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A modular-based approach for Just-In-Time Specification of customer orders in the aircraft manufacturing industry

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ABSTRACT

The demand for flexibility in the configuration of highly customized capital goods such as aircrafts is rising. Customers request specifying product options later than required by the currently defined order fulfilment process of the OEM. However, late changes of previously configured products can cause disturbances in global production networks.

In this paper, a modular-based approach is presented, allowing customers to specify options just-in-time depending on the respective lead times following an Engineer/Order-to-order (EOTO) strategy. The concept of Just-In-Time Specification with its respective phases of order specification and steps of production planning is described and applied to the aircraft manufacturing industry.

Introduction

Aircrafts are products entailing high capital commitments on the one hand and a wide range of customer-specific variants on the other hand. The cabin configuration of the aircraft is strongly influenced by the customer's requirements and preferences leading to high engineering efforts for every newly designed aircraft version, the so-called Head of Version. The request for customization is rising due to airlines facing growing competition, particularly in the low-cost business [2]. A rating of the potential for an application for product configuration with the selection of features at the latest possible point in time was given by thirty experts in the area of global production in a survey conducted at the 1st Expert Conference for Global Production. Twelve of them rated the potential as “high” and eleven as “rather high” among the given alternatives “low”, “rather low”, “rather high” and “high”. Consequently, the demand for more sophisticated customization as well as higher flexibility when defining the product configuration, e.g. the aircraft configuration, is increasing.

Due to customization requests, the architecture of each aircraft version delivered to one client is unique, even within the same aircraft family. Any customization on one component could imply some modifications on other connected components. Furthermore, there is the recurrent request for short-term changes of the aircraft configuration by customers after the regular specification freeze, so-called customer late changes. On average, there have been several customer late changes per delivered aircraft at Airbus in the past causing additional efforts for the engineering department responsible for processing customer late changes. One third of customer late changes were related to Head of Versions, but two thirds to Rebuilds, that are rebuilds of Head of Versions and thus actually are not meant to deviate from the Head of Versions. Most of the customer late changes are related to the cabin configuration that is an important indicator for the workload accruing in final assembly.

Moreover, customers worldwide order aircrafts with individual requirements regarding the order fulfilment process, e.g. requesting specific production locations, delivery locations and delivery dates.

In addition to such commercial constraints, aircraft manufacturers have to deal with industrial constraints regarding their global production and supply chain network. From a production planning perspective, the challenge not only lies in ensuring aircraft assembly on time and of high quality, but also in how and when to allocate orders to plants and periods such as months as well as to assembly lines and cycles in the existing global production network. When conducting such planning tasks, the various constraints driven by the customers as well as the suppliers

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of parts have to be taken into account in addition to the constraints of the internal global network of final assembly facilities.

Considering that today's aircraft specification process is limited by a fixed deadline, i.e. specification freeze, for order specification which is potentially set earlier than necessary while customers require a faster reaction to market trends, the need for a new concept of product configuration arises. To do so, manufacturers need to provide new interaction tools as a service helping customers to identify potential customization possibilities and to set easily their own preferences. Connected to other business tools, data gathered from such tools should help designers and production planning managers to anticipate the integration of these needs in the development process as soon as possible.

The benefits of using product configurators to improve the customization facilities during the ordering process are widely discussed in literature [47]. Increasing variety of products, simplifying the customer ordering process and connecting the product architectures and production strategies are examples of these benefits [24,44]. This conducts to cost saving and reduction of lead time along the whole development process [21,24].

However, answering to such customization requests using product configurators requires high flexibility of the production and supply chain processes. Smart co-definition of product structure and production network should be deployed to anticipate the customer changes and ensure the management of these changes' propagation across the product development process (i.e. aircraft), spanning all product, process and resource dimensions.

In this paper, a modular-based approach for Just-In-Time Specification (JIT Specification) of customer orders linking the product configuration phase with order fulfilment strategies as well as the production planning phases is proposed. The modular-based approach is applied to the Airbus A320 family, the world's best-selling single-aisle aircraft family of one of the global leading aircraft manufacturers.

The paper is structured as follows: in Section "Modular-based approach for the Just-In-Time Specification service", a modular-based approach for Just-In-Time Specification is introduced. The application of this approach to the aircraft manufacturing industry is presented in Section "Application of the modular-based approach for Just-In-Time Specification to the aircraft manufacturing industry". Finally, Section "Business models discussion" discusses the industrial business models exploiting the proposed approach. A conclusion is given in Section "Conclusion".

Modular-based approach for the Just-In-Time Specification service

It is actually agreed that focusing on innovative physical solutions for improving product quality is not enough to cope with the high pressure and competitiveness of the nowadays globalized markets. Companies should propose additional offers that increase the added value and attractiveness of their products [40]. Better understanding of customer needs and stronger relationships with customers along the product development process is one way to address this issue. In the aircraft manufacturing industry, the development process is very long and any decision has strong impact on the final results. Moreover, the ordering and production of one aircraft for a customer is challenging because the customer already requests for changes. It is of the interest of the manufacturing company to answer as far as possible to these challenging needs.

To cope with high customization requests and changes of requirements during the development process as well as the order fulfilment process, the aircraft manufacturer could offer new free services to his customer giving the possibility to select and/or modify some pre-defined product features, at different points in time. Customization itself is not a new paradigm; several platforms are often proposed to support mass customization strategies [32]. The positive impact of a product configurator on the customer–provider relationship performance is clearly highlighted by Trentin et al. [43]. By such tools, the customer is continuously involved in the product configuration process, with reference to the whole development process.

However, due to the particularity of the aircraft manufacturing domain, not all characteristics are available for customization. In all cases, customization possibilities should be carefully prepared and managed very early in the design process to avoid any negative impact of the customers' orders on the production planning. In this paper, the concept of JIT Specification is proposed as a customization support for the final assembly of multi-variant series products such as single-aisle aircrafts.

Just-In-Time Specification service

The JIT Specification service can be offered for free to customers such as airlines and aircraft leasing companies, which are considered as target customers of the aircraft manufacturer. By the JIT Specification service, the customers' requests influence the customization of the aircraft and the subsequent allocation of the orders within the production network. This can be managed as a customer-driven co-evolution of the product structure and production strategy.

To manage such co-evolution strategy, an interactive process involving several stakeholders is required as it is shown in Fig. 1.

Three main stages have to be distinguished in this process:

- **Design**: This is the preparation stage, which involves the product designer and production process engineer to define potential solutions as new offers to the customers. The customizable product is composed by a set of standard components common to all products from the same family and additional options to be selected by the customer to be implemented on his own product. In parallel, the production process is designed to define the implementation solution of the designed product. The main strategy of the design process is to anticipate the large variety of customer preferences based on preliminary surveys and previous customers' feedbacks. This contributes to enhance knowledge about real customers' needs. Thus, several alternatives of the main product architecture are created at the back office of the JIT specification configurator using a modular-based approach. Every alternative is an encapsulation of a common element and

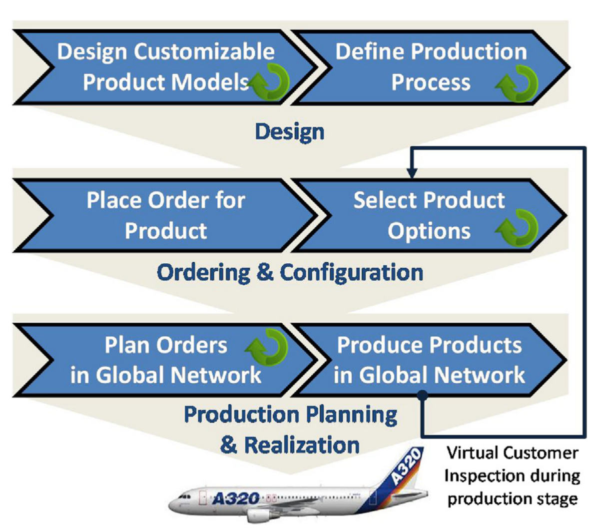

Fig. 1. Global JIT Specification process.

additional modules implementing options to be proposed to the customers in the configurator. However, taking advantages from the customer feedback and new technologies, the design department can improve the product architectures along the time by either replacing some modules by new ones or creating new alternatives of the architecture for the same family (i.e. A320 in this case). This will affect the number of options offered to the customers for future ordering.

