Aggregated Production Planning for Engineer-To-Order Products Using Reference Curves

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Abstract. The production of highly individualized engineer-to-order products has special characteristics that lead to a significant increase in the complexity of production planning and control. Therefore, aggregate resource planning is a dynamic and complex process that must always deliver reliable results. But without appropriate tools, these predictions can only be achieved with significant manual effort. Therefore, this paper presents a holistic method that predicts and schedules the required manufacturing resources for new customer orders based on a type representative by means of product modularization and data preparation of approximately identical historical manufacturing orders. This allows the actual processing status of the current customer project to be derived from the preplanning by means of a concurrent calculation in order to be able to initiate countermeasures at an early stage in the event of project delays and also to reduce the lead time of the customer order by preallocating the required production resources.

Keywords: Engineer-to-order · Aggregate production planning · Type representative

1 Introduction

Production companies are in a constant state of change. They are challenged to compete in global markets. Growing demands for individualized products with increasing quality and decreasing prices bring logistical performance, such as high delivery reliability or fast delivery and throughput times, into focus as a competitive factor. Delivery dates and manufacturing costs can be determined at an early stage and deviations from deadlines can be detected by a valid forecast of the required resources and their rough planning [1, 2]. In contrast, inaccurate forecasting can lead to missed delivery dates and manufacturing costs, resulting in a loss of customer confidence and subsequent costs for late deliveries [3]. This prediction is particularly relevant for mechanical and plant engineering, a typical example of the engineer-to-order process with predominantly a large number of individual parts and complex production processes. Here, resource

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rough planning includes not only manufacturing and assembly, but also upstream processes such as design, order planning, or the purchasing process of raw materials and purchased parts [4]. Furthermore, the products of a machine and plant manufacturer often consist of a large number of components that are individually designed in order to achieve a customized solution for the individual customer [5]. Thus, the product characteristics defined in the design process represent a unique selling point for the companies. In engineer-to-order processes, several strategies and concepts have been introduced that aim to predict the resource requirements of manufacturing processes. However, they are usually estimated without sufficient information on available capacity, mainly concern manufacturing processes, or include very general principles. Thus, a variety of approaches to manufacturing resource prediction have been proposed in the current literature, which consider different data and methods or algorithms [6, 7]. However, despite their importance, the needs of manufacturing companies operating under the engineer-to-order principle have rarely been considered [4]. In addition, it is clear that current production planning approaches have a strong preference for the short term planning level. Only a few approaches include multiple planning levels in their solution or consider the internal company supply chain holistically [2, 8]. Therefore, this paper presents and develops a holistic method that enables medium-term production planning for manufacturing companies according to the engineer-to-order approach along the entire customer order. The aim is to create a new form of dynamic process control and process monitoring for the current processing status of the current customer project already in the quotation phase and to significantly shorten the lead time of the customer order by scheduling the required production resources.

The presented method is based on product modularization and the allocation of the actually required production resources of the modules of comparable historical production orders. The modules are integrated into a predefined type representative according to the new customer order during the quotation process, so that the production resources and lead times can be forecast and scheduled in the planning environment of the manufacturing company. After scheduling, the type representative is designed as an aggregated, real reference curve corresponding to the desired customer order and presented as monetary value added over the order lead time. This easy-to-read form of visualization represents the core of the presented methodology and provides the basic prerequisite of the analysis for the holistic internal logistical supply chain.

Therefore, this paper is organized as follows: First, a brief overview of relevant work is given in Sect. 2. Next, the developed concept is presented and described in Sect. 3. Finally, Sect. 4 presents the conclusion and outlook of this research work.

2 State of the Art

Engineer-to-order (ETO) is a production strategy in which all development, engineering and production activities only start after a customer order has been confirmed [9]. The ETO environment is characterized by the following elements: Customized products and manufactured in small quantities. To achieve such product customization, ETO companies apply non repetitive processes that are labor intensive and require a highly skilled workforce [10]. The technical design therefore hardly includes the search for the optimal production process (i.e., the technical design effort cannot be amortized by many sold items), yet it must be possible to evaluate the profitability of the project as accurately as possible from the beginning [11].

