid-term planning horizon, planning is forecast-driven and thus based on sales forecasts for quantities of models and for relative frequencies of options in different markets on a monthly basis [6]. A preview on the demand for parts is given as a rough call-off to suppliers between 18 to 3 months before production, but it will be fixed at the "order freeze" [6, 7, 9]. The longer the preview is given before production, the less reliable it is [6].

However, for complex, multi-variant products it is not possible to directly calculate material requirements based on forecasted quantities of models and forecasted relative frequencies of options in mid-term planning [7]. As parts typically depend on more than one option, Boolean algebra rules for the combination of options have to be considered [7]. Therefore, the planning of material requirements may be based on the BOM (bill of material) explosion of fully specified orders [7]. Thus, the generation of planned orders based on forecasts should not be delayed to short-term planning but should already be conducted for mid-term planning to enhance the adequacy of the rough call-off.

In conclusion, this paper introduces an approach for mid-term planning based on planned orders that cannot only be used for mid-term planning of material requirements, but also for mid-term production planning, i.e. the assignment of planned orders to final assembly plants and periods such as weeks, days and cycles in assembly lines. Thus, the approach resolves planning inconsistencies between functional units of a company such as procurement, production and sales. Moreover, it allows for consistency between mid-term and short-term planning as not only short-term but also mid-term planning is based on orders. Therefore, a methodology for the generation of planned orders regarding products with a complex product structure such as automobiles and a methodology for matching of planned orders with customer orders are presented.

The paper is structured as follows: In section 2, a literature review on order fulfillment strategies, on product structures and documentation as well as on forecasting material requirements is provided. Section 3 proposes an approach for order processing as well as methodologies for the generation and for the matching of orders. A summary and outlook is provided in section 4.

2. Literature Review

2.1. Order fulfillment strategies

Since purchasing and assembling parts usually takes longer than the order lead time expected by the customers, some of the processes must be made independent from customer orders. Along the flow of material, the point whose following processes are connected to a customer order is called the customer order decoupling point (CODP). The location of the CODP is the basis for distinguishing the various order fulfillment strategies such as build-to-order (BTO) and build-to-stock (BTS). [10]

Due to the characteristics of the two strategies described, it is difficult to determine a dominant CODP. Therefore, Brabazon and MacCarthy [11] described a concept, in which a customer order can be fulfilled by any kind of inventory, meaning that for each customer order received, a suitable product from the order fulfillment pipeline is identified and assigned to the customer. This pipeline includes all products that are in stock and all planned orders that have not yet been assigned to customers. Since the matching of customer orders with planned orders can occur along the entire pipeline, the CODP is floating and not fix. When planned orders are generated, the customer behavior is anticipated as the coupling with customer orders, i.e. the matching, takes place later on. Therefore, the respective strategy is called Virtual-Build-to-Order (VBTO). The greater the quantity of product variants, the lower the probability for finding a suitable planned order for matching with an incoming customer order. Thus, for successful matching, it is necessary that the specifications of the planned orders can be adapted to the ones of the customer orders. This potential for adaptation is dependent on the position of the planned order within the pipeline because the nearer the order approaches to the time of assembly, the more difficult it is to change its specifications. [11]

Due to the individual decoupling point of VBTO, the delivery requests of customers can be considered significantly better than in the ordinary BTO strategy. In addition, the call-off can be based on planned orders. Compared to the BTS strategy, customers have greater influence on the specification of their product and inventories of finished goods are reduced. [11]

2.2. Product structure and documentation

Product structures can be described graphically as trees that can be converted into tabular forms such as bills of materials. Common trees used for product structures are the feature tree and the variant tree.

The feature tree consists of three levels with the product itself on the first level and its features, i.e. option groups, on the second level. The third level comprises the characteristics of the features, i.e. options. Therefore, the height of the tree is short. Each product variant is described by the selection of several leaves. Constraints regarding combinations of specific options have to be defined between nodes. [12]

In the variant tree, each level is dedicated to one product feature, i.e. option group, so that one feature characteristic, i.e. option, has to be chosen on each level. Thus, one product variant is represented by a path through the tree from the root to one of its leaves. Consequently, the number of leaves equals the number of different product variants. Combinatorial constraints can easily be integrated into the variant tree by eliminating nodes that cannot be chosen based on its predecessor nodes. Variant trees are quite complex as each option appears in the tree on each buildable path which results in a tall and wide tree. [12]

In the automobile industry, a variant tree can be used to represent a car model. The different levels in the tree represent the option groups of a car model such as wheels, tires and headlinings [13].

