A framework for production planning and control in Engineer-To-Order Small Enterprises

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Abstract: Production planning, programming, and control in Engineer-To-Order (ETO) organizations is particularly complex considering the high variability and level of customization of the products, whose structure and specifications are defined only at the time of the order by the customer. The existing scientific literature lacks easily implementable support tools for ETO planning and controlling. Most of the frameworks seem inadequate since they have been developed for less complex and less subject to variability production environments. In addition, it is clear from the literature the difficulty in proposing approaches that are feasible for real industrial ETO environments. The complexity of logical and mathematical modelling does not allow easy and practical applicability. Based on the gaps undiscovered in the literature and the unmet needs in companies with ETO configuration, with greater attention to Small Enterprises, the objective of this work is to provide guidance for the management of planning, programming, and control in ETO production systems. A general framework, based on a project management approach and made clear by a logical model that explores in detail the macro-steps identified, has been proposed. Starting from the receipt of the order and after the evaluation of its feasibility due to the conditions of the system, all the activities necessary to realize the product can be planned. The planning is strictly dependent on the monitoring of the activities, which is necessary to ensure that all is proceeding as planned. The proposal complements the best practices identified in the context of planning and control for ETO, while at the same time filling the existing gaps and making this complex task easier for micro and small enterprises, on which researchers still do not draw sufficient attention even though they represent a significant portion of active enterprises.

Keywords: Production Planning and Control, Digitalization, Decision-support systems, Small Enterprises, Workload Control, Information Flow

1. Introduction

The worldwide market and consumer needs are constantly evolving, making customization and flexibility key features for businesses. This dynamic landscape is further fed by the forces of globalization, which expand the scope and reach of these changing market dynamics. Customers, whether they are end consumers or intermediate buyers in the supply chain, demand ever greater customization in products, while maintaining high quality and costs almost unchanged compared to mass production and reducing delivery times (Fortes et al., 2023). It is therefore very complex to achieve all these objectives simultaneously: one possible way is to adopt the Engineer-To-Order (ETO) configuration for the production system. It represents an integrated process with the customer for the realization of unique products and services that meet the needs of each customer in relation to certain product characteristics through a highly responsive engineering process (Kumar Sriram & Alfnes, 2014). Having to take all these aspects into account makes the management of ETO systems considerably more complex than for other production configurations. Moreover, most of the activities are performed after the customer's order so capacity planning is extremely important to guarantee delivery on time, proper resource saturation, and inventory level (Nils-Erik Ohlson, 2023). Therefore, production planning and control represent a value-added process that continuously adapts to customer requirements and enables key decisions to be made by monitoring, scheduling, and reprogramming the production plan to ensure on-time delivery (Bonney, 2000; Bueno et al., 2020). ETO products are generally used in large projects, and for this reason, it is common for customers to impose large cost penalties for lateness, which is a direct consequence of inefficient planning of the orders.

Whereas production resources are managed using Manufacturing Resources Planning (MRP II), the nature of this tool makes it unusable in ETO systems, mainly because planning in general is difficult due to its dependence on multiple company areas, the variability of lead times, and the impossibility to forecast resources' workload (Cannas et al., 2018). The first characteristic of ETO companies that contrasts with the logic behind MRP II is that not only physical activities but also non-physical activities, such as engineering and design definition, are part of the customer's lead time and, therefore, subject to production planning and control (Fortes et al., 2023). In addition, it is not possible to know in advance which product with which characteristics will be requested by the customer, as there is no well-defined and valid Bill of Materials (BoM) available for each of the future orders processed (Sylla et al., 2017).

To support these complex management problems, project management comes into play: since orders in ETO systems are unique and unrepeatable, they can be managed in the same way as industrial projects (Jünge et al., 2019; Sriram et al., 2013). Once the customer order has been received, production must be planned and defined in detail because, given the uniqueness and high customization of the product, the order is typically very complex and characterized by a high lead time and uncertainty (Manzini & Urgo, 2015). Consequently, organizations of this type make common use of project management, to provide tools to support decisions on time, quality, and cost, aspects subject to constraints and agreements established with the customer (Denicol et al., 2020), but it also helps in managing project resources, communication and integration and coordination among multiple teams (Raharjo & Purwandari, 2020).

