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Critical components evaluation in Manufacturing-To-Order processes

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Abstract

In this paper we address the evaluation of the criticality of important components in *Manufacturing-To-Order* and *Assembly-To-Order* processes, where the management of the inventory is a critical problem, especially very expensive ones. In these situations, if an item is purchased only when needed for a specific order, the delivery time could cause the delay of the entire production process. In addition, these manufacturing environments are often affected by uncertainty, caused by the execution of several activities by human operators, and by the intrinsic complexity of the process (especially in assembly processes). In this background, we provide a method to evaluate the criticality level of each important component in an assembly process exploiting the *AoA* project network formalization. In particular we put the focus on the coordination between the scheduled arrive of an element from the supplier, and the actual needed of the component in the assembly process. To this aim we develop a method taking into consideration two different criticality indexes. The approach is validate in a real manufacturing case.

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Keywords: manufacturing-to-order; scheduling; uncertainty; inventory

1. Introduction

The global manufacturing sector lives in an evolving environment in which the customers ask for an increasing product's customization. The companies that want to compete in this sector have to re-design the products and the related manufacturing processes to be easily customized. From this point of view, every new order represents a new product and a new production process as well, specifically designed by the manufacturer. The complexity of elements and their cost make the production process more difficult to be managed and planned and, due to the high cost of the products, the *Make-To-Stock* paradigm is no longer suitable. Different production paradigms have been already studied and applied in the past to help the producer to handle this particular situation. The first one is the *Make-To-Order* approach, where the production of a good starts only when the order is received, hence, no stock is expected. The second one is the *Engineering-To-order* approach that provides the design of the product and the production process for every new order. These paradigms entail an heavy work to design and coordinate every new order placed; for example, for highly customized products, a new production process must be defined and the suppliers coordinated to assure raw materials and components. The focus of this is to evaluate the coordination between the arrival of a component at the production site and its utilization in a process. In particular we analyze the risk of a stock-out of these components. The analysis is focused on the mostly critical components, where critical means those components whose shortage can cause a delay in the production process, with high value and high purchasing cost or time. To this aim we exploit a method to calculate the makespan of a generic production process to assess the time when a component is expected to be needed, this value is then compared to the lead time of the suppliers. The analysis is carried out considering the uncertainty of the processed to obtain a criticality index to point the attention of the manager on the inventory of those component that can cause a delay of the production process.

2. State of Art

The presented study addresses the problem of evaluate the impact of the stock out of an important component in a *MTO* manufacturing process. There are several studies presented in the past that trying to face this issue from different point of view; in [12] and [14] are proposed two classification schemes for this evaluation, without taking into account the underlying manufacturing process. Instead, other authors, addressed this connection and proposed method for controlling the inventory process, like in [6] and in [9]; an additional evolution of this kind of approaches, that addresses also the *MTO* paradigm, is given in [1]. Regarding the manufacturing process is very important to take also into account the scheduling and planning tools, like in [13] and [5]; instead, the connection of this this

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Criticality Estimation
1 Formalization of the *AoA* network
2 Sub-net isolation
2.a Identification of the element to analyze
2.b Isolation of the interesting sub-net
3 Estimation of the distribution functions
4 Risk Evaluation

Fig. 1: Resolution procedure pseudo-code

kind of process with the inventory model is given in [11], where and aggregate risk level is estimated starting from the stock out risk of each component and the scheduling tardiness risk. Our purpose is to cope with the uncertainty affecting the execution of a manufacturing process, like in [2], and of its inventory activities, by formalize the entire process with a stochastic project network, also called *PERT* networks. The most typical application of this instrument is the estimation of the makespan of the project, i.e., the total duration of the project. This estimation is provided using two analytical methods presented in [10] and in [15], or with a *Monte Carlo Simulation* like in [3]. In this paper we will take advantage of all these tools to support a method to measure the criticality of a given component. Our work grounds also on an econometric approach regarding the estimation of the risk: the *Survival Function* and the connected *Hazard Rate*. This approach, studied in [4], estimates the probability of the occurrence of a specific event in a given temporal window.

3. Solution Approach

The proposed approach aims to compare the arrival time of a component and the time of its utilization in the production process. It is straightforward to notice that:

- if the component is available before the production process asks for it, no problem arises;
- if the component is not available when the production process asks for it, the production operation must wait for its arrival.

Our approach is based on these two simple concepts, and it is described in Figure 1.