For automobiles, a rule-based product documentation is applied in order to combine all possible variants in one structure. This documentation consists of two different layers: the option layer and the part layer. [7, 14]

The first layer comprises the features that can be chosen by a customer to configure a car and which are referenced as options. These options are encrypted as “codes” at the automobile manufacturer. Basically, two kinds of options can be distinguished: mandatory options and non-mandatory options. Mandatory options build option groups, and for each group one alternative option must be selected to configure a car. Non-mandatory options are additional features that are not necessary for building a complete car. [15]

Due to technical, legal and sales-related restrictions, options cannot be freely combined within an order. Therefore, rules are implemented by means of Boolean algebra regarding the combination of codes as constraints concerning buildability and dependency. Buildability rules contain the requirements that must be fulfilled so that options can be combined in a product. Dependency rules include information about mandatory combinations of options within a product, so that further options not chosen by the customer have to be added to the product based on these rules. [7]

Whereas the product is fully specified in terms of options, i.e. codes, on the first layer, the second layer represents the bill of material consisting of the parts required for the assembly of the product. Both layers are connected by built-in rules that have to be analyzed for a specified product in order to derive the required parts. [7, 14]

2.3. Forecasting material requirements

Due to the complex product documentation of multi-variant products, forecasting material requirements represents a challenge. In general, three dimensions of products are forecasted. The first one, the model mix, constitutes the quantity of vehicles of a certain model to be sold in a particular market. The second dimension to be forecasted consists in the option mix which is the relative frequency with which certain options are expected, i.e. the probability, for a car model in a particular market. The third dimension provides information on the product documentation that is valid during the respective planning period. As the BOM explosion is based on the combinations of options, required parts cannot be derived based on these three dimensions directly. [7]

Therefore, different approaches are presented in the following, addressing the issue of material requirements planning: non-order-based and order-based methods [16].

According to one of the non-order-based methods, parts are directly forecasted by conducting a time series analysis based on information about the amount of parts that has been required in the past. As this method only considers the part layer, it doesn’t respect buildability and dependency rules and it has no link to sales forecasts based on the option layer. To overcome the latter, forecasts on options can be used to determine parts by applying built-in rules. [7, 14, 15]

Stäblein [7] introduced such a method calculating intervals for the required parts using forecasts for the model mix and the option mix as well as built-in rules, buildability rules and dependency rules as input. Since the probabilities of different options are known, a minimum and a maximum probability for the combination of options in terms of built-in rules determining parts are calculated. If the interval is zero, it is possible to directly calculate the demand for this part. Otherwise, data from previous orders are applied within a mathematical optimization model. [7]

Kappler [9] presented the calculation of intervals not only for parts but also for the model mix and option mix forecasts. Thus, intervals for all options are calculated by transforming and analyzing the buildability and dependency rules. The combinations of options are considered more effectively than in Stäblein’s approach. [9]

Order-based methods generate planned orders to determine material requirements based on final products [16]. A planned order can either be a representative of a multi-variant product, a former customer order or a virtually generated order [15]. Different ways for generating virtual planned orders are introduced in literature.

Wagenitz [17] suggested the generation of planned orders starting with empty planned orders in the beginning and adding options subsequently. For this purpose, the options are grouped in feature families, as e.g. stereo, transmission and seats. Out of each family, a planned order receives one feature. While adding the features to a planned order, the buildability rules are checked. After having added the features, it must be checked if the planned orders are within the boundaries of the forecasted option mix. If this is not the case, the pool of planned orders is adapted by eliminating a respective order and adding a new one. [17]

Liebler [18] established a model consisting of three layers for generating planned orders. The first, outer layer is responsible for meeting the required quantity of orders while the second layer ensures that the forecasted option mix is met. Therefore, options are prioritized based on their influence on other options and the deviation of their current option mix from the forecasted option mix. According to their priority, options are added to planned orders. Buildability and dependency rules between options are considered in the third, inner layer. [18]

Order-based methods consider all combinations between options implicitly, which is not the case for non-order-based methods. However, the order-based methods found in literature do not use a tree structure that may enhance the efficiency of order generation.

3. Proposed approach and exemplary application

3.1. Order processing with planned orders

For a successful application of the VBTO system, high forecast accuracy of customer behavior is necessary, so that realistic planned orders can be generated. Inaccurate forecasts result in many adaptions of planned orders and in high inventories of finished goods due to planned orders being unsuitable for matching them with customer orders. Furthermore, it is necessary to create a holistic approach, which provides temporary continuity by pulling planned orders from the time of generation up to final assembly.