It is complex to achieve all these objectives simultaneously in the context of Small and Medium Enterprises (SMEs) ETO. On the one hand, SMEs are somewhat preferred to large international companies, especially if they are local, given the need of customers to obtain a highly customized product with a short lead time (Ruy Somei Nakayama & Mauro de Mesquita Spinola, 2015); on the other hand, they also have higher production costs, and this is a factor that could push potential customers away. There is a need to ensure high customization and, at the same time, to reduce lead times and production costs (Ciesla & Mleczko, 2021). ETO SMEs' strength is represented by the flexibility of their production systems, capable of carrying out difficult tasks from multiple, various, and often prototype projects. However, planning and control activities are still a problem for this type of company, due to the complexity of the product manufactured and, consequently, the difficulty of defining the resource requirements, which is greater than the difficulty of planning production capacity. The solutions generally provided, such as Enterprise Resource Planning (ERP) do not fit the ETO context and nature and do not seem appropriate in terms of cost, time, and practicality of implementation. It requires substantial alterations in operations and employees' roles and routines, as well as extensive training and preparation (Teerasoponpong & Sopadang, 2021) but not implying that the solution will be able to improve processes despite the effort involved.

To solve the problems particularly experienced by ETO Small Enterprises, a framework for order management was developed, further detailed through a logical model, to support these companies in the management of planning, scheduling, and progress control. The main objective of this initial proposal is to establish a generalized approach to complex tasks related to planning and control that can be easily adapted to different realities, based on the idea of considering each order as a project to be broken down into multiple and correlated tasks.

The remainder of this article is organized as follows. Section 2 provides an overview of the scientific literature to identify and deepen in detail the existing gaps to fill. Section 3 reports the developed framework and illustrates the detailed logical model, whereas Section 4 presents the conclusions and possible future developments.

2. Literature Overview

Production planning, scheduling, and control is a topic widely discussed in literature. However, there is a small number of articles regarding ETO production configuration, which remarks how it is less considered than other more easily and regularly managed configurations, such as Make-To-Stock or Assemble-To-Order, due to its complexity. This complexity also shows in difficulties encountered in capacity planning, since common techniques used for other production configurations are not suitable for ETO systems (Ameri et al., 2019; Carvalho et al., 2015, 2017). Therefore, to cope with these difficulties, companies began to adopt alternative production management techniques, considering orders as projects and employing project management techniques (Hicks et al., 2007). The contributions provided in the literature are mainly case studies: results obtained in the latter are hardly generalizable due to the peculiar characteristics of each ETO system (Adrodegari et al., 2013; Chin-Sheng Chen, 2006; Kumar Sriram & Alfnes, 2014). In addition, mathematical models for the management of planning, scheduling, and progress control are often presented alongside conceptual frameworks (Neumann et al., 2022; Zennaro et al., 2019). The study carried out by Neumann, for instance, presented a very interesting representation of planning, scheduling, and control flow but then focused on a mathematic model for job scheduling on resources, which should be improved by including a heuristic algorithm to manage long computing time.

However, these models are presented without highlighting the links between the proposed mathematical formulations and the framework sections. Moreover, these models are not further developed to obtain a software solution that would be applied, effectively making such formulations useless in business practice. On the other hand, some studies attempt to identify which features should be included in software that supports ETO systems in planning and control, while also pointing out the limitations of existing solutions (Adrodegari et al., 2015; Ruy Somei Nakayama & Mauro de Mesquita Spinola, 2015). These two aspects represent research gaps in the state of the art and can be summarized as follows:

- Absence of a logical link to understand the existing connection between frameworks and mathematical models and algorithms proposed for planning, scheduling, and control (Bhalla et al., 2023; Neumann et al., 2022; Zennaro et al., 2019).
- Lack of adequate software support, in the same management phases, for Small and Medium-sized Engineer-To-Order companies (Adrodegari et al., 2015; Ruy Somei Nakayama & Mauro de Mesquita Spinola, 2015).

2.1 Research aim and innovative contribution

To fill the gaps identified in the literature, a preliminary conceptual framework was developed, defining the main processes to follow to manage a job order in ETO production systems, which was then detailed with a logical model. The main Research Question (RQ) that this framework wants to address is: *How to model a comprehensive project-based framework for planning, scheduling, and monitoring activities in ETO environments adaptable to small enterprises' landscape?* The main innovative contribution of this work is the development of a simplified approach to planning and control easily adopted in small manufacturing enterprises, that, differently from big, but also medium enterprises, are not fully structured and significantly lack digitalization. The possibility of developing an easily implementable tool starting from this framework, closer to small companies' actual way of acting and tailored to it, will represent a viable alternative to the complex and expensive software systems that are already commercially available. The strength of this approach is represented by the project-based modeling of planning, scheduling, and monitoring processes that will support, but not completely replace, the planner in his/her decision-making processes.