- **Ordering & Configuration**: In this stage, customers may configure/specify their product by selecting available options offered to them from the designed product architecture. A feedback mechanism might be used to collect additional customer needs that are not aligned with the offered options. Alternatively, an iteration on the design stage can be envisaged to consider, if possible, part of the new specific requirements in updated product/process architectures. After specifying the different options, the client can confirm his order to start the final planning and realization stage. Product configuration is also an iterative process as the selection of modules by the customer does not have to take place at a single point of time, but can rather be distributed over a period of time specifying modules each at the latest possible point in time, being also referred to as Just-In-Time Specification or distributed order freeze [4,12,29]. JIT Specification offers the customer more flexibility when customizing the product in order to enable fast reactions to current market trends. Interoperability with production department is necessary to guarantee this flexibility without disturbing the final assembly process.
- **Production Planning & Realization**:This final stage starts directly after the confirmation of a customer order. After the integration of the new demand in the global production planning, each product configured by an individual customer, has to be allocated to a final assembly facility for production. Based on production network design, all facilities being capable of assembling the selected product architecture are valid for an order to be allocated. Moreover, the maximum availability of production capabilities within a certain production period restricts the number of orders with its specific options to be allocated to a period. Additionally, the distance from a customer's location to the final assembly facility may also be taken into account when allocating an order. Here also, iterative mechanisms are used for updating the production planning, when some customer options are selected. Communication with final assembly facilities and suppliers is required to validate these updates.

In addition, during the last stage of production, an additional free service may be offered to the customer to collect feedback through a virtual customer inspection of the aircraft showing the actual physical status and giving an overview about how the selected options look like. This is also an occasion for the customer to ask for late changes on a limited set of options.

In contrast to classical product configuration strategies [48], the main proposition of the JIT Specification approach is its flexibility and dynamic character, allowing customers' option selections and thus changes of customer requirements later than currently required, and in some cases even after production has already started. To do so, there is a need to track and manage the propagation of changes of requirements along the development process stages. This complexity requires the management of several product variants in the same product architecture [8], but also the splitting of this product architecture into a set of elementary items to easily handle the configuration of demand solutions. This decomposition should also allow the reference of the product structure (design solution) to the production process (manufacturing solution) to support the impact of any modification of the product structure on the final assembly process.

Co-evolution and modularity concepts seem proposing relevant advantages to deal with this problematic. The next section discusses the advantages of modularity concept to support the propagation of customer requirements along the whole development process till the assembly stage with the concept of JIT Specification.

Concepts of modularity and co-evolution

According to Tolio et al. [42] the term "co-evolution" represents the ability to strategically and operationally manage the propagation of engineering changes to gain competitive advantage from the resulting market and regulatory dynamics. The success of any co-evolution strategy should be based on robust models ensuring the global consistency between all data and decisions produced at different managerial levels of the development process.

The power of modularity to support co-evolution strategy is clearly laid out in the literature [36] since it consists of decomposing complex systems into independent but interconnected parts that can be treated as conceptual, logical, physical as well as organizational units [25].

In modular design theory [23], the concept of a module is used to represent a physical or conceptual grouping of product components to form a consistent unit that can be easily identified and replaced. Modularity is the concept of decomposing a system into independent parts (modules) that can be treated as logical units [4,23]. Based on this, the modular design process aims at connecting the constructional elements into suitable groups from which many variants of technical systems can be assembled. As an output of this process, a generic product architecture (GPA) can bring cost savings and enable quicker introduction of multiple product variants, through the concepts of product family [18] and configuration mechanism [17]. Pahl and Beitz [34] proposed to connect the concept of modules as a physical implementation of a product function, which answers to how the product will answer to a set of customer needs. Connecting modules to functions avoid any error on the identification of the borders of modules in one product architecture. It also allows the classification of modules depending on types of functions (basic, auxiliary, special and adaptive). Additional criteria are used for the definition of modules such as importance, complexity, combination, application, etc.

The product architecture describes the way by which the product functions are arranged into physical units and the way in which these units interact to implement these functions [45]. The whole product structure is obtained by the specification of modules' interfaces to support connections between modules in specific configurations.

The GPA can be constructed by using different methods [9,15,39]. However, the fundamental ideas are common: break systems into discrete modules; ensure modules interchangeability with other ones; and provide well-defined interfaces between modules in the targeted GPA. Thus, modularization consists of deciding about the characteristics used to group separate different components in one common module.

Following the modular approach, any product architecture is composed by a set of core modules that are not modified and flexible modules that can be replaced by other ones providing the same function. The degree of modularity for one product refers to the proportion of modules with high level of exchangeability for the same function [31], allowing the possibility to derivate several alternatives of architectures from a common product framework and offering more customization facilities.

The modularity concept is present at different stages of the product development process. As stated by Pandremenos et al. [35], three design and management fields can be considered for modularity application: product architectures, production process and customer needs. To exploit modularity for co-evolution perspective, the concept of modules is extended as a kernel, connecting in a structured way three complementary dimensions (so-called pillars).

Shows the connection between these three layers in both customer configuration view (at the bottom side) and the design of potential solutions (at the upper side) to be used by the product configurator.

- Customer Requirements Pillar:

The first pillar is to collect and classify all customer needs; regional market properties and constraints for the targeted business context. In the context of JIT Specification, two categories of needs can be distinguished: the first category concerns generic needs captured by the marketing department in the design stage and transformed to product functions. The second category of needs is specific to the customer when wanting to configure a customizable version of the product. These needs are considered in the design stage as additional product options to be selected by the customer in the configuration stage.

- Product Definition Pillar:

In the product definition pillar, every need is mapped to a set of functions that express what is really expected from the product to answer each need. Every product function is implemented in the design stage according to this pillar by one or several product modules representing possible physical solutions. Several alternatives of product architectures will then be built as a combination of module alternatives for one set of functions.

Following the JIT Specification process, every additional option is directly connected to a product module. The selection of a set of options within the customer requirements pillar (in the configuration stage) implies the selection of one and only one product structure from the set of predefined structures provided in the design stage.

- Production Pillar:

The last pillar aims to identify production capabilities and potential suppliers able to provide the designed modules. The whole production network is built as a combination of potential production capabilities and suppliers [11] considering market constraints and company policies. Based on the available production capabilities and suppliers, every product structure alternative designed in the Product Pillar, is connected to a process alternative in the Production Pillar, composed by a set of manufacturing and supplying activities.

Following the JIT Specification process, the selection of one product structure respecting a set of selected options in the configuration stage implies the selection of one and only one production process. In the production planning and realization stage, this process is used to define the final production planning based on the order dates and the local planning of involved production capabilities and suppliers.

Concretely, the navigation between the three pillars (Fig. 2) is a closed loop process where the first step concerns the design of