In mid-term forecast-driven planning, quantities of models that are planned to be assembled at each plant are assigned to markets or retailers as customer orders are assigned to plants not earlier than in short-term planning [6]. In contrast, in the presented mid-term order-driven planning system, planned orders being generated in monthly order pools are assigned to final assembly plants within the production network given the capacity of each plant. As material requirements can directly be determined by a BOM explosion [7] of planned orders, the rough call-off can be based on this information. Moreover, not only constraints on options in final assembly, such as Car Sequencing rules, but also supplier constraints regarding the levelling of parts can be taken into account on an aggregated monthly basis when assigning orders to plants [19]. At each production site, the monthly pool of assigned orders is the basis for further assigning orders to weeks and days. Finally, they have to be assigned to mixed-model assembly lines and to cycles within the lines, so they have to be sequenced [19].

In the presented planning system, the planning of assembly and supply is decoupled from customer orders, but coupled with planned orders and thus order-driven in the mid-term planning horizon. Incoming orders are not considered in the planning directly, but are matched with planned orders that are already in the planning pipeline. The order-to-delivery time of a customer order is therefore variable and depends on the location of the matching partner in the pipeline. Thus, the order fulfillment process is continuous between mid-term and short-term planning creating a planning reliability for all internal functional units involved, such as procurement, production and sales as well as for external stakeholders, such as suppliers and customers. In conclusion, the customer order decoupling point is floating in this VBTO system, but the planned order decoupling point (PODP) is fix. The PODP being located before the rough call-off allows pursuing a purchase-to-order strategy based on planned orders.

3.2. Generation of planned orders

As planned orders are required for the introduced VBTO system, an approach for the generation of planned orders using the product structure of a variant tree is introduced. Thus, material requirements are determined using an order-based method. However, the method should be used for parts with high value and steady demand as a program-oriented material requirement planning is applied for them in general [20]. Parts with low value and parts with very low probability of demand should be kept in stock. The latter might not be included in the planned orders due to the rounding that is necessary and which is introduced in the following.

In order to generate planned orders for each model and market, two different inputs are required. On the one hand, the product documentation is needed including buildability and dependency rules. On the other hand, the forecasted model mix and option mix have to be provided for each market. Furthermore, direct forecasts for conditional probabilities between options and joint probabilities of options, such as probabilities of option packages, can be included if available. It is assumed that probabilities are forecasted and thus provided by sales only for options that can be chosen by the customer in a product configurator, i.e. customer options, and not for options added due to dependency rules. Thus, a concept based on customer options is introduced in the following.

After having selected a car model, customers must choose mandatory options from several possible alternatives, e.g. wheels [13]. Furthermore, they can choose non-mandatory options, meaning optional equipment like a sunroof [13]. They can also choose packages, such as the “business” package including the options “parking pilot” and “seat heating” [13]. Thus, package options are options that refer to other options.

Mandatory options are essential for the structure of the product, meaning that a customer must choose one option o_i of a mandatory option group O. The sum over the probabilities of all options in one group must be one, as in each product exactly one of the alternative mandatory options is included (1). Thus, the variant tree of a product can be created including all mandatory options. As each node represents an option of a group, probabilities can be assigned as attributes to the nodes.

$$P(O) = \sum_{i=1}^{n} P(o_i) = P(o_1) + P(o_2) + ... + P(o_n) = 1 \qquad (1)$$

Creating the variant tree, a sequence for adding the option groups as levels of the tree has to be determined. Option groups influencing other option groups should be ranked first, e.g. wheels before tires. Considering the buildability rules, only options that are buildable as a successor of the predecessor nodes can be added as illustrated in figure 1. In the example, the two option groups O and P are illustrated of which O represents the wheels and P the tires, each with their several alternative options.