3. Framework proposal and logical modelling

As highlighted in the literature review (Section 2), most of the existing frameworks are general, describing the structure and the challenges of ETO systems (Bhalla et al., 2023; Kumar Sriram & Alfnes, 2014), or focused on the scheduling of jobs on production resources rather than on the overall problems of planning, scheduling, and progress control (Carvalho et al., 2017; Neumann et al., 2022). For this reason, a new framework was developed. The resulting proposed framework illustrates, in a general way, the steps that ETO companies should face when managing a job order, from the customer's request for quotation to the closing and reporting of the project. The framework, depicted in Appendix A, precisely describes the order management process, in its (i) planning, (ii) scheduling and monitoring, and (iii) closing phases. For its development, the IDEF (Integrated Definition) method was used, which is a graphic process modelling methodology used for design systems and software (Šerifi et al., 2009). It provides an overall picture of order planning, broken down according to its processes and time horizon: each process is represented as a block while all necessary inputs (such as resources, data, etc.), involved functions (i.e., the business functions such as Design office, Project Manager, etc.), tools (i.e. Masterplan), control rules and expected outputs are represented as arrows. All the necessary inputs are shown on the left, while on the right there are the outputs of the process; all the rules and constraints governing the process are represented above the box while the human, physical, and software resources are reported at the bottom. The logical model, detailed by flowcharts (Figure 1 and Figure 2), explodes each process of the framework (dashed blocks) into one or more subtasks, to make explicit which steps should be taken to adequately support planning, scheduling, and control operations in an Engineer-To-Order Small Enterprises. To simplify the discussion, each phase will be presented in a dedicated paragraph, starting with the framework, and exploding each phase with the corresponding logical model section.

3.1 Planning

Planning encompasses all the preparatory activities for design and actual production and refers to a further time period than the subsequent phases. This is particularly true in ETO systems, where product design and engineering are only launched after an order is received, delaying the start of operational activities compared to other manufacturing contexts. Looking at the framework (Appendix A), the process begins with the "Proposal design" followed by an analysis of the company's capacity to handle the workload derived from the new order ("Capacity assessment"). If the order is accepted, it proceeds to the "Planning" phase, where the activities required to complete the project are defined and included in the Masterplan, which is often referred to as a timetabled program of activities in the context of project management. In fact, in general, it can be seen as a plan for managing a complex project by breaking it down into activities and sub-activities. In this way, a framework that includes all the activities that need to be performed is obtained, including planning, scheduling, and monitoring, so that it is possible to follow the progress of the entire project or its parts. The logical model, shown in Figure 1, explains what happens in the long run during order management. First, the company receives a new order from the customer, indicating a desire to obtain a quotation on a specific product with precise technical specifications.

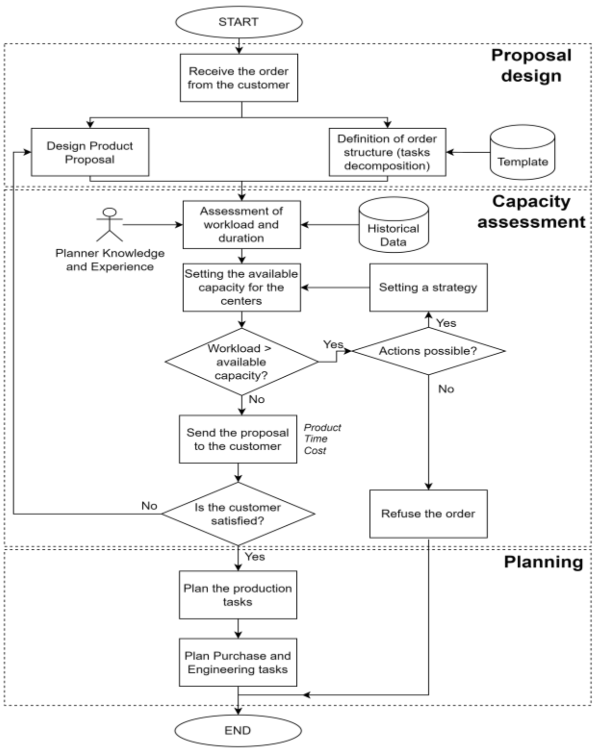

Figure 1: Planning Process flowchart.

For an ETO company, the product must be designed from scratch to define its features, but it is also necessary to perform preliminary planning to assess whether the product can be realized or not considering the available capacity. To support engineers during this step, and to break down the product into all the tasks that need to be carried out for its realization, a template containing a general structure of the production tasks that can be customized according to the specific requests could be useful.