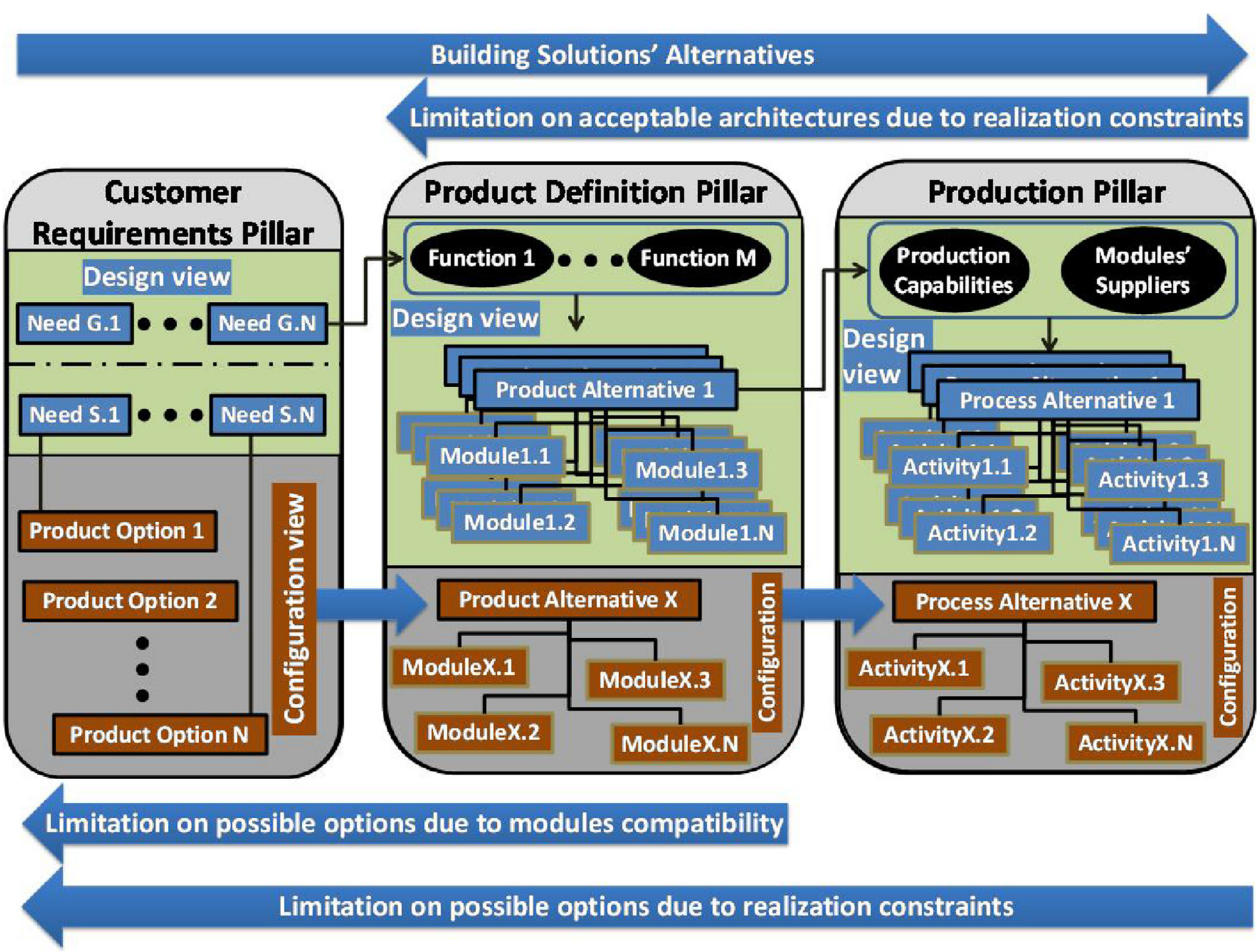

Fig. 2. Global modular-based approach.

potential solutions regarding a set of generic needs. Every need is mapped to at least one product and one production solution. The first loop is also part of the design process and aims to select only suitable product alternatives that are technically feasible regarding the production capabilities in the available production sites. The last loop is dedicated to the connection of the design view to the configuration and ordering view through the identification of one solution and only one that fully meets the specific customer options. Respecting the JIT Specification principle, only options that the company knows how to provide are allowed for being offered in a product configurator to be selected by the customer. This is possible through the propagation of production constraints and modules compatibilities in product architectures as a filter for the displaying of options able for customization.

To support the construction and the navigation between the three pillars, additional information has to be embedded in the modular approach. Module features are introduced as decision making criteria to address the objectives of product structure creation and connection between the three pillars. This is to support: (a) analyzing customer/market requirements and linking product modules to requested needs through the identification of modules' criticality in the whole product structure according to the importance of their related functions/needs; (b) defining parameters, compatibilities and interfaces of modules to support the consistent selection and combination of product modules; (c) responding to production systems through the integration of production process information in the involved product modules like the position of the module in the assembly process and suppliers' requirements.

The modular-based approach is tailored to support the back office of the JIT Specification service offered by a manufacturing company to its customers. The next sections describe the conceptual fundaments of the two main stages (ordering & configuration and production planning & realization) of the JIT Specification approach. Section "Application of the modular-based approach for Just-In-Time Specification to the aircraft manufacturing industry" explains how the modular JIT Specification approach can be really applied to an industrial use case.

Strategies for customer order fulfilment

For a more detailed description of the modular-based approach for JIT Specification of customer orders, the customer order decoupling point and strategies for order fulfillment are introduced and applied to the approach.

The strategy for order fulfilment generally depends on the position of the Customer Order Decoupling Point (CODP) in the order fulfilment process [22]. Production upstream of the CODP is forecast-driven while production downstream is order-driven [22]. Derived from the position of the CODP within the steps of order fulfilment (engineering, manufacturing, assembly, distribution) [3,22,33], there are mainly four strategies for order fulfilment discussed in literature:

1) Engineer-to-order: The customer is involved in all main order fulfilment steps, starting at a very early stage implying unique engineering or significant customization [3]. One of the key challenges of engineer-to-order (ETO) production is that designs and bills of materials are not complete and evolve over time [28]. The CODP is therefore set before engineering, manufacturing, assembly and distribution as they take place based on concrete customer orders [33].
2) Make-to-order: The manufacturing and assembly of modules starts only after receipt of a customer order [3,20], whereas the development of modules has already taken place beforehand [33]. Thus, the CODP is set after engineering but before manufacturing, assembly and distribution [33]. Order-driven manufacturing of modules can be performed either internally or externally [3]. Thus, in case of internal manufacturing, the modules will be produced by internal facilities. In case of external manufacturing, the modules need to be purchased.
3) Assemble-to-order: The basic parts for the product are already developed and manufactured but only assembled to the final product upon request by the customer [3]. The CODP is therefore set after engineering and manufacturing but before final assembly and distribution [33].
4) Make-to-stock: Products are assembled based on forecasts for final products and stored afterwards [22]. Demands are thus directly satisfied from the finished goods inventory [20]. The CODP is therefore set after engineering, manufacturing and assembly, just before distribution [33].

In terms of the JIT Specification concept, the CODP is set when the customer needs to specify the product configuration for the first time, i.e. when the first option has to be selected. Thus, the CODP is set as early as necessary in order to conduct product configuration and planning of production as well as ordering of modules completely based on customer orders.

For the case of external purchase of modules, the concept purchase-to-order is introduced in literature [37]. A manufacturer can reduce the risks which are related to forecast-based purchasing by placing the purchase order at suppliers only when needed by a specific customer order [37]. The lead time for receiving the modules from the suppliers might be shortened based on agreements with suppliers [37].

In contrast to make-to-order, purchase-to-order emphasizes the external purchase of modules after receipt of customer orders shifting manufacturing responsibility and the order fulfillment strategy related to the module towards the respective external supplier. Hence, particularly when using make-to-order manufacturing strategies, modules are manufactured based on customer orders, whereas in purchase-to-order situations, modules may either be supplied from stock or manufactured based on the ordering of the modules depending on the suppliers' strategies. The latter reflects the separated decision making of OEMs and their suppliers. Thus, depending on the order fulfillment strategy regarding modules of the internal or external supplier, modules may be produced based on orders or on forecasts. However, the latter is only possible in case no customer-related engineering of the respective module itself is required. If the production at the supplier is based on a specific order regarding the module and not on a forecast, e.g. for engineering reasons, this leads to a longer ordering lead time and a lower amount of inventory.

The ordering lead time is the time between ordering a module from a supplier and receiving it at an assembly facility. It may include time for engineering, production and transportation of the module. The creation of customer-specific variants implies engineering activities in order to tailor modules in interaction with the customer [27]. Thus, an engineering process may be necessary for a module itself and thus is included in the ordering lead time.

A shortening of ordering lead times due to reduced time for engineering of new modules can be achieved through an additional feedback mechanism from product configuration to product design [4]. Using this feedback, trends can be anticipated and product modules can be adapted and updated accordingly in the iterative design process and offered in the product configurator.

When specifying products, interfaces between modules have to be considered with regard to material, energy and information in order to connect modules according to the product architecture [27]. Thus, additional engineering activities may be required to verify the interfaces of a module with other modules before ordering. The respective additional time needed is referred to as interface engineering lead time. Strictly speaking, interface engineering lead times can be an indicator for the modular-based approach having reached its limits because in a perfectly modular-based approach, the need of verifying or even updating interfaces should not arise. Moreover, these interface engineering lead times cannot be regarded for each module independently as they concern interfaces between modules.

Considering the ordering lead time as well as the interface engineering lead time of a module, the module lead time is defined as the sum of a module's ordering lead time and its interface engineering lead time.

The JIT Specification concept implies that typically no inventory is held at any final assembly facility (except a limited range of options that still can be specified after start of the final assembly) and that modules are only ordered based on customers' product configurations. Neither requiring that modules have to be produced based on orders as it is the case for make-to-order, nor requiring that modules are purchased externally as it is the case for purchase-to-order, an alternative strategy, that can be called Order-to-order (OTO), can be applied for ordering modules from internal or external suppliers without consideration of the suppliers' order fulfillment strategies. Moreover, OTO means that there is not only one CODP for the fulfillment of a customer order in general, but one CODP regarding each module that has to be ordered from a supplier depending on its module lead time. As the interface engineering lead time as part of the module lead time may not be zero, a hybrid order fulfillment strategy called Engineer/Order-to-order (EOTO) is applied for the concept of JIT Specification. In general, when applying the JIT Specification concept, the customer is only asked to select certain options when the information is needed either for the ordering of modules or for the interface engineering of a group of interconnected modules.