In addition, several phases and parts of an ETO project are outsourced to specialized suppliers, increasing the number of companies involved in each project [11]. These ETO characteristics have a strong influence on the entire planning process, which also includes the scheduling of purchasing activities. Hicks et al. [4] identified that most ETO companies take a reactive approach to procurement, where functions are divided into departments and are predominantly bureaucratic in nature. This is also confirmed by Lalic et al. [12]. Since most ETO products are delivered by a project based approach, the management methods used by these ETO companies are inspired by the traditional order management literature. As an example, order lead times are determined by the production schedule, considering available production capacity, technical restrictions, due dates, and system status. The order sequence is determined according to the company's own rules in order to calculate the start and finish dates of the orders at the workstations [13].

Because the development, procurement, and production phases are often simultaneously executed, most ETO companies rely on effective collaboration and a dynamic planning process. According to the current state of the art, such traditional approach to ETO project planning does not take into account the iterative nature of most technical activities and the holistic view of project phases. As a result, project activities are often disorganized and schedule delays occur, resulting in late project deliveries and cost overruns [12].

3 Methodology

Cost curves, which show a monetary increase in the value of a new project over the time of its realisation, are a way for project manufacturers, e.g. the special machine-construction industry, to better monitor the cost progress of their projects. Cost curves can also be used as a tool for controlling new projects if a reference or ideal curve exists for a new project. Delays in the value growth of a project or an excessive increase in the value growth are signals that can detect potential deviations in project execution in the special machinery sector at an early stage. The effectiveness of this control instrument depends strongly on the accuracy of the fit between the reference curve and the cost curve of the new project. The methodology in the following describes a procedure for generating a suitable reference curve which over time, based on production data from projects already completed, identifies a suitable value development for the purchased material, for the working time, etc. The methodological procedure for the formation of an ideal reference curve, which serves as a cumulative representation of the value development of each individual assembly, contains eight steps as described below and additionally as overview in Fig. 1.

1. At the beginning all projects already completed by the company are assigned to a predefined number of product families. A product family is described by production characteristics, such as the number of processing steps, by the product segment and by the customer order [14].

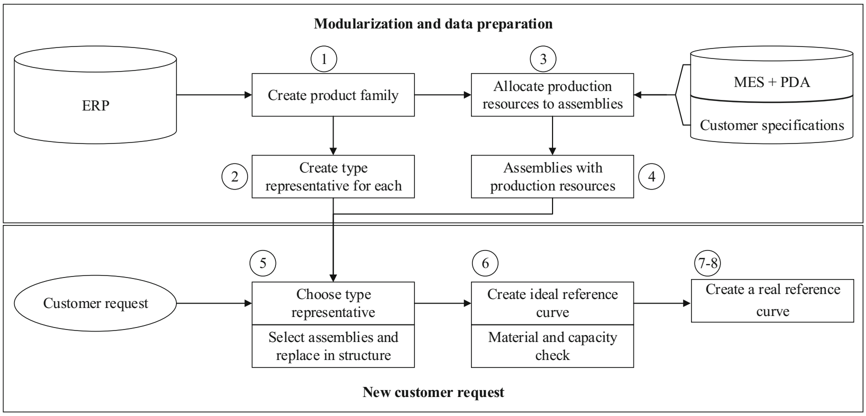

Fig. 1. Process flow chart for the creation of a real reference curve.