3.1. Formalization of the AoA network

We consider a stochastic project network, with the particular *AoA* formalization (*Activity on Arc*), modeled through a *Directed Acyclic Graph* represented with $D = (N, A, p)$ in which $A = \{1, 2, ..., m\}$ is the set of generic activities and $N = \{1, 2, ..., n\}$ is the set of generic project events (also named milestones) and p is a vector of independent random variables, modeling the duration of the activities. Using the *AoA* framework, the activities of the process are modeled through edges, instead milestones and event are represented by nodes. In addition, each activity $a \in A$ is associated to a vector p of independent random variables (discrete or continuous) modeling its stochastic duration. We assume that each activity is independent from the others and estimate each of those with a *Maximum Likelihood Estimation*. In our representation, we consider three classes of activities: *purchasing activities*, *production operation* and *dummy activities*. The *dummy activities* are fake activities, whose duration is equal to 0, useful to model specific precedence constraints on an arc with several input and output arcs.

3.2. Sub-net isolation

Our approach aims to evaluate the criticality of each component that has to be purchased by the analysis of its makespan exploiting the project network formalization. After the identification of the component that needs an evaluation, it is necessary to isolate a sub-net with the following characteristics:

- the source node of the sub-network is the source node of the original network;
- the sink node of the network is the node representing the milestone preceding the production operation requiring the component under study.

In other words, the described sub-net, represents the entire process in which is involved the component under study, starting from the beginning of the production process (source node), until the starting of the activity that uses that particular component; the sub-net contains all the edges from the original source node to the node preceding the production operation edge that uses the component under examination. This sub-net formalizes the purchasing process of a particular element and formalize also the utilization of that component in the production process. With this sub-net, then, it is possible to continue the evaluation.

3.3. Estimation of the distribution functions

After the complete formalization of the problem using an *AoA* net and the isolation of a sub-net, the following step is to calculate the distribution of the supplying time of a component at the production site as well as the time in which the component will be needed by the production process. The proposed approach estimates these two time distributions and provides a comparison between them. Let us consider *eventA* representing the event *the process needs the component*, and *eventB* the event *the component is arrived at the plant and it is ready to be used*. The associated distribution functions are, respectively, $F_A(t)$ and $F_B(t)$ given $0 \leq F_i(t) \leq 1$ with $i = A, B$. In particular, for the event A:

- $F_A(t) = 1$ if the process will need the component at time t with probability 1;
- $F_A(t) = 0$ if the process will not need the component at time t with probability 1;
- $0 < F_A(t) < 1$, otherwise.

Instead, for the event B, we have:

- $F_B(t) = 1$ if the component will be available at time t with probability 1;

- $F_B(t) = 0$ if the component will not be available at time t with probability 1;
- $0 < F_B(t) < 1$, otherwise.

To estimate the time when the production process will require a given component (*eventA*), we use a normal *Monte Carlo Simulation* applied at the *AoA* net (the isolated sub-net in this case), following the approach in [3]. The simulation algorithm is able to estimate the $F_A(t)$ using all the *s-t paths* from the source to the sink node, except those paths containing the purchasing activity under evaluation. As defined in [8], given a network with s representing its source and t its sink, an *s-t path* is a sequence of arcs with the form $(s, i_1), (i_1, i_2), \ldots, (i_k, t)$ where the notation (i_1, i_2) represents an arc that starts from node i_1 and finish in node i_2. In particular, the algorithm used, is an application of the *Depth First Search* on the *AoA* nets, it grounds on the classic *Tree search Problem*, whose the resolutive algorithm has been developed also by Knuth in [7]. In this way our approach estimates the makespan of the sub-net without taking into account the purchasing activity, then it estimates when the process will need the element on the production line. Instead, in the evaluation of the function $F_B(t)$ our algorithm takes into account two main situations. The first one is when the company already knows when the component is about to arrive in the plant, thus, the component is already ordered and the delivery date is known. The second one refers the opposite situation, in which the component is not yet ordered and the only way to know its delivery date is to make an estimation grounding on some historic data for the specific supplier. In the first case, having a deterministic delivery date, we obtain a *step distribution function*. In the second situation it is possible to use several methods, e.g., the *Maximum Likelihood Estimation* to estimate the $F_B(t)$ with a general shape. With these information it is possible to estimate the $F_A(t)$ and the $F_B(t)$.

