J Intell Manuf (2012) 23:575–585
DOI 10.1007/s10845-010-0396-1

A project scheduling approach to production and material requirement planning in Manufacturing-to-Order environments

Arianna Alfieri · Tullio Tolio · Marcello Urgo

Received: 4 August 2009 / Accepted: 1 March 2010 / Published online: 18 March 2010

Abstract Long- and medium-term production planning are tools to match production orders with resource capacity and that can also be used as a baseline for material procurement. The lack of a detailed schedule for the manufacturing operations, however, may cause difficulties in providing a proper material requirements planning and may affect the feasibility of the production plan itself. This paper proposes an approach, based on production process knowledge, to extract scheduling information from an aggregate production plan in order to support material procurement. The proposed approach is applied to an industrial case involving machining center production.

Keywords Production planning · Aggregate planning · Material requirement planning

Introduction

In the management of production systems, production planning represents the core activity dealing with how and when to produce, considering customer orders and material and resource availability while aiming at minimizing production time and costs, efficiently organizing the use of resources and maximizing efficiency in the production system.

To this end, production planning can suggest to use the resource availability of a given period to satisfy the demand of other periods. Anticipation of production leads to inventory costs (parts produced in advance have to wait in inventory), while unreadiness may lead to penalty costs (late delivery of the orders or lost demand). Moreover, the quantity produced in a given period impacts the resource and material usage and thus the production costs. This problem can be analytically formulated by means of variables representing the decisions to be taken and of constraints representing resources availability, precedences and due dates. However, in practical cases, the mathematical formulation of the problem leads to a large-scale mathematical programming model including both long-term (e.g., capacity planning) and short-term (e.g., shop-floor scheduling) decisions the solution of which can be computationally impossible.

A common method to reduce the planning complexity and make this task more manageable is the use of a hierarchical production planning and control framework (Hax and Meal 1975; Bitran and Tirupati 1993; Hopp and Spearman 2000).

Hierarchical production planning and control techniques perform a time-based decomposition of the planning problem, i.e., they separate the problem into distinct subproblems to be considered at different time horizons. It is called “hierarchical” because the different time horizons usually correspond to different hierarchical levels in the company. Long-term subproblems (e.g., capacity planning or resource allocation) are usually strategic problems; medium-terms subproblems (e.g., aggregate production planning) are tactical problems; short-term subproblems (e.g., lot-sizing problem) are operational problems. When using hierarchical approaches, higher level subproblems are solved first, and their solution becomes a constraint for lower-level

A. Alfieri
Production Systems and Economics Department, Politecnico di Torino, Torino, Italy
e-mail: arianna.alfieri@polito.it

T. Tolio
ITIA CNR, Institute of Industrial Technologies and Automation, National Research Council, Milan, Italy
e-mail: tullio.tolio@itia.cnr.it

M. Urgo (✉)
Manufacturing and Production Systems Division, Department of Mechanical Engineering, Politecnico di Milano, Milan, Italy
e-mail: marcello.urgo@polimi.it

subproblems. For example, at the strategic level, resource capacity is a variable, constrained to the available budget. When the resource capacity has been decided, it becomes a constraint for aggregate production planning. Given the available resource capacity, aggregate production planning defines the quantity to produce. At the shop floor level, given the quantity of each product to be produced in a time interval, production scheduling defines the sequence of the detailed production activities (Tan and Khoshnevis 2004).

In this framework, production planning, scheduling and material procurement, work at different hierarchical levels and time horizons according to the duration of the activities and operations to be *planned* (in a broad sense). Longer activity durations have longer time horizon, thus requiring less detailed *plans*.

Production planning is typically done at an aggregate level for both products and resources. Distinct but similar products are combined into aggregate product families that can be planned together so as to reduce planning complexity. Similarly, production resources, such as distinct machines or human workers, are combined into an aggregate machine or labor resource. When devising a production plan, the availability of raw materials and components must also be considered. End items are usually comprised of many fabricated components and subassemblies, which must be available in the production system to assure the execution of the production plan. Material requirements planning (MRP) works at a shorter time horizon and provides the supply plan for these dependent-demand items in a coordinated and systematic way (Vollman et al. 1992). Aggregate production planning and material requirement planning are strictly dependent activities, and their interactions have a strong impact on the production performance (Harris et al. 2002).

This framework fits very well to mass production systems, while in Manufacturing-to-Order (MTO) and Engineering-to-Order (ETO) systems producing complex items, its effectiveness is somewhat decreased. This decrease is due to the fact that, in such systems, production planning, scheduling and material procurements tend to work on similar time horizons, as will be discussed in section "Manufacturing-to-Order and Engineering-to-Order systems". A project scheduling approach is, in such cases, a suitable tool to model the production planning problem (Márkus et al. 2003), provided adequate attention is given to the definition of precedence relations (Váncza et al. 2004).