2. In the second step a fictive type representative is created for each product family defined in point 1 using the type representative method. According to Helbing, a type representative is a representative of a group and it represents all relevant elements of a project group with their characteristics and characteristic relationships [15]. A fictive type representative is a theoretical product that has not been manufactured, which was formed from the characteristics of the group. The newly generated bill of materials for the fictitious type representative contains all component groups including all associated in-house production and procurement parts and it forms the basis for the subsequent work steps.
3. In the next step, the development costs incurred in the past and the production costs (e.g. assembly costs) are assigned to each product family. At this point it is important to distinguish between expenses that can be assigned to an individual assembly and expenses that relate to the entire product. When each assembly group is assigned its actual reported costs, the average costs of the projects containing the relevant assembly groups identified below are included for the project as a whole.
4. Each assembly of the identified product family is then clearly described using product-specific characteristics. The characteristics have been selected in such a way that they reflect the customer requirements from the specifications with their influence on the costs and the required production time. For this purpose, the customer requirements with the cost-influencing factors are previously identified in already completed orders by means of a Pareto analysis and narrowed down to the most relevant factors.
5. In the fifth step, the customer project request is assigned to a product family. After the assignment, those assemblies are identified in the fictive type representative of the product family that have the highest match between the customer requirements of the requested project and the assembly characteristics of the fictive type representative. If one or more customer requirements are met by different assemblies, the most similar assembly is selected.
6. The identified assemblies with the associated routings and bills of material for the in-house production and procurement articles form the basis for generating an ideal

reference curve. In the first step, all the routings used for the identified assemblies are analysed with the aim of fully recording the resources (booking units) used for the production of the respective assembly and arranging them according to the value stream of the respective product family. In the second step, all required production and assembly hours (execution time-ex) for the production of the assemblies identified in step 5 are assigned to each resource and summed up per resource. Equivalently, the effort for product development and work preparation of the respective assembly is determined (see Fig. 2).

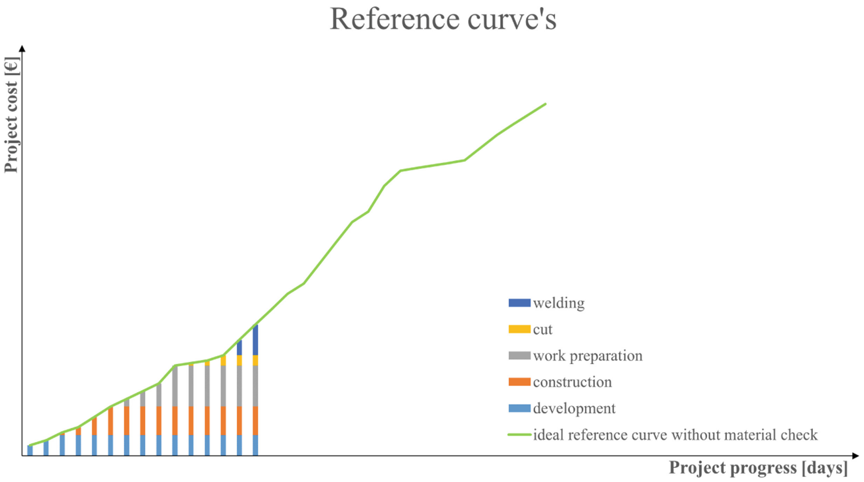

Fig. 2. Building an ideal reference curve.

7. The procedure for creating the ideal reference curve is continued with the analysis of the externally procured parts of the assemblies identified in step 5. Thus, the re-procurement times (rt) for the raw material and for the purchased parts of the relevant assemblies of the fictitious type representative are identified in order to determine the earliest times for the value added, which are defined as rt (e.g. the material is made available for the processing of the resource) and rt + ex (the effort for the material processing) (See Fig. 3). The creation of the ideal reference curve takes place under the assumption that the theoretically possible capacity of the resource required for the execution of the work step is available at all times (assumption of unlimited capacity).
8. Finally, the ideal reference curve for the new product is generated. An ideal reference curve does not consider any resource availability (no capacity constraint) and is initially plotted cumulatively along the value stream by means of forward scheduling of the value added points (duration of resource utilization by all relevant work groups), with the amount of value added points being calculated by multiplying the duration and the cost rate of the resource. Subsequently, the points of the generated curve are checked for plausibility. For this the material availability for the execution of the work on the respective resource is examined, while the procurement times of the raw material or purchase components from the step 5 with the identified demand times