Production planning steps and product specification process

In the following, mixed-model assembly with the ability to produce variants of a basic product on an assembly line in any sequence, also referred to as mixed-model assembly line (MMAL), is considered for the planning & realization phase. Hence, the lot size of one can be reached by using flow lines in such a configuration that flexibility and efficiency is maintained despite the huge number of variants to be assembled [6]. When using MMALs in order to produce rather high amounts of customized variants, modularity of the products is advantageous. Modularity not only allows for customization, but also increases the efficiency in production [27].

Planning tasks for the co-definition of product structure and production network realizing products according to the modular-based approach can be decomposed into strategic and tactical-operational tasks [4]. According to hierarchically planning, strategic decisions are taken long-term, whereas tactical and operational decisions are taken mid-term and short-term respectively [13,30].

For realizing the product, the following strategic decisions have to be made: the production network has to be designed determining locations for final assembly facilities being capable to assemble specific product modules. Modules are supplied by internal and external suppliers that have to be selected.

On the tactical planning level, a production program is usually set up based on forecasted demand determining which model is produced in which quantity at which production facility [46]. However, in case customer orders have been accepted when tactical planning takes place, the planning should be based on actual customer orders instead [4,10]. These known customer orders have to be assigned to production facilities for final assembly as well as to production periods such as months [10]. For this first assignment step, also being referred to as global order assignment [10], the costs for the supply and for the assembly of each module of a product, i.e. the supply and production costs, have to be considered for each possible assembly facility respectively. Regarding the supply costs, the costs for the modules itself and their transportation to the assembly facilities has to be considered. As part of the production costs, the costs for the workload deviation, which is the deviation between the workload caused by the assembly of modules of assigned orders and the production capacity at an assembly facility, may also be considered at each facility and in each period. Moreover, costs for the deviation from the delivery period preferred by the customers may be taken into account in terms of inventory and penalty costs as well as costs for the distribution of orders to customers may also be considered [10]. The task of global order assignment is generally illustrated in Fig. 3.

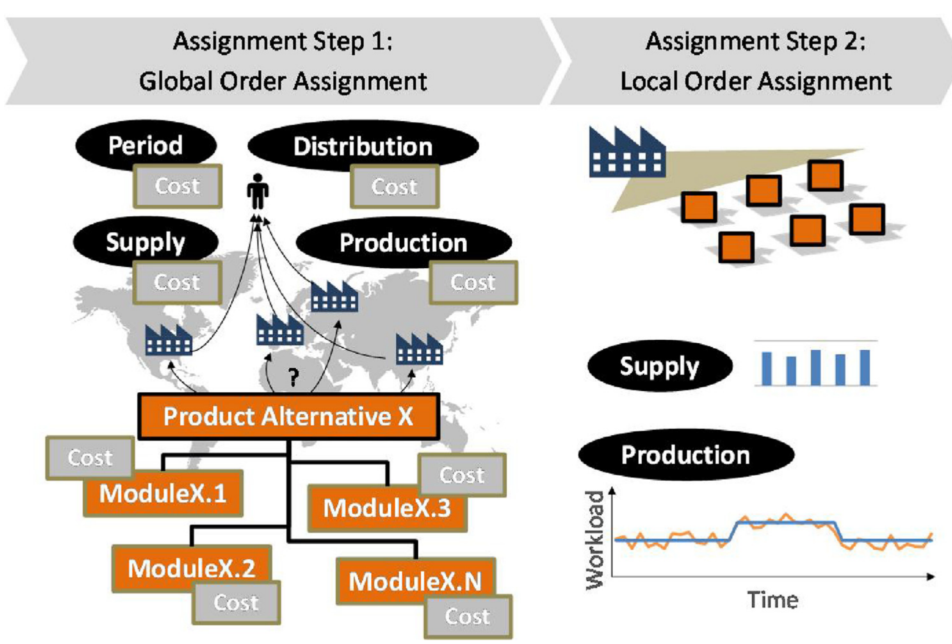

Fig. 3. Global view on the planning process.

Based on global order assignment, the customers whose orders have been allocated can be informed about the planned assembly facility as well as the production period and thus the respective delivery period. Moreover, as the assembly facility needs to be known in order to deliver modules to the right place, the modules of orders can be ordered after global order assignment according to the Engineer/Order-to-order strategy. The latest possible point in time for specifying modules before assembly depends also on the order assignment as each assembly facility might order from different suppliers with different ordering lead times.

Regarding product configuration, modules, which are fundamental regarding the product type such as structural parts, have to be specified before other options that depend on the product type. Moreover, in case not all product types can be produced at all assembly facilities, modules related to the product type have to be selected by customers before the first assignment step takes place. There may also be other modules which cannot be assembled at each final assembly facility due to their regional specification, but which are requested by customers. In such cases, they also have to be selected before global order assignment takes place to guarantee that the order is assigned to an assembly facility being capable of assembling its modules. All modules related to options which have to be selected before the first assignment step can be regarded as long lead time options (LLTO). LLTO represent the first category of options to be selected during the product specification process. As all other options are not specified at this point in time, the first assignment step, global order assignment, has to be performed under uncertainty [29].

Giving the customers the freedom for specifying orders after global order assignment, the risk that the respective workloads caused by the assembly of modules exceed available production capacities and modular-based material requirements exceed supplier limitations in terms of maximum quantities has to be borne by the manufacturing company offering its customers the JIT Specification service [4,10].

In a second assignment step also illustrated in Fig. 3, there has to be a more detailed planning of the production of orders on the operational level at each assembly facility [10]. Thus, the second assignment step can also be called local order assignment [10]. For assembling standardized modules, mixed-model assembly lines (MMALs) may be used as explained at the beginning of this chapter. In case more than one assembly line is available at an assembly facility, each order has to be assigned to one of the existing lines [10]. Moreover, each order has to be assigned to a cycle in which it should be produced on the assembly line [10].

Depending on the manufacturing company, there might be several reasons for splitting up the order assignment process into two steps. Hierarchical planning in several steps is needed to address responsibilities at different times and different globally distributed hierarchical levels within the company. Moreover, starting planning at an early point in time will lead to an increasing visibility of the upcoming production program including the arising risks for production. Such risks could be the rising dependency from one supplier or the detection of upcoming trends such as complex product customization patterns. As most manufacturing companies have globally distributed manufacturing plants entailing different capabilities each, the need for a central global order assignment taking the plant-specific capabilities into account arises. Besides, certain high-tech suppliers may require an early but realistic production forecast or even the real production program early in time due to their long internal lead times which may result from their respective supply chain.

The second assignment step has to be planned when internal and external suppliers require more detailed information regarding selected modules, such as a day instead of a month for the delivery of each module. Whereas the first assignment step alreadydefines a time period such as a month for the start of final assembly, the second assignment step defines the point in time dependent on the duration of a cycle, e.g. on a daily basis. Moreover, more detailed information may also be required for the assembly planning department when conducting planning tasks, e.g. workforce planning and material flow planning based on the sequence of orders on each line. Furthermore, customers can be informed about the planned production cycle and thus about the planned delivery day after having planned the second assignment step.

Considering mixed-model assembly lines, the corresponding workload and material requirements for each variant depend on the modules selected by the customer. Thus, the basic objectives of sequencing orders on lines are to minimize workload deviations and to balance material requirements, i.e. modules to be ordered [7,14]. Therefore, modules causing respective amounts of workload and requiring different material, i.e. modules that should be balanced individually, should preferably be specified before planning the second assignment step. Otherwise, they cannot be taken as input or at least not as deterministic input for sequencing, so that the objectives of sequencing may not be reached in the end. Such options related to modules that should be considered as deterministic in assignment step 2, can be referred to as regular lead time options (RLTO). Thus, the supply costs related to the balancing material requirements as well as the production costs related to the workload deviations, but on a more detailed level than in assignment step 1, can be considered in assignment step 2. The task of local order assignment is illustrated in Fig. 3.

However, from a customer point of view, a maximum of flexibility is generally required in terms of the product configuration so that some options can be specified even after the second assignment step. Such modules, that also have to be delivered by the suppliers before final assembly of the respective order starts, can be referred to as short lead time options (SLTO). Other options, that still can be selected after final assembly has already started as the modules, for instance, may be stored in inventory resulting in very short module lead times, can be called ad-hoc options (ADHO).