In this paper, the problem of the coordination of aggregate production planning and material requirement planning with particular reference to Engineering-to-Order and Manufacturing-to-Order production system is addressed. Rather than providing a production plan approach, we use an existing aggregate planning approach and then exploit the knowledge of the product and production process to enrich the information of the aggregate production plan. The production planning approach developed in Tolio et al. (2008) is considered, but any other aggregate planning approach can be used. An aggregate production plan provides start and finish times for the aggregate activities. Thus, the material requirement plan will ask that all the components needed for an aggregate activity are available before the aggregate activity starts. However, when the duration of aggregate activities is considerable, this could be an unnecessary constraint because some of the components could be actually needed days or weeks after the aggregate activity has started. The proposed approach, given the aggregate production plan, exploits the detailed information related to the production process to determine temporal ranges for the execution of the production operations within the aggregate activities. These temporal ranges are used as an estimation of the due dates for the material procurement. The proposed approach is applied to an industrial case study of a company producing machining centers.

The paper is organized as follows. In section "Literature review", the existing literature is analyzed. A brief description of the characteristics of MTO/ETO systems with respect to production planning are described in section "Manufacturing-to-Order and Engineering-to-Order systems". The planning approach based on project scheduling with feeding precedence is briefly described in section "RCPSP with variable intensity and feeding precedences". The disaggregation of the aggregate activity plan, to be used as a basis for material procurement, is accomplished in section "Activity disaggregation". sections "Industrial application" and "Computational test" contain, respectively, the description of the case study and the results of computational tests on different industrial instances. Finally, section "Conclusions" concludes the paper and proposes future research.

Literature review

The traditional hierarchical planning approaches, as discussed in the previous section, do not well fit MTO/ETO systems that produce complex items. In particular, it is not possible to disaggregate the aggregate plan to support material requirement planning and thus material procurement due to the structure of the planning horizon. In MTO/ETO systems producing complex items, in fact, an aggregate view to production planning is required due to the prohibitive dimension of detailed production planning. To our knowledge, no paper in the literature discusses the link between aggregate planning and material requirement planning in such systems.

In MTO/ETO systems producing complex items, the use of aggregate activities results in a plan that is missing detailed information on the operations sequence. The plan suggests when a given aggregate activity should be performed; nevertheless, at the shop floor level, all of the operations "contained" in the planned activity have to be scheduled in detail. Aggregation can also have undesirable effects on the behavior of production planning approaches.

Many papers in the literature, studied the influence of aggregation on planning. Just to cite a few, Váncza et al. (2004) address the influence of activity aggregation on the performance of production planning methods. Excessively large aggregate activities can induce infeasibility in the short-term schedule due to poor consideration of the effects of precedence constraints on the resource load within the same time bucket. The impact of this side effect can be reduced by adequately modeling precedences in the planning phase. The role of precedence modeling is addressed in Tolio and Urgo (2007). Further studies related to the factors influencing the aggregation criterion can be found in Kovács and Kis (2004).

Aggregation at different decision levels has also been addressed by Axsater (1981), where optimal aggregation is investigated as the possibility of deriving detailed material requirement planning from the aggregate plan. However, in contrast to our case, in Axster's model, the aggregation affects the products and the resources but not the planning time buckets. Thus, either the aggregate or the detailed plans have the same time resolution.

After material requirement planning has been derived from the aggregate plan, the feasibility of the detailed production is not yet guaranteed. This problem is sometimes titled *disaggregation of aggregate production plans*, referring to the disaggregation of the aggregate material requirement planning to deal with detailed production plans, and has been studied in Axster and Jonsson (1984), Axsater (1986), Toczylowski and Pienkosz (1991) and Yalcin and Boucher (2004). These papers, however, refer again to typical hierarchical systems, where the time horizon can be changed passing from less detailed problems to more detailed ones.

The problem of aggregate production planning in project-oriented production systems is more similar to ones we are considering and is addressed in Hackman and Leachman (1989). They derive a continuous-time model of the activity execution at an aggregate level, based on a detailed model of the production process. This model incorporates a synthetic description of the time execution of the aggregate activity and can be used to provide a more detailed description of the plan execution.

Starting from the same idea, we aim at designing an effective disaggregation phase to be used after the production plan has been devised, but in a discrete-time model. In the aggregation phase, detailed information on the production process is used to compose distinct production operations into larger activities. The same information can be used, given the devised production plan, to disaggregate the planned activities and enrich the information embedded in the plan in support of the material request planning phase.

Manufacturing-to-Order and Engineering-to-Order systems

In MTO systems, parts are produced to meet orders, rather than being produced for stock. In ETO systems, parts are also produced to meet firm orders, but they also allow customization that can require a partial or complete re-engineering. MTO and ETO systems are very important in fields such as mechanical machinery, plant construction and naval and aerospace industries. In such systems, inventory levels are less important because there is no demand uncertainty and because the final product delivery date can be decided with customers, so as to include resource capacity constraints.

Moreover, in MTO/ETO systems producing complex items, manufacturing and assembling operations usually have a large duration, e.g., a single operation can last 1 or 2 weeks. In this case, the time horizon used for operation scheduling becomes of a length comparable to that of planning problems typical of higher hierarchical levels, such as production planning, capacity planning and material requirement planning. In this situation, capacity planning, production planning, material requirement planning and operation scheduling often interact and must be considered at a same level or even carried out at the same time.