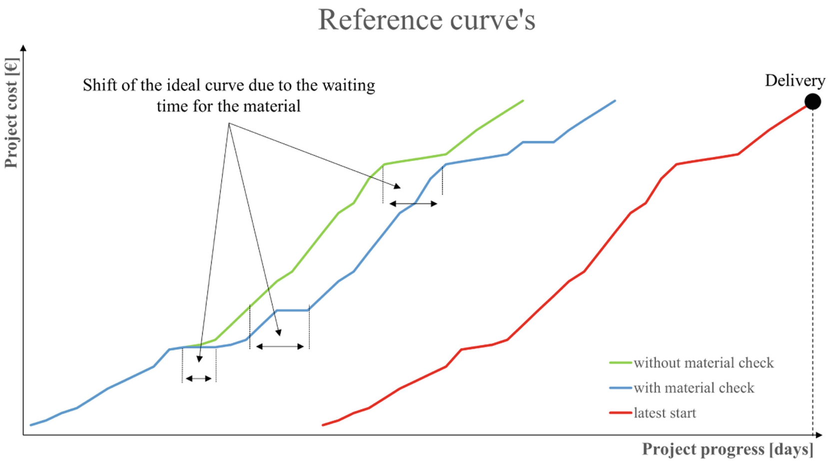

Fig. 3. Ideal reference curve with material check.

starting from the planned project start are compared. For rt > the time of need, then the ideal reference curve is shifted by the resulted difference starting from the time of need into the future. After checking the temporal plausibility of the ideal reference curve, the total value of all required raw material or purchased components, which are needed for the execution of the work of a resource, is plotted at the beginning of the processing. The step is completed with an addition of the ideal reference curve with the material values.

If the delivery date for the new project is known or specified, the company can use backward scheduling to determine the latest times for an increase in the value of the project and the latest project start (see Fig. 4, latest start). If, after the customer has placed the order, the company loads the required effort and takes into account the current resource availability, it receives the real reference curve for the value based control of the new project (see Fig. 4, with material and capacity check).

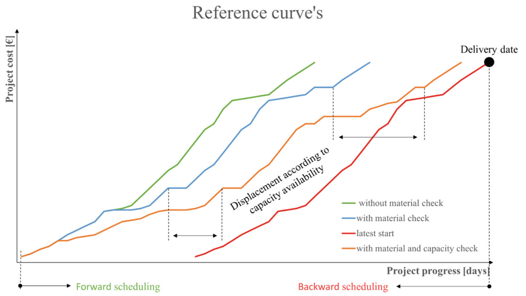

Fig. 4. Real reference curve with material and capacity check.

4 Case Study

The method described in Sect. 3 has been validated at a project manufacturer in the field of special machine construction whose core competencies include the customer specific production of conveyor belts. These conveyor belts (customer projects, in short: projects) have an average project duration of currently 60 days and are manually precalculated by an employee of the project manufacturer according to the customer's requirements.

The structure of the projects consists of four assemblies (ASM). Due to their required production resources and fixed order of allocation planning, these have been combined into a product family, which includes the following sequence of value creation: Quotation preparation, development and design, work preparation, cutting, turning, milling, and assembly. Afterwards, the fictive type representative of this product family has been created, which contains the bill of material structure and routings of all used articles from the assemblies, as well as its past resource requirements. For the scenario presented in the following, the project specific characteristics for the individual assembly groups were identified and served as the basis for the rough planning. Thus, two characteristics for each ASM (e.g., the total length and the total width) were used for selection.

Following the selection of the most similar ASMs, the ideal reference curve was created from their aggregated production resources and the project schedule by means of forward scheduling (see Fig. 5, without material check.) and backward scheduling (see Fig. 5, latest start.). The following assumptions have been made:

- The capacity utilization of all required booking units is 85%.
- Disruptions due to delivery date deviations in the external supply chain (e.g. due to the Corona pandemic) have been corrected by equating the planned procurement time (rt) with the goods receipt posting.
- The sequence in the routing serves as a template for the production process.
- The material requirements have been distributed accordingly to the required booking units by setting the longest rt of the articles of the respective assembly before the required processing step.