As the first assignment step defines the solution space of the second assignment step, the first one has to anticipate the second one. As only long lead time options are specified at the first assignment step, the specification of other options also has to be anticipated, which could be done if customers and their option specifications of previous orders are known [10]. For a more detailed discussion on both assignment steps, please see Buergin et al. [10].

Furthermore, it has to be mentioned that the idea of JIT Specification does not only apply to option specification, but both assignment steps are planned at their latest possible point in time. The whole process for JIT Specification including both production planning steps as well as the phases for product specification is illustrated in Fig. 4. The objective functions of the mathematical models of both planning steps are presented. For a detailed formulation of the mathematical model of assignment step 1, it has to referred to the development in coherence with this paper published by Buergin et al. [10]. The detailed formulations of both assignment steps are beyond the scope of this paper.

Fig. 5 exemplary illustrates the gradual rising degree of product specification during the specification phases. For the assignment steps the degree of automation at the respective point in time is taken into account.

Application of the modular-based approach for Just-In-Time Specification to the aircraft manufacturing industry

Modularity as a major enabling factor for Just-In-Time Specification

The aircraft cabin is a complex system of various elements that have to fulfill customer requirements under physical limitations. In

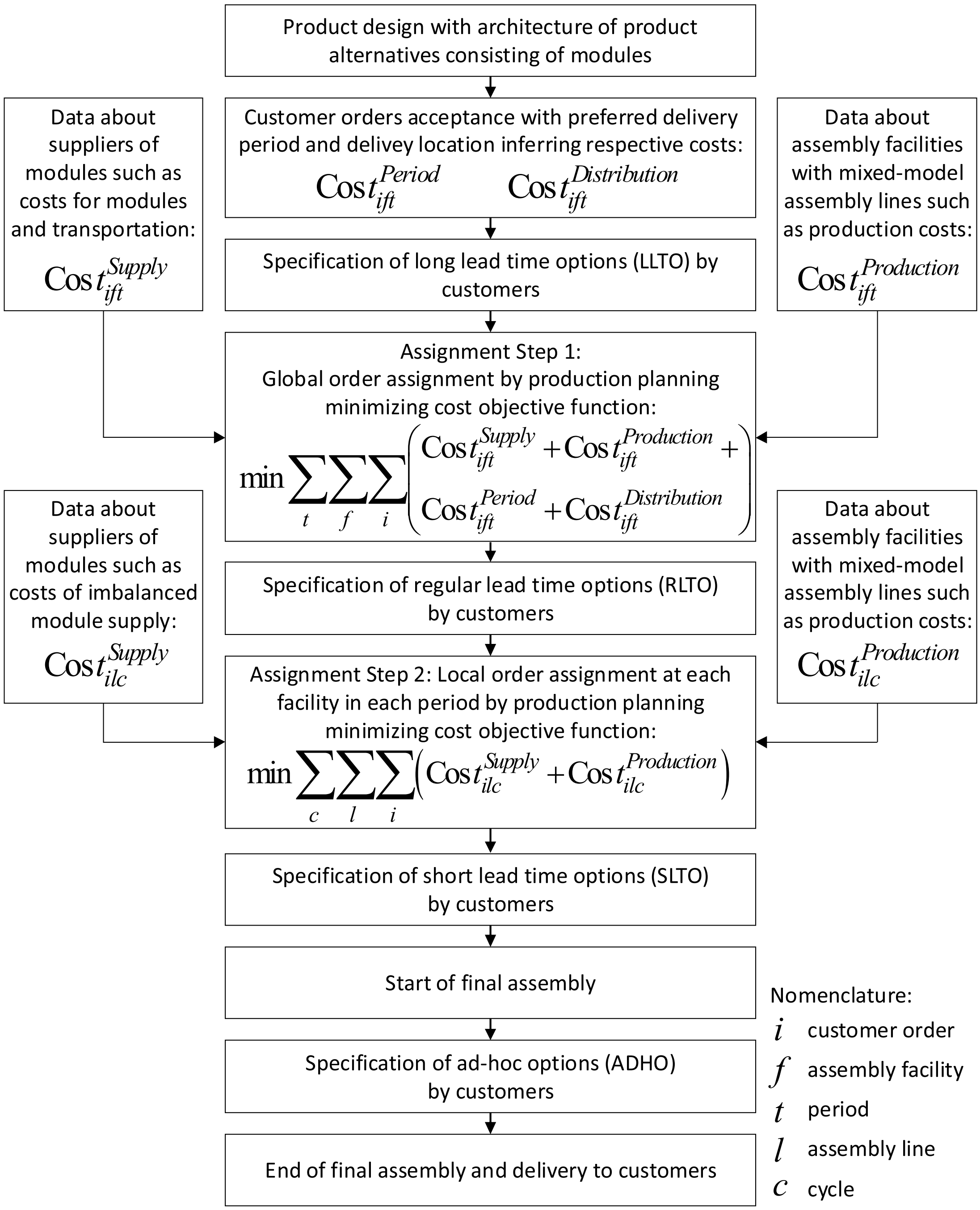

Fig. 4. Ordering, configuration and planning phases of JIT Specification.

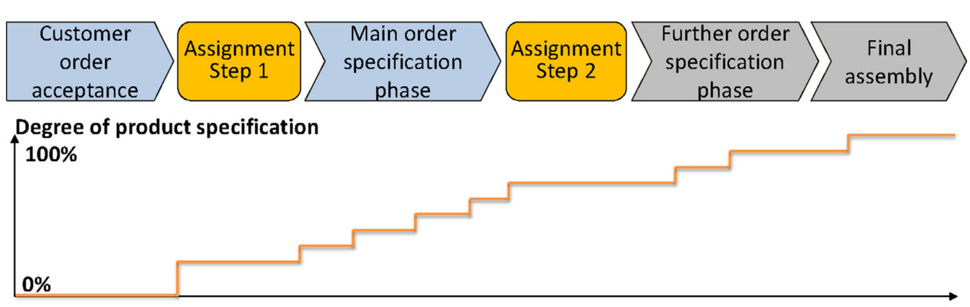

Fig. 5. Degree of product specification for JIT Specification.

order to overcome the existing limitations and to combine customer requirements and product-related limitations, an increased degree of modularity could be an advantage to reduce engineering efforts and thus lead times. In a perfect modular approach, there would be no need for additional engineering activities, at least not for adaptation or combination of modules. However, customers may require specific additional features and branding of parts. They may also have specific requirements regarding the location of rather big components such as galleys or lavatories within the aircraft.

A suitable example to depict the principle of modularity is the galley of an aircraft, where food and beverages can be prepared for serving to the aircraft passengers. For instance, if an airline plans to serve their passengers a warm meal including a variety of drinks on a specific route, the corresponding galley has to contain galley inserts such as oven, coffee maker, water heater and rubbish bin. Depending on the service offered, the galley will contain specific inserts. A galley must therefore be as modular as possible to allow a selection of inserts even after the selection of the amount of galleys in general. There are several geometrical, electrical and water supply related interfaces to a galley's environment. Thus, the environment needs to be adapted to the customer's choice. Whereas in a galley without water and power supply, in simplified terms, only the geometrical interfaces remain, a galley offering ovens, coffee makers, water dispenser et cetera has many links with the physical (infra-)structure as well the systems of the aircraft. Thus, modularity is crucial when certain complex modules entailing a high amount of interfaces have to be already selected in the early product definition phase due to their long lead times but still a broad range of remaining modules with shorter lead times should be selectable even later. The more modules have already been selected, the less degrees of freedom remain for other modules in case of a low degree of standardization due to interface-related (geometrical, electrical, hydraulic) aspects. However, there are certainly limitations of modularity, in particular regarding complex aircraft options, which are subject to high customization requirements leading to the inevitable situation of not having all modules predefined. A way to face this challenge consists in the re-use or the adaptation of existing solutions, thus "to extend predefined solution space by integrating order specific solutions, making them reusable for future projects, and eventually increasing standardization" [16].

In brief, the Just-In-Time Specification approach needs a strong modular-based fundament as far as the product itself is concerned to ensure a sequential selection of options. However, this approach is limited by customer-related, industrial and physical constraints depending on the industrial use case. Nevertheless, a new approach for the definition and production planning process of a new aircraft version seems promising.

