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Swapnil Bhalla, Erlend Alfnes, Hans-Henrik Hvolby

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Swapnil Bhalla[1]✉[0000−0003−4905−2488], Erlend Alfnes[1][0000−0002−9892−3916], and Hans-Henrik Hvolby[1,2][0000−0002−5574−5216]

[1] Department of Mechanical and Industrial Engineering, NTNU, Norwegian University of Science and Technology, Trondheim, Norway
[2] Department of Materials and Production, Centre for Logistics, Aalborg University, Aalborg, Denmark
swapnil.bhalla@ntnu.no

Abstract. The paper studies an engineer-to-order (ETO) manufacturing firm. A novel approach is used to assess the fit of capacity planning methods in the planning environment of the firm, and towards delivery date setting, which is of strategic importance for ETO firms.

Keywords: Engineer-to-order (ETO) · strategic fit · delivery date or due date · capacity planning · rough-cut capacity planning (RCCP)

1 Introduction

Developing product designs for specific customer orders allows manufacturers to deliver customised products that address customers' unique requirements. This manufacturing approach, known as customer-driven manufacturing, is a key concept for future factories [9, 19, 26]. Such a customer-driven approach to manufacturing is prevalent among enterprises producing high-value capital products, such as shipbuilding, offshore equipment manufacturing, etc. [11, 22]. Based on the customer order decoupling point (CODP) framework, such manufacturing contexts are characterised by a supply chain strategy or product delivery strategy known as engineer-to-order (ETO) [17]. While firms producing high-value products benefit from an ETO strategy, which enables them to address specific customer requirements, they also operate in relatively complex planning environments due to increased uncertainty regarding specifications of the product and production process [23].

Customising products for every customer's requirements leads to newness within order fulfilment activities for each customer order, which include engineering, purchasing, production, etc. The newness of order fulfilment activities for a product is managed by organising these activities as a project [27]. A precursor to planning a project and confirmation of customer orders is the customer enquiry stage, where estimated price, project delivery date, etc. should be quoted by the manufacturer [23]. The acceptance of these delivery dates by potential customers are often a criterion for confirmation of customer orders [23]. Due to the uncertainty in product and process specifications, and the newness or non-repetitiveness of production activities, identifying reliable production delivery dates at this stage is not a trivial task in these manufacturing environments. It is worth clarifying that while ‘project delivery date’ is used here to refer to the date promised to the customer for handing over the finished product, ‘production delivery date’ refers to the estimated date when production is expected to be completed, which precedes the project delivery date. The possibility to determine reliable production delivery dates through capacity planning in ETO (and make-to-order (MTO)) environments, is a primary criteria for applicability of production planning and control (PPC) systems in these environments [23].

The fit between PPC systems and corresponding planning environment, has often been emphasised as consequential to manufacturers’ performance [1, 16, 24]. Motivated by the importance of this fit towards improving manufacturing performance, different frameworks for mapping planning environments have been proposed in literature [3, 13, 18, 20]. These frameworks for mapping planning environments are intended to be starting points for identifying suitable PPC systems.

This paper presents a case study that set out to investigate the applicability of relevant theoretical knowledge to delivery date setting practice in ETO manufacturing. Through the case study, the paper also demonstrates a novel approach for investigating how the mapping of a planning environment can be used to assess the fit of PPC methods, as called for by Buer et. al. [3] in possibilities for future work.

The paper is organised as follows. Section 2 contextualises this paper using literature. Section 3 outlines relevant capacity planning techniques. Section 4 presents the research framework and case study. Section 5 serves as a brief conclusion to the paper.