Once known the product features, it is possible to assess the workload for each center and the hypothetical project duration using historical data (i.e. related to similar projects/orders realized in the past) and the knowledge and experience provided by the planner. The workload is intended as the quantified capacity needed to perform one or more tasks allocated on a center, i.e. a resource such as a machine or a worker or a group of them employed for the task.

After setting the available capacity for each center it is possible to evaluate whether the workload is higher than the available capacity: if so, the decision maker must evaluate all the possible actions and set a certain long-term strategy to modify the capacity of the centers, i.e. plan the purchase of new machines or a recruitment campaign for increase the available capacity. In case there is no possibility to change the actual situation, then the order must be refused. On the other hand, if the workload is less than or equal to available capacity, it is possible to send the proposal to the customer, with details of the product, costs, and time required, and wait for their acceptance. The next step is to plan all the production tasks, and consequently, the engineering tasks, which must design not only the components manufactured in-house but also all those parts that will be manufactured by subcontractors according to its specifications and the purchase of the necessary raw materials and components.

3.2 Scheduling and monitoring

Scheduling and monitoring represent the second section of both framework and logical model. Previously planned activities must now be scheduled, then ordered, and placed over a time horizon that has been kept generic in the present discussion to make this logical model adaptable to all ETO realities. Scheduling is followed by control, useful to verify that everything is proceeding as planned: if not, it is necessary to intervene to restore the situation to the ideal planned condition or modify the existing constraints to meet the deadlines stipulated and defined with the customer. In summary, this section shows all the steps to be performed in the medium to short term. The first step of this section of the framework (Appendix A) involves reassessing resources capacity ("Capacity reassessment"), scheduling the activities on a Gantt chart ("Scheduling"), to assess if the capacity is enough, and then starting them ("Start of activities"). Finally, the progress of activities is constantly monitored to ensure that deadlines are met ("Progress control"). Looking at the logical model (Figure 2), before scheduling all the tasks, looking at a closer period of time, it is possible to reassess the total workload and set the available capacity for each work center.

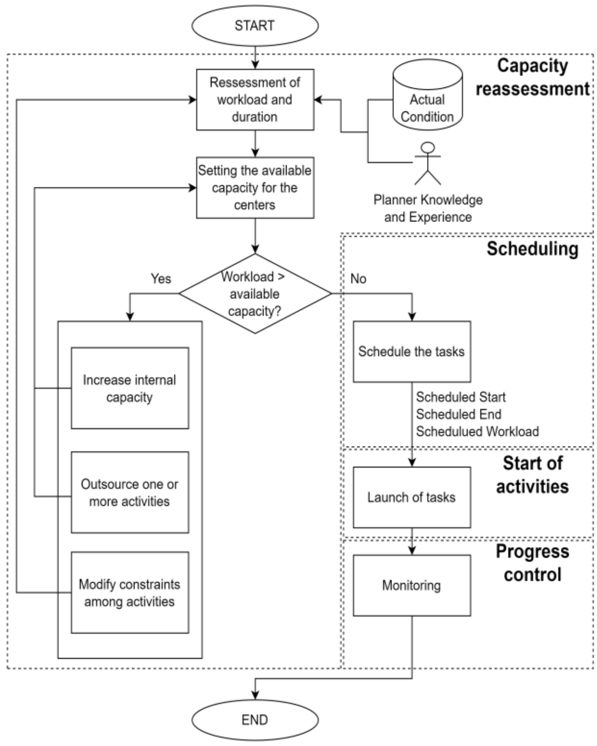

Figure 2: Scheduling and Monitoring flowchart.

Two or more activities of the same project or different projects may have to commit to the same center in the same period. It is therefore essential to ensure that the order established for the activities at this stage is compatible with the company's capacities. So, as done previously, it is necessary to check whether the workload is higher than available capacity; if so, the planner must choose a strategy to overcome this shortage: (i) modify constraints among activities, acting on precedence relations or priority rules, thus modifying the scheduling previously performed with the Gantt chart, thus re-executing the whole cycle until a new capacity check, (ii) increase internal capacity, by using overtime for example and/or (iii) outsource one or more activities (i.e. decide not to carry out all the necessary activities in-house but to outsource one or more of them to reduce the load on the most critical resources). These three alternatives, downstream of the decision, result in a re-evaluation of the workload, duration, and available capacity made by the planner. If the workload is less than or equal to available capacity, it is possible to effectively schedule all tasks to establish their start, end, and related workload. This step consists of placing the planned activities in order on the Gantt Chart, once the time horizon of the analysis and the time unit in relation to which they must be scheduled have been chosen. This order depends on the constraints that exist between the activities, such as priority constraints, offsets imposed upstream, etc. It is essential to respect these constraints to obtain realistic scheduling of the activities and to avoid production stoppages due to a lack of necessary components. At this point, tasks can be started and must be monitored throughout their duration and actual workload to check that everything proceeds as expected until all tasks of the project are completed.