Categorization of options for Just-In-Time Specification based on module lead times

The JIT Specification concept and the corresponding module lead times mainly apply to the so-called Head of Version, the first aircraft of a series of identical aircrafts for a customer. In order to build identical aircrafts after the Head of Version, the so-called Rebuilds, manufacturing engineering and production can refer to existing drawings from the Head of Version and the customer does not need to specify options again. An aircraft can be divided roughly into two major parts: the low customized fuselage and the highly customized cabin. In many cases, the system provisions for the cabin customization influence the fuselage as well, e.g. in the form of screws or brackets.

Applying the Just-In-Time Specification concept to the case of the Airbus A320 family, the module lead time is calculated considering the ordering lead time and the interface engineering lead time. The analysis at Airbus regarding a JIT Specification shows that selectable options can be classified into the four categories based on the specific module lead times with respect to the introduced assignment steps performed in production planning (Fig. 6).

The modules of the first category, the long lead time options (LLTO), which have to be specified before the first assignment step, are characterized by their high complexity in terms of structure, weight, size and/or the supply chain. Being assembled from several separate sections supplied by companies located in Europe and in some cases in Asia, the fuselage of an aircraft is the most significant part of this LLTO category. The sections of the fuselage are pre-assembled externally, shipped to the Airbus-internal section plant

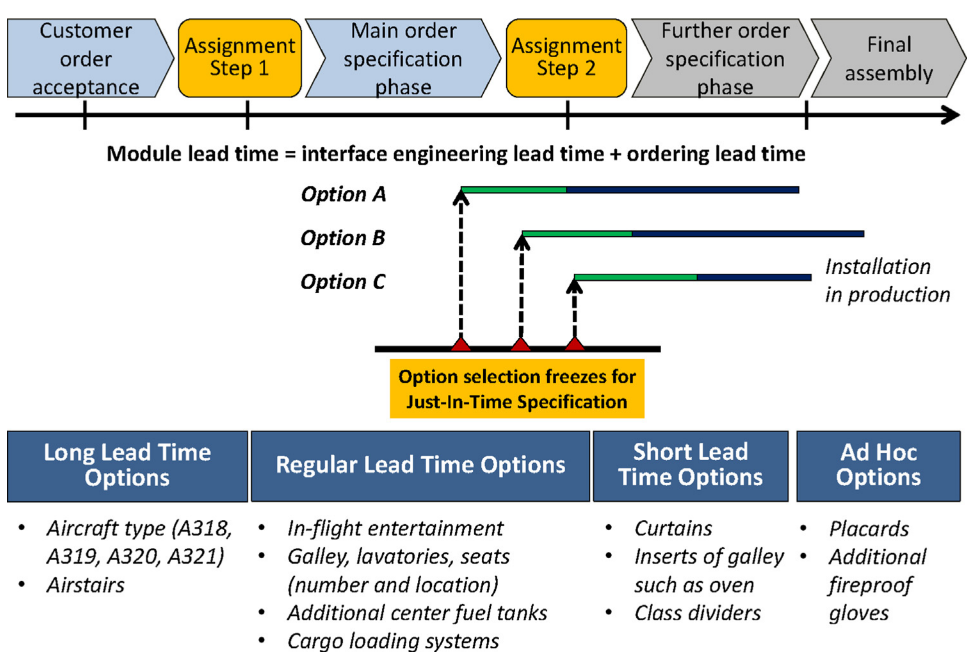

Fig. 6. Option classification regarding the JIT Specification process.

where they are pre-joined to bigger sections and then transported to the final assembly facilities where they are joined to the final fuselage. Depending on the customer's choice concerning the aircraft type of the A320 family (A318, A319, A320 or A321), four different kinds of fuselages are to be assembled. In the same manner, further structural parts such as wings need to be assembled. In general, in case the selection of an option has an impact on the structure of a long lead time module such as the option air stairs, this option also needs to be specified at the same time as the latter.

The second category of modules contains regular lead time options (RLTO). This group can be subdivided into two subgroups. Currently, numerous items need to be selected as an entire system due to their direct and indissoluble interdependencies as well as their high customization requirements. Thus, this first subgroup of the regular lead time options comprises main cabin configuration modules. For instance, in-flight entertainment (IFE) for passengers, lavatories and galleys belong to this category. In-flight entertainment requires displays which are either located in the overhead stowage compartments or in the seats and thus have an impact on other parts of the aircraft. Due to their impact on the overall energy consumption and the geometrically available space in the cabin, the number of lavatories in an aircraft is limited. Galleys are relatively complex due to their physical impact on other parts of the aircraft and their inserts may vary considerably with the aircraft version as described in Section "Modularity as a major enabling factor for Just-In-Time Specification". The location of lavatories and galleys influence the amount of seats in the cabin due to the interfaces between these components. Hence, the amount and location of galleys, lavatories and seats defining the cabin layout need to be specified simultaneously. Assuming a modular-based system, for instance the exact module of a galley or a lavatory can still be specified later on. The second subgroup comprises options with impact on the fuselage such as additional center fuel tanks (ACTs) and cargo loading systems (CLS). The installation of system provisions for these options require specific workloads and specific skills at the Airbus-internal fuselage section plants after the external section pre-assembly.

The module lead times of regular lead time options allow a selection later in time than the long lead time options but the modules still need a considerable number of months before being delivered to the final assembly lines or at least need to be selected due to massive interdependencies with time-sensitive modules.

Modules belonging to the third category, the short lead time options (SLTO), can be selected shortly (several months to weeks) before the final assembly process starts. The analysis of possible short lead time options at Airbus shows that options likely belong to this category if the following criteria are fulfilled: (1) low amount of geometrical and electrical interfaces, (2) mandatory tests and certification requirements already conducted as in case of standardized modules, (3) minor mandatory documentation requirements.

For instance, curtains could still be defined by the customer during the time for SLTO as fabrics might be on stock at the supplier. Moreover, in case of a modular galley, the respective inserts such as oven and water heater might be selected as SLTO. Class dividers, which are typically used for visual separation of Economy Class and Business Class can be specified as SLTO, too, because they are less complex than options such as galleys and lavatories, have no electrical interfaces and their geometrical interfaces are limited.

The fourth category of options contains those options which can still be selected during the final assembly process, the so-called ad-hoc options (ADHO). Obviously, the above-mentioned criteria for SLTO also need to be fulfilled for ADHO. Additionally, as the modules of ADHO have to be delivered to the final assembly line in a short term, the respective module lead times have to be very short. This is the case, if one of the following criteria is fulfilled: (1) module is on stock at the OEM, (2) module can be manufactured internally in a short term, (3) module can be purchased externally in a short term. For instance, placards that are used to indicate general and safety information in the aircraft might be produced in a short term in the language required. Furthermore, ADHO could be small, non-mandatory emergency equipment modules such as fireproof gloves that can be held on stock.

Aircraft configuration with Just-In-Time Specification

A product configurator for the selection of customer options, i.e. modules, following the JIT Specification concept for a new version of an aircraft will be introduced in the following. By taking the specific lead times per option, i.e. module lead times, into account, each option has to be specified by the customer exactly at the latest point in time from an industrial Engineer/Order-to-order perspective offering the customer a maximum degree of flexibility. At the same time, the configurator ensures that customers do not generate incompatible combinations of modules guiding the customer through the order specification process.

Fig. 7 shows the principle of the product configurator for JIT Specification tailored to the Airbus A320 family. On the left side, different options are offered with a description to the customer with the remaining time for selection. On the right side, a picture (or virtual reality view) of the related module is included to help customer visualizing the selected option in the final solution.

In the back office of the proposed configurator, there is co-definition of the product structure and the production planning. Each option is represented by a product module in the design process. Every combination of product modules is defined as an alternative of the product structure (aircraft architecture). Every structure alternative is connected to the production process indicating the first time when the different modules are assembled. By considering information from the process, module lead times and the delivery date of an order, the JIT configurator provides a calculation of the last accepted date of possible option selection.

In parallel, only compatible options are allowed for selection by the customer. When an option is selected, all possible structure alternatives including the related module are activated. All other modules that are not considered in the activated structures will be declared as incompatible with the selected module and their related options are not selectable for the customer.

Module features like supplying capacities, interface compatibility, exchangeability and process position are used in the configurator back-office to achieve different computations for each module and product architecture [5] for hiding forbidden options in the configurator when some options are being selected (yellow boxes of Fig. 8) [4].