2 Delivery date setting in ETO manufacturing

The strategic importance of estimating, quoting and setting production delivery dates for customised manufacturing environments such as ETO and MTO, has been emphasised often in literature [12, 14, 15, 25, 29]. The repeatedly emphasised importance has triggered much research on the subject. However, much of the literature is found to be primarily focused on MTO contexts. Undeniably, firms operating with strategies that are a hybrid of ETO and MTO can be found in practice [19, 21]. Nevertheless, the primary difference between the two strategies is the engineering aspect, which may introduce uncertainty into the planning environment depending on the level of customisation [29]. As a result, delivery date setting approaches applicable in MTO contexts may not demonstrate equivalently satisfactory performance in ETO contexts. The remainder of this section discusses some salient contributions to delivery date setting literature to contextualise the contribution of this paper.

Zorzini et. al. [28] studied the delivery date setting process at 15 capital goods manufacturers. They report that majority of the studied firms opted to perform aggregated capacity analysis for quoting delivery dates, as compared to detailed or no workload analysis. While the sampled firms using aggregated capacity analysis are scattered across the spectrum of customisation and complexity, Zorzini et. al. [28] point out that the assembly process was found to be a fixed bottleneck resource for all of these firms. However, this might not be the case for all ETO environments. It was also not found to be true for our case study context where historically, different machining resources have been observed to be the bottleneck resource for different products. Further, among the firms sampled by Zorzini et. al. [28], it is also not clear how firms across different levels of customisation differently manage uncertainties regarding product and process specification. Their proposed model assumes that average lead times can be estimated based on past orders, but the validity of this assumption can be expected to vary with the level of customisation and size of the product portfolio.

Ebadian et. al. [7] propose a heirarchical PPC model to support delivery date setting, which assumes that incoming orders can be prioritised according to the service level desired for different customers. Carvalho et. al. [6] present an optimisation approach developed for tactical capacity planning under uncertainty in an ETO firm, calling for exploration of the validity of the proposed approach in other ETO contexts. As outlined above through the discussed literature, context-specificity can be observed as a common feature among most research on delivery date setting in ETO. While these are valuable contributions to theory, generalised validity of the findings is only limited. This highlights the contingent nature of the applicability of delivery date setting methods, as also argued by Zorzini et. al. [29] for taking a contingency theory approach to studying customer enquiry management. Therefore, the case study presented in this paper assesses the applicability of basic theoretical methods in an ETO setting, while explicitly demonstrating the approach, which can be replicated in other ETO contexts for assessing applicability of seemingly relevant methods.

3 Rough-cut Capacity Planning

Capacity planning refers to “the process of determining the amount of capacity required to produce in the future” [2]. It entails different activities at different hierarchical levels of PPC, such as strategic or long-term resource requirement planning, rough-cut capacity planning (RCCP) on a tactical or master production scheduling (MPS) level, and detailed capacity requirements planning (CRP) at the material requirements planning (MRP) level [2]. As emphasised frequently in literature, delivery date setting is most commonly observed on a tactical level of PPC [5, 10, 23, 28], and therefore, RCCP methods can be classified as most relevant for delivery date setting. This section briefly presents three basic RCCP methods that are later assessed for their fit to the case environment and for their capability to support delivery date setting. The methods are explained using descriptions from Vollman et. al. [24] and the APICS dictionary [2].

Capacity planning using overall factors (CPOF). Using overall factors for RCCP is a relatively simple approach where the MPS is used as the starting point. The scheduled quantities of end products in different time buckets serve as basis for estimating the capacity requirements for different work centres, by applying historical percentages to the total number of hours for producing the item. This essentially gives the estimated workload requirement from different work centres for producing the scheduled quantities, without consideration of the actual timing of the capacity requirement projections. The advantages offered by this approach are minimal data requirements and computational simplicity.

Capacity planning using capacity bills (CPCB). Using capacity bills follows a similar computational procedure as CPOF, but differs in the data requirements. Instead of using historical percentages for different work centres, as in CPOF, CPCB requires bill-of-material (BOM) and routing data with labour-hour or machine-hour data for each operation. Not unlike CPOF, CPCB also does not consider the production lead times, and capacity requirements are not time-phased.