Subsequently, the ideal reference curve (forward scheduling, see Fig. 5, without material check) with the capacity availability and procurement times of the items was adjusted with the determined requirement times to obtain the real reference curve (see Fig. 5, with material and capacity check). The rt of the articles has thereby started after the project step development and construction. After material receipt, the incoming goods department then books the material costs (m€) to the project (see Fig. 5, m€ cost jump). Subsequently, after expiration of the waiting time (wt), the respective processing step (see Fig. 5, Process time, pt, continuous cost increase) can take place.

Due to the daily feedback via the ERP system of the conveyor belt manufacturer, the real resource requirements of the customer project could be recorded and compared with the real reference curve with material and capacity check (see Fig. 5, with material and capacity check, real project).

When predicting the manufacturing costs incurred for a new sales order, a difference of 9.3% ($< 10\%$) of the manufacturing costs was achieved in the comparison of pre- and post-cost calculation. This shows that the described concept is suitable for the prediction

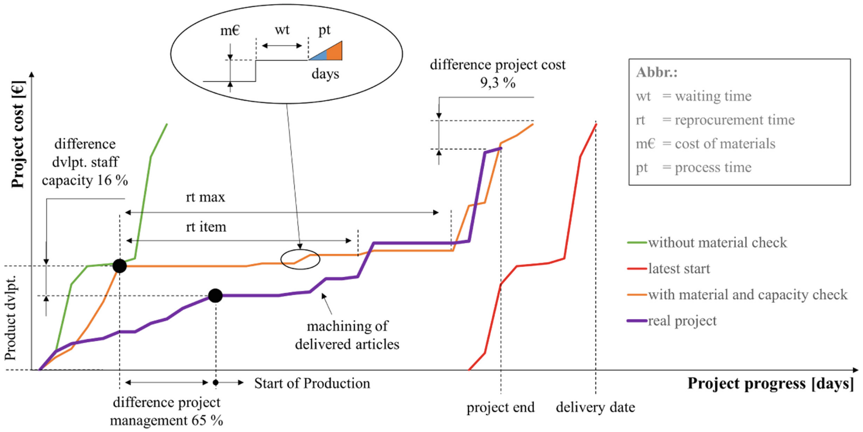

Fig. 5. Evaluation of a real project from the conveyor belt manufacturer.

of manufacturing costs based on a selected example. The agreement in the prediction of the selected AMS's in comparison to the real product manufacturing process is structured as shown below in Table 1.

The different cost increases after the product development of the real project to the ideal reference curve result from newly developed articles and work steps that have been brought forward with articles from stock. However, an intersection can be identified that reflects the planned rt with the real rt and will be further investigated in ongoing research project.

The required overall resources in product development, as an initial reference point for project progress control, have been estimated with a manufacturing cost variance of 16% (see Fig. 5, difference dvlpt. Staff capacity). The current time offset within project management of 65% shows a manipulated deviation for optimization in personnel planning. In personnel planning, it was not possible to clearly differentiate downtimes, e.g. due to illness, overtime reduction, etc. from past customer orders, as these were previously documented by the conveyor belt manufacturer in a traceable manner.

Table 1. Percentage match in aggregate project steps.

Quotation preparation	Development	Work preparation	Cutting	Turning	Milling	Assembly	Material costs
57%	89%	82%	114%	134%	42%	145%	109%

5 Conclusion and Outlook

This paper uses the example of a conveyor belt manufacturer in the field of special machine construction to show that it is possible to predict aggregate production planning on the basis of past customer projects. It could be shown on the basis of an example that the required production resources for new customer orders could be determined even before product development. The clear and easy to understand presentation of the target variables of production costs and order lead time as a real reference curve means that project progress can be monitored and countermeasures can be initiated at an early stage in the event of deviations from the planned schedule. However, this has so far required close comparability of the assemblies within the product family to the new customer project. Therefore, it is necessary to make this variance easier to estimate in the further course of the research project. The customer requirements from the product specifications must be classified more precisely and their influence and effects on the entire value creation process of the product family and the requested product must be determined. Furthermore, the occurring process disturbances (schedule deviations, personnel management) are to be analyzed and classified in order to incorporate them into the aggregated production planning. In this way, the order throughput time can be further specified and a more robust planning basis can be ensured.

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