One approach to deal with this problem is the use of a Resource Constrained Project Scheduling Problem (RCPSP) (Márkus et al. 2003), in which the production of an item is considered as the execution of a project. In a production system, different projects are executed contemporarily and use a common set of capacitated resources. Thus, as usual in project scheduling, the obtained plan contains information about both the time execution of operations and the resource allocation, assuring the feasibility of the production plan at the scheduling level, as well.

However, because a medium/long planning horizon is used, the application of such an approach can be difficult due to the very large number of operations and their precedence relations. Thus, to reduce the complexity of the planning problem, distinct manufacturing and assembling operations can be aggregated into larger activities, while different production resources, such as distinct machines or workers, are aggregated into an aggregate machine or labor resource.

RCPSP with variable intensity and feeding precedences

As previously discussed, production planning in MTO/ETO systems can be performed by rephrasing the problem as a

Resource Constrained Project Scheduling Problem (Neumann and Zhan 1995; Banaszak and Zaremba 2006).

Starting from fully detailed information about product characteristics, production technology, routings and suppliers, similar resources are combined into resource groups, and operations into aggregate activities. Different technological criteria can be used for operations aggregation:

Resources Operations requiring the same resource(s) are aggregated into a single activity. The single aggregate activity will be obviously scheduled around the given resource(s), but it is not representative of a single product processing or an entire production phase.

Parts Operations needed to process a same part are aggregated into a single activity. In this case, the aggregate activity represents the manufacturing of an entire part and can require different resources.

Production phases Operations performing the same production phase of a part (or a batch of parts) are aggregated into a single activity. The activity represents, in this case, an entire production phase and, as in the previous case, can require different resources for its processing.

Moreover, when aggregate activities are planned, finish-to-start precedence relations between operations must be transformed into Generalized Precedence Relations (GPRs) (Elmaghraby and Kamburowski 1992) between activities. In fact, when finish-to-start precedence relations are used between aggregate activities, all operations in the predecessor activity must be fully executed before any operation in the successor activity can begin. Clearly, this behavior over-constrains the original problem, requiring different types of precedence relations to allow overlapping between aggregate activities. GPRs allow the overlapping between pairs of activities by introducing the so-called maximal and minimal time lags. A minimal time lag $SS_{ij}^{min}(x_{min})$ specifies that activity j can start only if its predecessor i started its execution at least x_{min} time buckets earlier (Fig. 1a). A maximal time lag $SS_{ij}^{max}(x_{max})$ specifies that activity j should be started at most x_{max} time buckets after the start of activity i (Fig. 1b).

GPRs rely on the assumptions of indivisible activities with fixed execution modes and fixed processing times. In fact, when both the execution mode and the duration are fixed, the amount of resources dedicated to each activity in each time bucket is also determined.

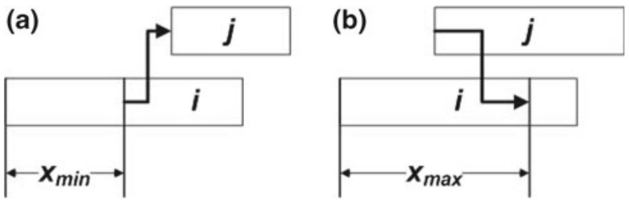

Fig. 1 Generalized Precedence Relations with time lags

Another characteristic of the considered MTO systems is the presence of activities to be manually processed. In these cases, a single worker can be assigned to different activities or several workers can be assigned to the same activity, and these assignments change over time (i.e., different time buckets can have different activity/worker assignments). Under this assumption, either the resource used in each time period or the duration of the activity are not univocally defined.

A solution to this problem is the use of the Variable Intensity formulation of the Resource Constrained Project Scheduling Problem (Leachman et al. 1990; Kis 2005). In this formulation, the amount of resources (considered to be continuously divisible) allocated to activities is time varying. Thus, the time needed to completely process an activity is not a priori known but depends on the amount of resources dedicated to the activity in each time bucket.

It should be noted that if the amount of resources dedicated to each activity in each time bucket is fixed, then so are the number of time buckets needed to complete each activity and the percentage increment of each activity execution in each time bucket.

In the case of activities to be manually executed, because durations are not a priori defined, the executed percentage of each activity does not exclusively rely on the number of time buckets in which it has been processed. Clearly, this renders the use of maximum and minimum time-lags to allow activity overlapping ineffective, i.e., GPRs are ineffective in case of activities to be manually processed (Kis 2006; Tolio and Urgo 2007).

In the project scheduling approach to production planning presented in Tolio et al. (2008), a new set of precedence relations, called *feeding precedence* relations, is developed to allow overlapping between aggregate activities in variable intensity formulations, thus also improving the effectiveness of aggregation in the short-term framework.