The product configurator population consists of the extraction of a set of data from legacy business tools such as PLM (Product Lifecycle Management) for product structure and ERP (Enterprise Resource Planning)/MPM (Manufacturing Process Management) for production processes and suppliers' characteristics. This data is then used to compute for each option the last acceptable date for selection regarding the delivery date and all other options able to be integrated in the same architecture. For instance, the process position feature indicates the first time when the related module of one option has to be considered in the production process. This is combined with the supplying capacities that indicate the possible delivery time after ordering a module from potential suppliers. The compatibility matrix is obtained by analyzing the interfacing capabilities between modules in different product architectures.

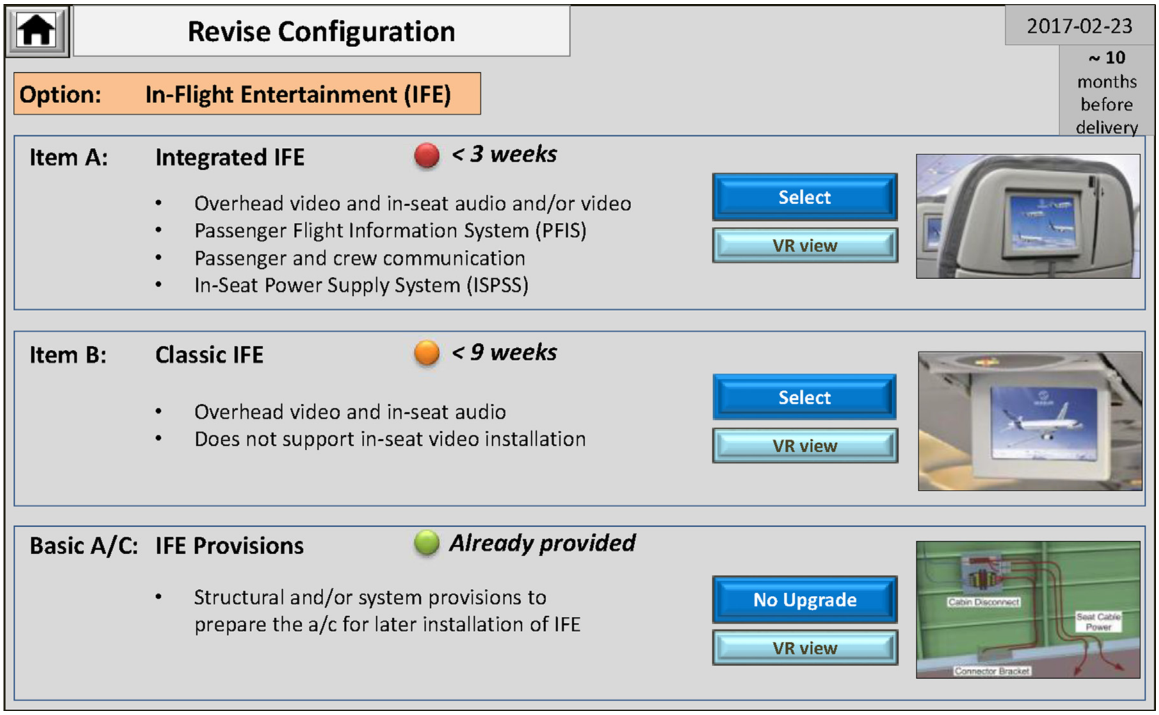

Fig. 7. Product configurator for JIT configuration.

The formal description of computation algorithms for the evaluation of module lead times and compatibility matrix building are out of scope of this work. However, the following short procedure shows how the configurator manages the configuration task based on a connection to the modular architecture in the back office data base.

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1) *Customer starts new configuration demand*
2) *Customer selects product type*
3) *System searches for acceptable pre-defined architectures available for this type of product (list 1)*
4) *System identifies from these architectures the modules connected to options and displays these options (list 2)*
5) *Customer selects one option*
6) *System identifies related modules*
7) *System activates all architectures from list 1 that contains the identified modules (list 3)*
8) *System searches for options from list 2 that have no corresponding module in the architectures of list 3 (list 4)*
9) *System hides all options of list 4 and makes them unavailable for selection in the configurator*

Just-In-Time Specification order fulfilment process for aircraft configuration

The first phase of order fulfilment planning, also referred to as the "order acceptance phase", starts several years before deliveries take place and ends when specific orders are allocated to assembly facilities. During the order acceptance phase, customers place orders for aircrafts. The sales department assigns a delivery quarter to the customer order, which will be later specified to a delivery month. In addition, the customer has to decide whether he wants to specify a Head of Version according to the JIT Specification concept or if he or she wants to order a previously configured version, a Rebuild.

Moreover, customers already have to decide on LLTO such as the type of aircraft (A318, A319, A320 or A321) during the "order acceptance phase". When specifying the first option, the first CODP is set. For every following option, the introduced Engineer/Order-to-order (EOTO) order fulfilment strategy will be applied in a way that every option will be characterized by its own CODP.

Offering the service of JIT Specification and thus a high degree of flexibility to the customer selecting each module just in time regarding its module lead time, uncertainty remains regarding options other than long lead time options when assignment step 1 takes place. Therefore, option selections of accepted customer orders can be anticipated by the relative frequencies of option selections of historical orders of the same customers. In this manner, the OEM's production planning department can consider probabilities for option selections when assigning orders to locations and months for assembly. Considering a standard lead

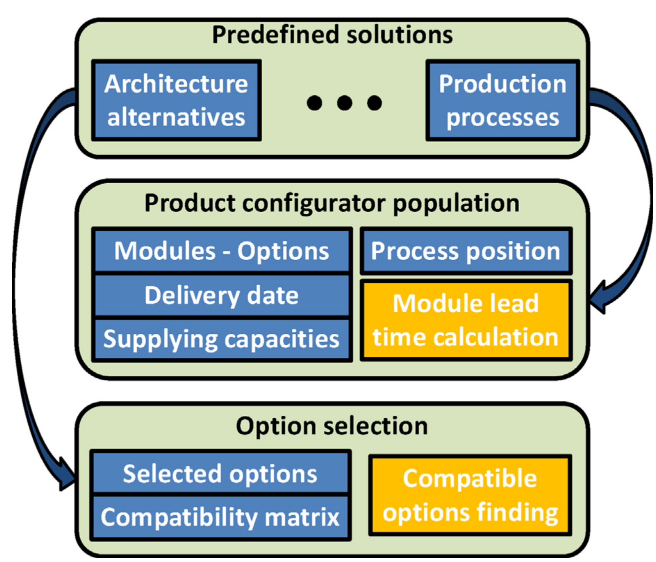

Fig. 8. Product configurator back-office. (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

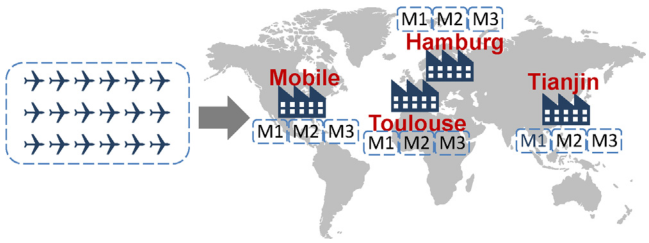

Fig. 9. Global order assignment to A320 family final assembly facilities.

time for the time period from start of final assembly to delivery, the customers can be informed about the delivery month of their orders.

In case of Airbus A320 family, orders can be assigned to four facilities for final assembly: Hamburg, Toulouse, Tianjin, and Mobile (Fig. 9). The respective planning task of global order assignment minimizes costs for the supply and assembly of selected options as well as workload deviations. It also considers the confirmed delivery quarter.

The main reason for the timing of assignment step 1 is that the corresponding data mainly concerning the selection of the aircraft type needs to be frozen and transmitted to the internal plants and external suppliers. After having received this information, the plants themselves place the purchase orders for the single sections which are assembled externally and which will later be joined to the fuselage. As the fuselages for the production sites in China and the USA will be shipped from Hamburg via vessels, an additional month of transportation lead time needs to be taken into account for the respective fuselages. Besides industrial constraints regarding the timing of assignment step 1, there are commercial constraints such as customer requirements, for instance, at which location delivery should take place. At Airbus, the delivery usually takes place at any of the four final assembly facilities. Thus, the facility for delivery could be considered when assigning orders to facilities for final assembly in order to save additional transportation costs that otherwise would occur for transportation after final assembly to the delivery location.