3.3 Closing

Closing is the last section of the framework. The moment of closing a project is consequent to the conclusion of all activities and is typically characterized by a meeting: not only the progress of the project is evaluated, but also the performance of the team, production department, etc. Therefore, it can be useful to collect data regarding the results obtained not only to be able to compare them with the forecast values, i.e., data on costs and time estimated before the start of activities, and to understand whether the project had an outcome similar to what was expected but also to improve the management of future projects. This procedure involves the evaluation of the actual workload defined for the tasks by all the personnel involved in the design and production and of the time and materials used so that they can be compared with the values defined in the beginning. This assessment concludes the project, giving it a positive or negative rating depending on whether the actual values are close to the forecasted values or not: in particular, any kind of deviation, whether positive or negative, is to be considered an error since the quality of a forecast is measured by its overlap with the actual values.

4. Discussions and conclusions

Companies with an Engineer-To-Order production system experience particular problems in managing production planning, scheduling, and control. These difficulties can be attributed to their configuration, which requires that all activities of design, purchase of raw materials and semi-finished products, production, and marketing are subordinated to the receipt of an order from a customer. This makes it virtually impossible to forecast what should be produced over very long-time horizons, as Make-To-Stock realities do. However, the market demands more and more customized products with increasingly shorter lead times. This makes it necessary to understand how planning and, subsequently, production scheduling and control can be managed under such conditions of high uncertainty. The ETO characteristics and problems were therefore analysed and a literature review about planning, scheduling, and control in such systems was conducted. It has been highlighted that planning, scheduling, and control do not receive sufficient attention from researchers above all in the context of Small and Medium Enterprises. To answer the gaps identified in the literature (i.e. the absence of a generalizable approach for order planning and scheduling), a framework for the order management in ETO systems was first developed and further detailed through a logical model. The proposed framework will meet the real needs of small ETO companies, being easier than the existing approaches developed in the literature to be transformed into a software solution that will be not difficult to apply in these specific contexts, since it is not complex and over structured as ERP systems and is more adaptable to ETO companies' not-standardized processes characteristics. The practical implementation of the model could be the possibility to make the planner aware of the production centers' saturation in advance and to let him simulate different planning scenarios. Moreover, if the collection of data is realized over the years, it may be possible to define a more rational offer for new orders that can be aligned with real future advances. Finally, even in the case of a complex product, the decomposition of an order in tasks (as in the classical Project Management approaches) associated with different capacity centers can help the planner simplify the problem. The main aim of this framework is to combine the strength of the planner experience, who still represents a key element in the order management for small enterprises and is not completely replaceable, and his/her strategic/tactical approach, with a structured, simplified, and generalizable approach that helps in planning and scheduling the order tasks.

However, even if the logic could be clear and defined, there are some limitations or in some way some steps to be taken before the possible real application of a model like this in a real industrial environment. It is necessary to analyse the production processes, to define the production centers and their capacity, and to identify tasks and workloads so that they can be assigned to the appropriate centers. In addition, the presented model works with a generic time horizon that only distinguishes between long and medium-to-short: it must therefore be established according to the features of the specific company. The proposed framework, which has been developed specifically for ETO small companies as detailed in Section 1, is generalized and adaptable to different types of companies. Based on an initial analysis of the production system, the framework would be customized in terms of time horizon, centres, and their related resources for capacity assessment, maintaining the overall logical approach. Future work may consist of giving a mathematical definition of the proposed model and its variables, followed by validation with small ETO enterprises. The logical model is also the first step in answering the second gap: from the model, it is possible to define the structure of an easy-to-implement software solution that effectively supports small companies in the management of planning, scheduling, and progress control. Its development may be the subject of future work, including its application in real case studies. Furthermore, this framework lacks the constraints and controls related to material availability. Given the ETO nature of the companies for which this model has been developed, one of the assumptions has been to consider the future availability of materials that are mainly purchased for the specific project/order and only manage the planning and monitoring of material purchasing tasks. This limitation could eventually be overcome in future investigations.

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Appendix A. IDEF representation of the framework proposal.