Feeding precedences take into consideration the real execution of activities. Four types of relations can be defined:

- *%Completed-to-Start (CtS) precedence* Successor activity j can begin its processing only when, in time bucket t, the percentage processing of predecessor activity i becomes greater than or equal to q_{ij} (Fig. 2a).
- *Start-to-%Completed (StC) precedence* The percentage execution of successor activity j, in time bucket t, can be greater than g_{ij} only if the execution of predecessor activity i has already begun (Fig. 2b).
- *%Completed-to-Finish (CtF) precedence* Successor activity j can be completed only when, in time bucket t, the percentage processing of predecessor activity i becomes greater than or equal to q_{ij} (Fig. 2c).
- *Finish-to-%Completed (FtC) precedence* The percentage execution of successor activity j, in time bucket t, can be

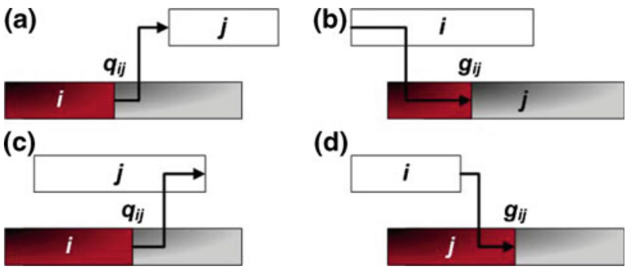

Fig. 2 Feeding precedence relations

greater than g_{ij} only if the execution of predecessor activity i has been completed (Fig. 2d).

In the computational experience described in section "Industrial application", we use the approach proposed in Tolio et al. (2008) to devise the aggregate plan. This will be then disaggregated to create a detailed operation schedule, as described in section "Activity disaggregation".

Activity disaggregation

The aggregate plan (i.e., the plan based on aggregate activities) provides start and finish times for each activity but no information about the execution of each single operation within the aggregate activities. However, such information is required to properly plan material procurement.

A method of extracting such information from the aggregate plan is to use start and finish times of each activity together with the information on the manufacturing operations aggregated into the activity and the precedence relations among them. In the following, we call this phase *activity disaggregation*.

Even though long/medium-term planning gives exact time intervals for each activity execution, it is quite unlikely that the activity disaggregation is able to asses the exact execution interval for each operation. A more realistic result is the possibility of defining a range for start time and finish time of each operation. The length of these ranges mostly relies on the structure of aggregate activities, as shown in the example in Fig. 3.

Given an aggregate activity and a manufacturing operation within it, the information concerning the other operations in the aggregate activity is used to provide further constraints on the start time of A. Given the precedence relations structure, it is possible to identify a set of operations (highlighted in blue) that must be executed before operation A can start. The percentage of these operations, with respect to all operations in the aggregate activity, represents the percentage q of the activity that must be processed before operation A can start, i.e., the Earliest Start Execution Fraction for operation A ($ESEF_A$). Similarly, it is possible to find a set of operations (highlighted in green) that can be executed only if A has been completed. This second set of operations represents the percentage g of the aggregate activity, and thus $1 - g - A$ is the maximum fraction of the aggregate activity that can be executed before starting operation A, i.e., the Latest Start Execution Fraction ($LSEF_A$) for operation A.

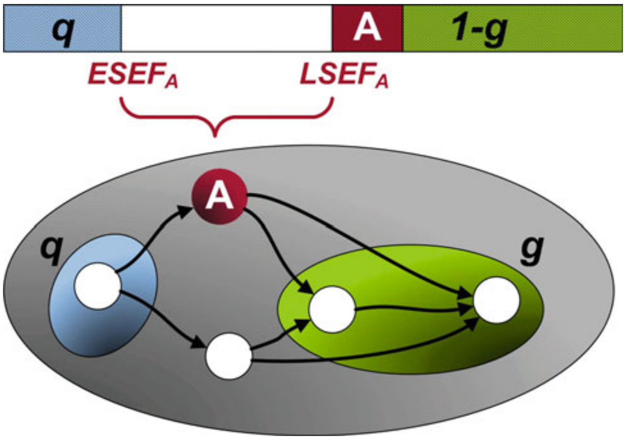

Fig. 3 Earliest and latest start execution fraction

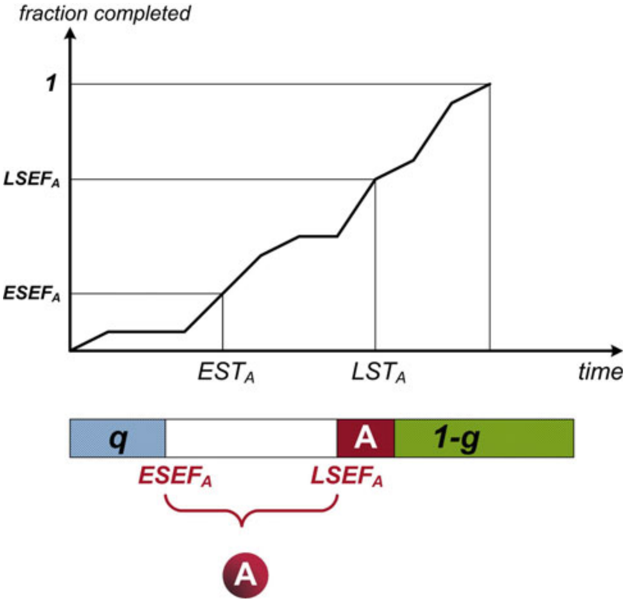

Fig. 4 Earliest and latest start time

Both $ESEF$ and $LSEF$, for a given operation, are based on the percentage execution of the aggregate activity. Thus, percentage and temporal execution of an aggregate activity must be matched, which can be achieved using the the information contained in the production plan. Given such a match (Fig. 4), $ESEF$ and $LSEF$ provide the Earliest Start Time (EST) and the Latest Start Time (LST) for the considered operation.