Capacity planning using resource profiles (CPRP). Among the three basic RCCP techniques, using resource profiles for capacity planning is the most sophisticated. It takes production lead times into account, and provides time-phased projections of capacity requirements. Using the MPS, BOM and routing data, capacity requirements are estimated as in CPCB. These estimates are further utilised to develop time-phased projections by offsetting the capacity requirements.

4 Case study

The case company is a supplier of equipment for the maritime industry. The main products and spare parts for previously sold products constitute the manufacturing activities, which are undertaken at the same facility. Their products can be broadly classified into four types, where every type has various sub-types and size alternatives that essentially serve as templates for tailoring the product designs to specific customer requirements. The cumulative production volume of different product types is typically below 500 units per year. Presently, at the customer enquiry stage, production delivery dates are determined using a method that is a hybrid of CPOF and CPRP methods. The product templates and experience from past projects are used to estimate the total workload for a project and consequently, workloads for different work centres. These workloads are then offset in time to get time-phased projections of capacity requirements, and delivery dates are estimated based on these projections. Maintaining delivery precision for the production department has been challenging, and has worsened in recent years with widening of the product portfolio and variations in the product mix of demand.

4.1 Methodology

The purpose of the case study was to better understand the challenges in setting delivery dates in ETO environments. As it was revealed during earlier collaboration that the case company recognise delivery date setting as one of the

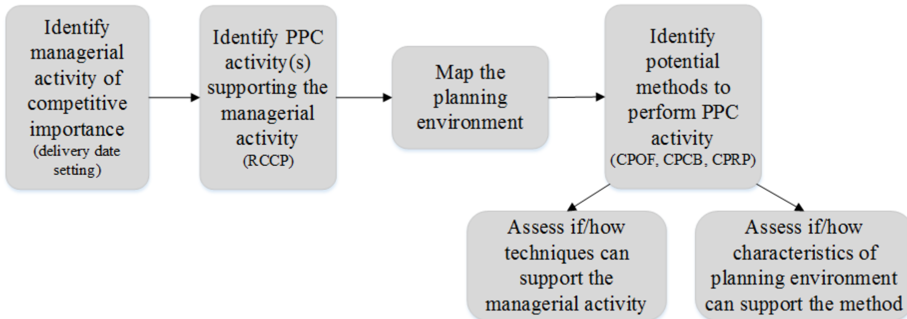

Fig. 1. Research framework underlying the case study

challenging managerial tasks, the firm served as an appropriate context for this case study. The case sample presented in this paper is limited to a single in-depth case study due to space constraints and can be expanded in the future to test generalisability of the findings. Figure 1 shows the underlying research framework for the case study process, which can be utilised in future studies to assess fit of planning activities or PPC systems towards planning environments.

4.2 Assessing fit

The case company is mapped using Buer et. al.'s [3] framework, where characteristics of a planning environment are classified into product, market and manufacturing process related variables. The fit of the RCCP methods is then assessed towards the clustered environmental variables and delivery date setting, based on a combination of literature synthesis and logical assumptions, as shown in Table 1. The planning environment is characterised as follows.

Product-related variables. CODP placement: ETO-MTO; level of customisation: some specifications are allowed; product variety: high; BOM complexity: 3-5 levels; product data accuracy: low-medium; level of process planning: fully designed process.

Market-related variables. P/D ratio < 1; demand type: customer order allocation; source of demand: customer order; volume/frequency: few large customer orders per year; frequency of customer demand: unique-sporadic; time distributed demand: annual figure; demand characteristics: dependent; type of procurement ordering: order by order procurement; inventory accuracy: medium. The market-related variables can be further distinguished into demand-related (from P/D ratio to demand characteristics) and supply-related variables (type of procurement and inventory accuracy).

Manufacturing process characteristics. Manufacturing mix: mixed products; shop floor layout: fixed-position - cell; type of production: single-unit - small-series; throughput time: months - weeks; number of major operations: high; batch size: equal to customer quantity; frequency of production order repetition: infrequent repetition; fluctuations of capacity requirements: medium; planning

Table 1. Assessing fit of RCCP methods towards planning environment and delivery date setting.