During the subsequent phase of several months, the regular lead time options are to be specified. Main cabin items which influence the cabin layout and aircraft systems (electricity, hydraulic system, water supply) need to be specified, however, as distributed in time as possible offering the customer a maximum degree of flexibility. The related activities are accompanied by engineering efforts due to the uniqueness of every new cabin specified by the customers. Depending on how complex and how modular an item is as well as its specific module lead time, the customer will be reminded to choose between several pre-defined options with a deadline for each. For instance, an overhead video entertainment system is less complex than an integrated in-flight entertainment system for which a separate monitor will be placed in every single seat. When selecting the former, only the overhead compartments are affected, when selecting the latter, the seat infrastructure and a wide range of electrical systems are affected. Hence, there is a constant need of verifying the corresponding interfaces between the selected modules and their setting in the cabin layout by the customization engineers.

Due to technical restrictions and legal regulations, not every combination of components within a cabin layout is feasible and interdependencies have to be considered. Hence, not all the points in time for selecting certain options can be distributed over time. Nevertheless, an increased degree of modularity will ease the combination of items and therefore reduce the engineering efforts. Lastly, the purchase orders for modules of regular lead time options are transmitted to suppliers.

If the planned utilization of resources in production has not reached the target level yet, an upselling of RLTO may be used as an instrument to promote specific options. The objective is to sell additional options to the customers in order to both increase the utilization of resources and the financial result. At the same time, the customer satisfaction can be improved, e.g. via incentives for selection of such options.

Using the information of the selected main cabin options and thus having eliminated a major part of uncertainty concerning the cabin configuration and its related significant workload, the assignment step 2 is performed. Orders, already allocated to facilities and months for assembly, will be assigned to final assembly lines and cycles, i.e. they are sequenced, within each facility already several months before delivery. In this way, an efficient balancing of the workload and the respective resources needed can be achieved. After having performed assignment step 2, the customer will be informed about the preliminary start of production and the preliminary delivery date.

During the succeeding phase, the main cabin configuration is already frozen but the process of final assembly has not started yet. Customers can select short lead time options in this phase such as a class divider that does not necessarily need an electrical power supply and that has a clearly limited amount of geometrical interfaces.

The last phase from a customer and aircraft definition perspective is characterized by the fact that the final assembly process of the aircraft has already started. As a consequence, the range of selectable options is limited and their additional workload must be minimal in order to avoid disturbances in production. For instance, customers could still change the language of placards being in stock at the aircraft manufacturer. These options do not entail big changes in production and can be assembled to the aircraft with limited efforts.

A measurement by sensors could be performed to obtain a real-time visibility of the aircraft's production status. The resulting information could be the base for a limited and well-defined range of options that still can be offered.

Moreover, comparable to the upselling of RLTO, certain SLTO and ADHO can be offered to the customer to avoid under-utilization of resources on the one hand and to slightly increase profit by upselling on the other hand. Whereas the upselling of RLTO is based on an anticipation of resource under-utilization before assignment step 2 is performed, the upselling of SLTO and ADHO is a reactive measure for utilizing resources which are under-utilized based on the result of assignment step 2.

Although the presented JIT Specification of options offers a regular process for product configuration with a high degree of flexibility to the customer, there might still be requests for changing options after their freeze being based on their module lead times. In such cases, a feasibility check for a special process is necessary consuming additional costs like switching from shipping to air transportation for shortening their module lead times. Therefore, the engineering department will have to check such a request in a special process individually in order to determine if the realization of the request is possible and at which cost.

Business models discussion

Business models for customer-oriented services

In order to turn the Just-In-Time Specification into a sustainable and profitable service, an appropriate business model has to be set up [19].

A business model can be described by products, services and information flows as well as business actors, their corresponding roles and potential benefits [41]. Additionally, the sources of revenue should be part of the framework [41]. In general, a firm should use its business model in order to offer its customers better value than its competitors [1]. As a result, the firm may obtain a sustainable competitive advantage [1]. Exploiting this competitive advantage in the short and in the long term enables the firm to make money [1].

As a fundamentally new concept such as JIT Specification may create additional efforts and expenses which may not be compensated in the short term, it is important to put such concepts on a larger scale. Therefore, factors such as customer satisfaction that cannot easily be quantified need to be taken into account. A decisive aspect of business models is the creation and delivery of value.

The term 'customer value proposition' is used to describe the way how a company helps the customer to solve a certain problem in a given situation [26]. Besides the customer value proposition, the profit formula, the key resources and the key processes need to be specified [26]. The customer value proposition and the profit formula describe the value for the customer and the company, respectively [26].

From a manufacturer's perspective, the profit formula is of particular importance. Moreover, the key resources and key processes describe how to deliver that value to both the customer and the company [26].

In contrast to a B2C relationship, a B2B relationship is established in the case of aircraft manufacturing where the customers usually are globally operating airlines. There is an intense rivalry in the aviation sector, particularly in the low-cost segment [26], so that airlines have to attract passengers by differentiation of products and services. As a consequence, the way of customizing products as referred to in this paper is mainly driven by the strive for differentiation related rather to various market segments of airlines than to regional-dependent markets.

Business model for Just-In-Time Specification

Considering the aviation industry, one competitive advantage for aircraft manufacturers might be offering its customers an enhanced service for product specification. The implementation of JIT Specification in a product configurator serves as a link for exchanging information on modules, i.e. options, between the customer on the demand side and the producing company on the supply side. As the service of JIT Specification is directly combined with the product itself, not only a product, but a service is offered to the customer [12].

In case the service is applied to the aircraft manufacturing industry, the customer benefits from a guided order fulfillment process using the product configurator and a regular process for late product specification not causing additional efforts, costs and disturbances [12]. Thus, the risk for deliveries being delayed is reduced. In addition, the provider of the service, i.e. the aircraft manufacturing company, profits from less disturbances in production planning and less related costs [12]. The opportunity for upselling is an additional benefit for the service provider [12].

However, the service of JIT Specification defines a regular process for late product specification allowing for uncertainty in assignment step 1. From a planning perspective, the advantage compared to not offering the service but allowing for customer late changes is that the uncertainty can be explicitly considered when planning. However, if not allowing for customer late changes at all, assignment step 1 could be executed under certainty making it possible to find the optimal solution for assigning orders to locations and periods. Therefore, the cost regarding a sub-optimal solution has to be considered as part of the cost related to the JIT Specification service. Nevertheless, an aircraft manufacturing company taking the strategic decision to offer the customer such a high flexibility in configuring an aircraft, might be better able to save costs and utilize its resources when explicitly offering the service of JIT Specification to the customer compared to having to deal with irregular requests for customer late changes which have not been anticipated before. Thus, the number of customer late changes can be reduced by offering JIT Specification with later specification freezes for several options.

To sum up, JIT Specification has the potential to contribute to increased customer satisfaction, improved on-time delivery and higher production rates [12]. Therefore, the necessary IT infrastructure has to be set up integrating the JIT Specification concept in a product configurator and processing the relevant data [12].

Conclusion

In this paper, the concept of Just-In-Time Specification has been introduced based on a modular approach. It offers the flexibility of selecting a product's modules just-in-time based on each module's lead time. Moreover, it links the product configuration phase following an Engineer/Order-to-order order fulfillment strategy to production planning steps. Thus, the planning procedure comprises planning steps for order assignments as well as phases for product specification regarding modules within specific categories, namely long lead time options, regular lead time options, short lead time options and ad-hoc options.

In accordance with the literature survey highlighting the benefits of a configurator to reduce cost and delay in case of mass customization product, this paper confirms the interest of such a tool to enhance customer integration in the aeronautic domain where the customization process is very complex implying high dependencies between product architectures and production strategies. Due to the specificity to the aircraft as a product, classical mass customization supports could not be suitable and there is a real need to propose a product configurator that is strongly connected to the production facilities. Using modularity for co-evolution is a good answer in such a context and will also help facilitating risk pooling. For example, ad-hoc options are kept on stock to be ordered by any customer.

The application of the JIT Specification concept to the aircraft manufacturing industry has been analyzed and presented. Therewith, it has been pointed out that modularity is necessary to distribute the specification of items with interfaces over time. In reality, sufficient modularity has not yet been fully reached so that still a considerable engineering workload is required leading to module lead times that are longer than requested. However, a product specification in multiple steps is already partially performed at the Airbus A320 family in terms of long lead time options and regular lead time options. The application of the concept could be extended by the introduction of short lead time options and ad-hoc options as well as by conducting the planning according to the introduced planning steps. Considering the on-going massive production ramp-up of the A320 family, improved concepts for product specification and production planning might be promising.

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