The time span between EST and LST corresponds to the range for the start time of a given operation. Because there is a group of materials (components) associated with each operation, according to its bill of materials, such a range gives the earliest and latest due dates for the necessary components. If such components are available before the earliest due date (EST), the operation can start at any time within the range. Conversely, if the components are available only after the latest due date LST, the aggregate activity may experience a delay with respect to the expected completion in the production plan. Finally, if the components are available between the earliest and latest due dates, although the plan is considered feasible by the time analysis, it cannot be assured that no delay will occur because joint utilization of resources can further constrain operation execution. Because detailed resource utilization is not provided by an aggregate production plan, it is not possible to infer complete knowledge about this issue only from the production plan and the aggregation information.

Although not providing a complete description of the feasibility region for material procurement, the information obtained through the disaggregation process can play a significant role in the definition of the material requirement plan, as shown by the industrial test case reported in section "Industrial application".

Industrial application

To evaluate the effectiveness of the proposed approach in enriching the information contained in the production plan, it has been applied to an industrial case dealing with the production of machining centers. The case adequately represents MTO/ETO production systems because, although some machining center types are standard, most of them usually require complex customization. In fact, given the base structure and the general characteristics, different tailored equipment is usually designed according to customer requirements.

The production of machining centers entails eight main phases:

Structure preparation The machine center structure is prepared for the assembling phase. Scraping operations are performed to provide a proper finishing level where needed.
Structure painting The machine center structure is painted.
Autonomous components assembling Autonomous components (e.g., spindle head, machine table, electrical cabinet), to be installed onto the machining center, are separately assembled.
Assembling The machine center structure is placed in the assembling area and all components are installed.
Wiring Electrical connection is provided for all installed components and for the control system.
Testing The main functionalities are tested according to the main regulations and internal standards.
Metrological testing Machine center accuracy is tested according to its declared capabilities and to customer specifications.
Disassembling and delivery The machining center is partly disassembled and delivered to the customer.

These phases are mainly processed by workers. Workers are grouped according to their skills and work on one specific production phase.

The most important phase is Assembling. Due to the complexity of the machining center (i.e., many components to be assembled together) this phase can reach a considerable length (between one and 5 months, depending on the machining center type). Thus, a critical issue is to assure a timely supply of the needed components.

In the studied case, 17 different groups of components are taken into consideration. Each group is installed through a specific assembling operation ($AO_1 \dots AO_{17}$). In practice, the assembling activity is divided into seventeen assembling operations dealing with the installation of different components such as axes and actuators, different types of sensors, the hydraulic system, spindle head, table, security protections, pallet changer and mover, pallet buffer, cooling system, and options and accessories, if any. Each assembling operation needs the availability of its group of components to begin. In the experiments, real data corresponding to 10 different machining center types are used. Not all machine types require all of the components, i.e., some of the aforementioned seventeen operations may be not present in some machine type assemblies.

Computational test

Two classes of experiments have been carried out to test the effectiveness of the disaggregation approach.

In the first class of experiments, given a machining center type, a production plan has been devised considering a detailed production process with no aggregation of the assembling phase (i.e., all assembling operations are individually considered). The production plan has been devised aiming at the minimization of the makespan over a time horizon divided into daily time buckets. The percentage of each operation processable in a single time bucket has been bounded according to technological considerations and resource constraints.

In the second set of experiments, for each machining center type, a production plan has been devised considering the aggregate assembling activity. Thus, given the aggregate production plan and the information about the aggregation, Earliest Start Times (EST) and Latest Start Times (LST) have been computed for each assembling operation. These

Table 1 Aggregate results

	Range			Percentage			Average Δ
	Average	Min	Max	Average	Min	Max	
AO1	1.20	1	2	0.02	0.01	0.04	0.00
AO2	1.80	1	2	0.04	0.02	0.05	1.00
AO3	17.10	12	33	0.33	0.17	0.53	1.00
AO4	3.70	2	6	0.07	0.05	0.12	1.40
AO5	3.70	2	6	0.07	0.05	0.12	1.30
AO6	4.50	3	6	0.09	0.07	0.12	1.00
AO7	0.90	0	2	0.02	0.00	0.03	1.00
AO8	7.20	6	8	0.17	0.13	0.21	1.40
AO9	6.00	6	6	0.13	0.13	0.13	4.00
AO10	12.50	7	22	0.23	0.15	0.39	2.00
AO11	11.30	5	25	0.22	0.07	0.44	1.30
AO12	11.30	5	25	0.22	0.07	0.44	1.20
AO13	11.30	5	25	0.22	0.07	0.44	1.90
AO14	11.30	5	25	0.22	0.07	0.44	1.10
AO15	10.70	5	24	0.21	0.07	0.42	1.30
AO16	10.70	4	25	0.21	0.06	0.42	2.30
AO17	7.00	4	9	0.15	0.06	0.20	3.67
Average	7.78	4.29	14.76	0.15	0.07	0.27	1.58

values have been used to provide the Earliest and Latest Due Dates for the supply of the components associated with each assembling operation.