	Overall factors	Capacity bills	Resource profiles
Product characteristics	CPOF reflects a poor fit to the product characteristics. Values of mutually causative variables such as CODP, customisation, product variety, BOM complexity and data accuracy [3] render CPOF unreliable for the case environment. This is consistent with CPOF's success criteria of flat BOM [13, 24].	CPCB reflects a poor fit to the product characteristics. This is primarily due to relatively low product data accuracy, which is detrimental to the use of CPCB [8]. Product data entails detailed BOM and routing data, the availability and reliability of which, are integral to the success of CPCB [4].	CPRP reflects a poor fit to the product characteristics. Performance of CPRP, like CPCB, relies on the availability and reliability of detailed BOM, routing data and time standards, accuracy of which is significantly low during RCCP. Customisation and high product variety indirectly contribute to this [3].
Market characteristics	CPOF reflects a poor fit to the market characteristics, and more specifically, to the demand-related variables such as customer-allocated and customer order-originated demand, low frequency and uniqueness of demand. While a P/D ratio < 1 is a favourable situation for the fit of CPOF [13], the overall fit is rendered poor by other majority of variables.	CPCB reflects a poor fit to the market characteristics, and specifically, to demand-related characteristics. However, these characteristics affect the fit of CPCB indirectly rather than directly. Dependent demand influences time distribution of demand [3], which in turn influences the CODP placement [3], and leading to the unavailability of BOM and route during RCCP.	CPRP reflects a poor fit to the market characteristics of the planning environment. Demand-related characteristics that cause CPCB to be a poor fit to the planning environment, also cause CPRP to have a poor fit. None of the discussed RCCP methods are influenced by supply-related characteristics, as on-hand stocks of components are not considered in any of them [13].
Process characteristics	CPOF reflects a poor fit to the manufacturing process due to environmental characteristics such as non-homogeneous manufacturing mix [13], production in single-unit or small series, long throughput times, relatively high number of operations and planning points, and infrequent repetition of production orders.	CPCB reflects a poor to neutral fit to the process characteristics of the planning environment. Lack of homogeneity in the manufacturing mix does not cause any particular challenges in using CPCB, as it uses detailed bill of resources [13]. Large number of major operations is expected to negatively influence the CPCB's reliability.	CPRP reflects a neutral to good fit to the manufacturing process characteristics of the planning environment. A high number of major manufacturing operations is expected to increase the importance of offsetting the capacity requirements in time for reliable projections, thus qualifying CPRP to have the best fit.
DD setting	Using CPOF for RCCP is expected to provide unreliable delivery dates, as it does not offset capacity requirements in time.	Using CPCB for RCCP is expected to provide unreliable delivery dates, as it does not offset capacity requirements in time.	Using CPRP is expected to give reliable delivery dates, as it offsets capacity requirements in time to get time-phased projections.

points: medium; set-up times: medium; sequencing dependency: medium; part flow: one-piece/lot-wise; material flow complexity: medium; capacity flexibility: low; load flexibility: medium.

5 Conclusion

The studied case environment demonstrated an overall low applicability of the theoretical RCCP methods. It can be concluded that the fit of RCCP methods to the planning environment is relatively less influenced directly by the manufacturing process as compared to the market and product characteristics. The case study also revealed that existing mapping frameworks [3, 13, 18, 20] lack 'production monitoring accuracy' as an environmental variable. Production monitoring accuracy refers to the accuracy of data that is used to monitor actual production with respect to planned production. The availability and reliability of this data was found to play a vital role in the success of the delivery date setting process by providing information about available capacity in different planning periods, and was found to be a factor in the low delivery precision observed at the case company. More comprehensive investigation of the influence of production monitoring data on delivery date setting is a possibility for future work.

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