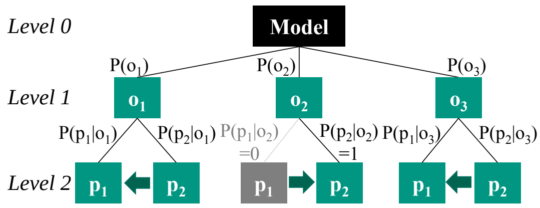

Figure 1: Variant tree for order generation with mandatory options

If no conditional probabilities are explicitly given, probabilities are assigned to the nodes according to the option mix as implicit conditional probabilities, e.g. in (2).

$$P(p_1) = P(p_1|o_1) = P(p_1|o_2) = P(p_1|o_3) \qquad (2)$$

However, in the case of a non-buildable combination of options, such as o_2 and p_1 in the example given above, with $P(p_1|o_2) = 0$, the conditional probabilities have to be adjusted inasmuch as (1) and (2) are violated. Therefore, probabilities have to be shifted in order to attain the required option mix of p_1, which is $P(p_1)$. Therefore, probabilities $P(p_1|o_1)$ and $P(p_1|o_3)$ have to be increased according to (3). As $P(p_2|o_2)$ has to be increased up to 1 because $P(p_1|o_2) = 0$, the probabilities $P(p_2|o_1)$ and $P(p_2|o_3)$ have to be decreased in order to attain the required option mix of p_2, which is $P(p_2)$, following (3).

$$P(p_j) = \sum_{i=1}^{n} (P(p_j|o_i) \times P(o_i)) \qquad (3)$$

Having created the variant tree with all mandatory options and respective probabilities, the implicit conditional and joint probabilities following the paths in the tree reflect the option mix forecasted by sales as well as the buildability rules given in order to build the final products. Each product variant, which is represented by a path from the root to a leaf, is described by all mandatory options. Multiplication of the probabilities along the path results in the probability of the specified product variant. By multiplying this probability with the forecasted quantity of the model, the quantity of the respective variant can be calculated. To achieve an integer number, the number has to be rounded.

As reduced planned orders only consisting of mandatory options are gained by the described procedure, non-mandatory options have to be added in order to get the planned orders with fully specified products based on customer options. Therefore, the number of planned orders of a model containing a specific non-mandatory option has to be calculated by multiplying the quantity of the model by the probability of the option given in the option mix. Having this number for each non-mandatory option and rounding it to an integer number, the options are added to the reduced planned orders under consideration of the buildability rules until the calculated integer number is reached.

The resulting output of this method is a pool of planned orders based on customer options. Options that cannot be selected by customers and thus are not forecasted by sales, can be added in a next step based on dependency rules. Based on the resulting fully specified orders, the required parts can be determined by a BOM explosion evaluating the built-in rules.

3.3. Matching of planned orders with customer orders

The structure of the order fulfillment pipeline can be divided into a set of segments as proposed by Brabazon and MacCarthy [11] for the VBTO system. However, in order to maintain the highest adaptability of planned orders, so that they are suitable for matching with customer orders, there might not be only one “order freeze” for the whole product, but also an independent “order freeze” for each option [11]. As procurement lead times of different parts may not be the same, each option can be specified individually at the latest possible point in time being referred to as distributed order freeze [21, 22]. The order freeze may even not be at the same point of time for different options within one option group [21]. And even after the distributed order freeze of options, they could be swapped between planned orders. Thus, not only one but two different types of freeze points per option are introduced: the call-off freeze and the swap freeze.

The examplary pipeline for one plant with one assembly line with the option groups wheels and tires, including altogether five options as shown above, is divided into 18 segments as illustrated in figure 2. In segment 0, the monthly pools of generated orders for each market are assigned to plants and, later on, to weeks. Orders assigned to weeks are assigned to days later on and then to lines on which they are sequenced. To keep the example simple, no further monthly pools, but two weekly pools and two daily pools are given. In the planning pipeline, a new segment is created either by an assignment of orders to weeks, days, lines and cycles or by the achievement of the call-off freeze or swap freeze of an option. Segments 1, 3, 6, 8, 10, 16 and 17 in the example are started due to the assignments, segments 2, 4, 5, 7 and 9 due to call-off freezes and segments 11, 12, 13, 14, and 15 due to swap freezes. The virtual part of the pipeline ends when an order in the sequence enters the final assembly line and thus, the physical part starts. After the final assembly orders that haven’t been matched with a customer order are stored in the plant stock and after distribution in each market stock. Since the planned orders along the pipeline have originally been generated in order pools for different markets, they are permanently assigned to and can only be matched with customer orders from the respective markets.