The results achieved with the disaggregation of the aggregate plan are compared to the information directly provided by the detailed production plan. In Table 1, the average results of the computational experiments are reported.

Column *Range* contains the average, minimum and maximum time span (over the 10 instances), expressed in days, between EST and LST. This value represents the absolute accuracy obtained in the estimation of the operation start time. Column *Percentage* reports the (average, minimum and maximum) fraction represented by *Range* with respect to the makespan of the entire machining center. This value represents the relative accuracy in the estimation of the operation start time.

The results show that several manufacturing operations (AO_1, AO_2, AO_4, AO_5, AO_6, AO_7, AO_8, AO_9, AO_{17}) have an average *Percentage* value in the interval (0%, 13%). Therefore, the ranges for such operations have a length between 1 and 10 days within the time span needed to produce an entire machining center (i.e, the makespan, between 37 and 70 days in our experiments). In such cases, the accuracy in the estimation of the start time of the operation can be considered good.

Other assembling operations show a bigger range, between 6% and 44%. Such higher values, however, are mainly due to the fact that these assembling operations (AO_8 and from AO_{10} to AO_{16}) can be processed in parallel with other assembling operations that are, instead, on the critical path. In this case, a shift of a single operation within its range, due to a late component supply, hardly causes a delay of the whole assembling activity. However, when more than a single group of components is supplied later than the EST of the operation they are needed for, then only a detailed scheduling can verify the effective occurrence of a delay. Operation AO_3 has the widest range; this was expected because it represents the installation of the hydraulic system, an external component that can be installed at any time after the axes and actuators have been assembled onto the machining center.

Column *Av.* Δ contains the average time interval between the EST of the considered operation (calculated by disaggregation of the aggregate production plan) and the start time of the aggregate activity (obtained from the detailed production plan). This value considers the difference between the use of an aggregate planning approach and that of a detailed one. The comparison of the two production plans provides an idea of the penalty incurred with the adoption of a planning approach with less details. This value represents the anticipation in material requirement in case the plan is not disaggregated. The detailed results of each single instance are reported in the “Appendix”, in Table 2.

As a concluding remark, it should be noted that, in traditional approaches, no disaggregation is performed and thus either detailed scheduling has to follow the aggregate planning or the material requirements have to be planned using only the information included in the aggregate plan. In the first case (i.e., detailed scheduling phase), a more accurate material requirement planning can be achieved, but it requires a greater time effort to perform it. In the second case (i.e., material requirements planned using aggregate information), the possible extremely large anticipation in material procurement could lead to high inefficiency in terms of inventory costs. The advantage of the proposed method lies exactly in the possibility of achieving a fair compromise between the anticipation of procurement and the avoidance of a usually computationally intensive detailed scheduling phase.

Conclusions

In this paper, we considered production planning in MTO/ETO production systems and proposed an approach to extract from an aggregate plan the information needed for material procurement at single operation level. The approach is based on the detailed knowledge of the production process. Given an aggregate plan (where only aggregate activities, each containing several operations, are considered), a disaggregation phase allows to enrich the information in the production plan, providing an estimation of the dates for the supply of the required components.

Although not able to provide as much information as a detailed scheduling, the proposed approach is a suitable tool to support material requirement planning on a medium time horizon. A better result, however, could be reached by including in the aggregate activities additional information on their *execution profile*, which depends on the contained manufacturing operations. Such an improvement has been proposed in Hackman and Leachman (1989) for a continuous model, and it will be the subject of future research.

Acknowledgments The authors would like to thank MCM S.p.A for their support in the definition of the real case. This research has been partially funded by the "XVII Executive Programme of Scientific and Technological Cooperation between the Republic of Hungary and the Republic of Italy".

Appendix

Columns EST and LST report the Earliest Start Times and Latest Start Times of each operation, respectively, while column *Range* and column *Percentage* have exactly the same meaning as in Table 1 (time span between EST and LST and percentage of *Range* with respect to the makespan). Column ST, instead, reports the Start Time of the operations obtained through a detailed production planning. This value can be used to verify the effectiveness of the calculated EST and LST. It can be seen that, as expected, Start Time is always in the interval between EST and LST. Finally ΔEST reports the value $(ST - EST)$.

See Table 2.

Table 2 Results

		AO1	AO2	AO3	AO4	AO5	AO6	AO7	AO8	AO9	AO10	AO11	AO12	AO13	AO14	AO15	AO16	AO17
Machine	EST	11	14	14	14	14	14	18			19	19	19	19	19	19	20	20
M1	LST	13	16	27	18	18	18	19			27	27	27	27	27	27	27	27
	Range	2	2	13	4	4	4	1			8	8	8	8	8	8	7	7
Makespan	%	0.044	0.044	0.289	0.089	0.089	0.089	0.022		0.178	0.178	0.178	0.178	0.178	0.178	0.156	0.156	
45	ST	11	14	14	15	15	14	18			19	19	19	20	19	19	20	21
	Δ EST	0	0	0	1	1	0	0			0	0	0	1	0	0	0	1
Machine	EST	11	13	13	14	14	13	17	18			18	18	18	18	18	18	18
M2	LST	12	15	25	17	17	17	18	25			25	25	25	25	25	25	25
	Range	1	2	12	3	3	4	1	7			7	7	7	7	7	7	7
Makespan	%	0.027	0.054	0.324	0.081	0.081	0.108	0.027	0.189			0.189	0.189	0.189	0.189	0.189	0.189	0.189
37	ST	11	14	14	15	15	15	18	19			20	19	21	19	19	20	21
	Δ EST	0	1	1	1	1	2	1	1			2	1	3	1	1	2	3
Machine	EST	11	13	13	14	14	13	17	18	19	20	18	18	18	18	18	18	18
M3	LST	12	15	27	17	17	17	18	24	25	27	27	27	27	27	27	27	27
	Range	1	2	14	3	3	4	1	6	6	7	9	9	9	9	9	9	9

Table 2 continued

		AO1	AO2	AO3	AO4	AO5	AO6	AO7	AO8	AO9	AO10	AO11	AO12	AO13	AO14	AO15	AO16	AO17
Makespan	%	0.022	0.044	0.311	0.067	0.067	0.089	0.022	0.133	0.133	0.156	0.200	0.200	0.200	0.200	0.200	0.200	0.200
45	ST	11	15	14	16	16	14	18	19	23	26	19	19	20	19	19	20	21
	Δ EST	0	2	1	2	2	1	1	1	4	6	1	1	2	1	1	2	3
Machine	EST	10	12	12	13	13	12	17			18	18	18	18	18	18	19	19
M4	LST	11	14	26	17	17	17	18			26	26	26	26	26	26	26	26
	Range	1	2	14	4	4	5	1			8	8	8	8	8	8	7	7
Makespan	%	0.020	0.039	0.275	0.078	0.078	0.098	0.020			0.157	0.157	0.157	0.157	0.157	0.157	0.137	0.137
51	ST	10	13	14	14	14	13	18			20	20	19	22	19	19	21	22
	Δ EST	0	1	2	1	1	1	1			2	2	1	4	1	1	2	3
Machine	EST	28	30	30	31	31	30	35				37	37	37	37	37	38	38
M5	LST	29	32	42	35	35	35	37				42	42	42	42	42	42	42
	Range	1	2	12	4	4	5	2				5	5	5	5	5	4	4
Makespan	%	0.014	0.029	0.171	0.057	0.057	0.071	0.029				0.071	0.071	0.071	0.071	0.071	0.057	0.057
70	ST	28	32	32	34	34	32	38				40	40	40	40	42	45	45
	Δ EST	0	2	2	3	3	2	3				3	3	3	3	5	7	7
Machine	EST	11	13	13	14	14	13	17	18			18	18	18	18	18	18	
M6	LST	12	14	26	16	16	16	17	26			26	26	26	26	25	26	
	Range	1	1	13	2	2	3	0	8			8	8	8	8	7	8	
Makespan	%	0.026	0.026	0.342	0.053	0.053	0.079	0.000	0.211			0.211	0.211	0.211	0.211	0.184	0.211	
38	ST	11	14	14	15	15	14	18	19			19	19	20	19	19	20	
	Δ EST	0	1	1	1	1	1	1	1			1	1	2	1	1	2	
Machine	EST	11	14	14	14	14	14	20	21			21	21	21	21	21	22	
M7	LST	13	15	29	20	20	20	21	29			29	29	29	29	27	29	
	Range	2	1	15	6	6	6	1	8			8	8	8	8	6	7	
Makespan	%	0.040	0.020	0.300	0.120	0.120	0.120	0.020	0.160			0.160	0.160	0.160	0.160	0.120	0.140	
50	ST	11	14	14	15	15	14	20	22			21	21	21	21	21	22	
	Δ EST	0	0	0	1	1	0	0	1			0	0	0	0	0	0	
Machine	EST	11	13	13	14	14	13	17			18	18	18	18	18	18	19	
M8	LST	12	15	43	17	17	17	18			40	43	43	43	43	42	43	
	Range	1	2	30	3	3	4	1			22	25	25	25	25	24	24	
Makespan	%	0.018	0.035	0.526	0.053	0.053	0.070	0.018			0.386	0.439	0.439	0.439	0.439	0.421	0.421	
57	ST	11	14	14	15	15	14	18			20	19	19	19	19	19	21	
	Δ EST	0	1	1	1	1	1	1			2	1	1	1	1	1	2	