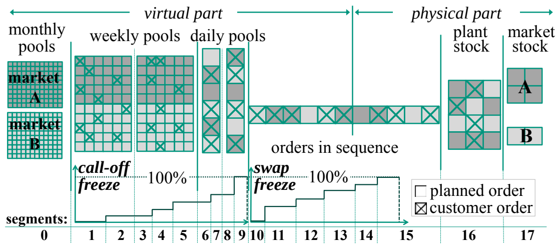

Figure 2: Order pipeline of one plant of a VBTO system

The call-off freeze of an option is reached at the point in time for the precise call-off of the parts depending on the selection of the option according to the built-in rules. Changing options before the call-off freeze allows the flexible adaption to planned orders so that they are suitable for matching. The downside of this, however, is that the mid-term rough call-off of the respective parts communicated to the suppliers has changed. However, through this system, the difference between rough and precise call-off can directly be made transparent for both the OEM and the supplier. It would also be possible to restrict the number of changes regarding each suppliers’ parts. The option o_i of the planned order po_i can only be replaced by option o_j, o_i and o_j being options within one order group, if the planned order po_i has not reached the call-off freeze of both options o_i and o_j. So, the planned order has to be in a segment before the call-off freeze of o_i and that of o_j. Moreover, adaptations of orders are only feasible if the orders are still buildable afterwards according to the buildability rules, and if option-based production restrictions still apply at the plant to which a planned order is already assigned.

If the call-off freeze of option o_i or option o_j is reached, the specification of option o_i of the planned order po_i can only be changed by swapping the option with another planned order po_j that has the favored option o_j and is in the same pool. The swap freeze of an option depends on the time when the sequence of the parts depending on the option has to be built, either by the suppliers or internally. Thus, for a swap, the planned orders po_i and po_j have to be in a segment before the swap freezes of both options o_i and o_j. Moreover, the planned order po_j can only be selected for an option swap, if it has not been assigned to a customer already and if it is of the same pool, the same market and the same model as po_i. Moreover, the orders po_i and po_j have to follow buildability rules and production restrictions also after the option swap.

It has to be ensured that the options are changed in a way that the parts required for both planned orders are the same, before and after the swap, according to the built-in rules. In general, the call-off freeze of an option always takes place before its swap freeze, and they may differ among plants.

When a dealer receives the customer order co, a suitable, vacant planned order within the pipeline ($po_i \in P$) has to be identified. Therefore, a model is formulated that minimizes the matching costs (4) regarding two cost factors. $a_{po_i,co,o}$ represents the cost for adaptation of the planned order po_i in terms of changes and swaps with respect to the call-off and swap freeze in order to make it suitable for matching with the customer order co regarding option o. The cost for a call-off adaptation may be higher than the cost for a swap adaptation as the former affects the suppliers. The cost for a delivery effected earlier or later than desired by the customer is considered by $t_{po_i,co}$ based on the pool of the planned order. The cost may be regarded in terms of inventory cost in case of a delivery made earlier than desired and in terms of penalty cost in case of a delivery that is performed later than desired [19, 23]. Distribution cost from the final assembly plant to the customer as well as cost for material and assembly [19] may not be considered in this model for matching but when assigning planned orders to plants. The cost factors may be normalized and weighted (w_a, w_t).

$$min \sum_{i=1}^{P} (x_{po_i,co} \times (w_a \times (\sum_{o=1}^{O} a_{po_i,co,o}) + w_t \times t_{po_i,co})) \quad (4)$$

$$\sum_{i=1}^{P} x_{po_i,co} = 1 \quad (5)$$

$$x_{po_i,co} = 0 \ \forall po_i \in \{P \mid m_{po_i} \neq m_{co} \vee o_{M,po_i} \neq o_{M,co}\} \quad (6)$$

$$x_{po_i,co} \in \{0,1\} \quad (7)$$

The constraint found in (7) defines the decision variable as a binary variable for matching. Constraints found in (5) and (6) ensure that only one planned order is selected for matching and that planned orders of other markets m and of other product models o_M are not considered for matching.

4. Summary and outlook

In this paper, an approach for order-driven planning with the generation of planned orders including material requirements planning in the mid-term planning horizon and the matching of planned orders with incoming customer orders is presented. The approach provides a consistent planning pipeline from mid-term to short-term planning with buildable orders guaranteeing a high planning reliability for all stakeholders. Thus, production networks and supply chains become more sustainable as resources are utilized more efficiently by avoiding short-term disturbances as well as respective transportation of parts and high safety stocks for parts. A variant tree is used as product structure for mandatory options in order to generate buildable planned orders. The model for matching offers the customer a product-service of highly flexible order specification able to consider desired delivery dates with direct confirmation.

Next, it will be necessary to validate the approach with data from an automobile company.

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