Table 2 continued

		AO1	AO2	AO3	AO4	AO5	AO6	AO7	AO8	AO9	AO10	AO11	AO12	AO13	AO14	AO15	AO16	AO17
Machine	EST	11	13	13	14	14	13	20			21	21	21	21	21	21	21	
M9	LST	12	15	46	19	19	19	20			43	46	46	46	46	45	46	
	Range	1	2	33	5	5	6	0			22	25	25	25	25	24	25	
Makespan	%	0.015	0.030	0.500	0.076	0.076	0.091	0.000			0.333	0.379	0.379	0.379	0.379	0.364	0.379	
66	ST	11	14	14	16	15	14	21			22	22	23	22	22	22	23	
	Δ EST	0	1	1	2	1	1	1			1	1	2	1	1	1	2	
Machine	EST	13	15	15	16	16	15	19	20		22	20	20	20	20	20	21	22
M10	LST	14	17	30	19	19	19	20	27		30	30	30	30	30	29	30	30
	Range	1	2	15	3	3	4	1	7		8	10	10	10	10	9	9	8
Makespan	%	0.019	0.038	0.288	0.058	0.058	0.077	0.019	0.135		0.154	0.192	0.192	0.192	0.192	0.173	0.173	0.154
52	ST	13	16	16	17	17	16	20	23		23	22	22	22	22	22	25	27
	Δ EST	0	1	1	1	1	1	1	3		1	2	2	2	2	2	4	5

References

Axsater, S. (1981). Aggregation of product data for hierarchical production planning. *Operations Research, 29*(4), 744–756.

Axsater, S. (1986). On the feasibility of aggregate production plans. *Operations Research, 34*(5), 796–800.

Axster, S., & Jonsson, H. (1984). Aggregation and disaggregation in hierarchical production planning. *European Journal of Operational Research, 17*(3), 338–350.

Banaszak, Z., & Zaremba, M. (2006). Project-driven planning and scheduling support for virtual manufacturing. *Journal of Intelligent Manufacturing, 17*(6), 641–651.

Bitran, G. R., & Tirupati, D. (1993). *Handbooks in operations research and management science, (Vol. 4), Logistics of production and inventory, chap hierarchical production planning* (pp. 523–568). Amsterdam: Elsevier.

Elmaghraby, S. E., & Kamburowski, J. (1992). The analysis of activity networks under Generalized Precedence Relations (gprs). *Management Science, 38*(9), 1245–1263.

Hackman, S. T., & Leachman, R. C. (1989). An aggregate model of project-oriented production. *IEEE Transactions on Systems, Man and Cybernetics, 19*(2), 220–231.

Harris, B., Lewis, F., & Cook, D. J. (2002). A matrix formulation for integrating assembly trees and manufacturing resource planning with capacity constraints. *Journal of Intelligent Manufacturing, 13*(4), 239–252.

Hax, A. C., & Meal, H. C. (1975). Studies in the management sciences, vol. logistics, North-Holland, chap hierarchical integration of production planning and scheduling.

Hopp, W. J., & Spearman, M. L. (2000). *Factory physics : Foundations of manufacturing management*. New York: McGraw-Hill.

Kis, T. (2005). A branch-and-cut algorithm for scheduling of projects with variable-intensity activities. *Mathematical Programming.*

Kis, T. (2006). Rcps with variable intensity activities and feeding precedence constraint. In *Perspectives in modern project scheduling* (pp. 105–129). New York: Springer.

Kovács, A., & Kis, T. (2004). Partitioning of trees for minimizing height and cardinality. *Information Processing Letters, 89*, 181–185.

Leachman, R. C., Dtncerler, A., & Kim, S. (1990). Resource-constrained scheduling of projects with variable-intensity activities. *IIE Transactions, 22*(1), 31–40.

Márkus, A., Váncza, J., Kis, T., & Kovács, A. (2003). Project scheduling approach for production planning. *Annals of the CIRP, 52*(1), 359–362.

Neumann, K., & Zhan, J. (1995). Heuristics for the minimum project-duration problem with minimal and maximal time lags under fixed resource constraints. *Journal of Intelligent Manufacturing, 6*(2), 145–154.

Tan, W., & Khoshnevis, B. (2004). A linearized polynomial mixed integer programming model for the integration of process planning and scheduling. *Journal of Intelligent Manufacturing, 15*(5), 593–605.

Toczylowski, E., & Pienkosz, K. (1991). Restrictive aggregation of items in multi-stage production systems. *Operations Research Letters, 10*(3), 159–163.

Tolio, T., & Urgo, M. (2007). Planning of machining centres production: the role of precedence modelling. *In Proceedings of the 7th AITeM congress*.

Tolio, T., Urgo, M., & Alfieri, A. (2008). Project scheduling with variable intensity activities and feeding precedence relations: an application to production planning in Manufacturing-to-Order environments. In *Proceedings of ESDA 2008, 9th biennial ASME conference on engineering systems design and analysis.*

Váncza, J., Kis, T., & Kovács, A. (2004). Aggregation: The key to integrating production planning and scheduling. *Annals of the CIRP, 53*(1), 374–376.

Vollman, T. E., Berry, W. L., & Whybark, D. C. (1992). *Manufacturing planning and control systems*. Burr Ridge Ill: Richard D. Irwin.

Yalcin, A., & Boucher, T. O. (2004). A continuous-time algorithm for disaggregation of hierarchical production plans. *IIE Transactions, 36*(11), 1023–1035.