3.4. Risk Evaluation

In this section we address the comparison between the two estimated distributions. The aim of this analysis is to evaluate the criticality of a component and the related purchasing activity, grounding on a function of the associated risk. We consider the definition of the risk r as the quantile of the makespan distribution: with $r = 1\%$ for example, we have the 99% of probability that the component will be needed before the considered quantile, more rigorously we have $t^* :| F_A(t^*) = (1 - r) = 99\%$. In the daily management of the company, if the manager decides to anticipate a certain activity, he takes some risk. Both the indicators that we are going to expose to the reader, ground on these formalization and use the risk level r. The first risk index $IR(t)$ measures the risk of having the production process blocked because a component is not available and its lack blocks the progress of the process. Taking into account the *eventA* and *eventB* described before, it is possible to define:

$$IR(t) = F_A(t)\,[1 - F_B(t)] \tag{1}$$

The index, thus, is the product of the cumulative density function (*cdf*) representing the *eventA* (*the component is needed at time t*) and the *cdf* representing the *event*$\bar{B}$ (*the component is not available at time t*). The results is a *cdf* too, representing the the event *the component is needed on the production line, given its lack in the warehouse*. Using this type of index, the criticality of a certain purchasing activity, and then of the correlated component, can be evaluated in two different way: in a general mode and in a punctual mode. Starting from the second one, it is possible to compare the functions by simply look which function is the highest in a given point like $\tilde{t}$. More rigorously, given two different components, named α and β, it is possible to identify the same index for both, $IR_\alpha(t)$ and $IR_\beta(t)$ respectively, and, with a a fixed time $\tilde{t}$, it is also possible to have the following situations:

- product α is more critical than β, if $IR_\alpha(\tilde{t}) > IR_\beta(\tilde{t})$ and vice versa;
- the products have the same criticality, if $IR_\beta(\tilde{t}) = IR_\alpha(\tilde{t})$.

The first, or general, comparison mode uses another characteristic of the distribution function: the area existing between the X-axes and the function, calculated as the integral of the function itself; this area can be seen as the the risk level of a product cumulated on the entire time horizon. More rigorously for the calculation of the area of a criticality function of a certain product, named α:

$$RiskArea_\alpha = \int_0^\infty IR_\alpha(t)\,, dt \tag{2}$$

Grounding of this calculus, a product α could be evaluated more critical compared to a product β, if the first has a bigger area, that is $RiskArea_\alpha > RiskArea_\beta$. It is also possible to set up an individual evaluation by fixing a threshold in terms of area occupied by the function or in terms of the max value that the area can have (then the max level of aggregated risk); it is also possible to fix some range and assign at each range a criticality level.

The second index, named $IC(r)$ uses two time values taken from the already defined distribution functions. In particular, given a fixed risk value r, the $IC(r)$ is the ratio between the time value corresponding that risk level in the distribution of *eventA* and the time value corresponding the arrival of the component concerning the distribution of *eventB*. More rigorously we have:

$$IC(r) = t^* / \hat{t} \tag{3}$$

where

$$t^* = t :| F_A(t) = (1 - r) \tag{4}$$

and

$$\hat{t} = t :| F_B(t) = 1 \tag{5}$$

with

$$F_B(t) < 1, \forall t < \hat{t} \tag{6}$$

Then, the approach, at first extracts a time value from the distribution representing the *eventA*, that is the presenting of the needed of the component at the production line, and compared it with the arrival time (fixed or estimated) of the component at the production line (or warehouse). Then with a fixed risk r, it is possible to obtain a ratio that represents the following situation:

- if $IC(r) > 1$, the component will be available before the its necessity occurs, no criticality;
- if $IC(r) = 1$, the component will be available exactly when its necessity occurs, no criticality;
- if $IC(r) < 1$, the component will be needed at the production line before its arrival, there is criticality.

Starting from this point, it is possible to develop a more dynamic study on those function by extracting a collection of time instant concerning different risk levels, and thus, calculate different indexes for different r values. The result is a function of the criticality of a certain component, on the risk level on which our approach calculates the sensibility of the index with the elasticity. The elasticity is an economic concept that measure the sensibility of a certain value against the changing of another value. In general, the elasticity of a certain variable y, is the ratio between the percentage variation of that variable, on the percentage variation of another variable x. The meaning of this value is: an increase of the 1% of the variable x, will cause an increase (or decrease) of the ε% of the variable y. Then it is possible to define three different cases in the resulting elasticity: if the $|\varepsilon| > 1$ the variable y is considered *elastic*, if the $|\varepsilon| < 1$ the variable y is considered *inelastic* and if the $|\varepsilon| = 1$ the variable y is considered with *unity elasticity*. Applying these concepts in our cases we obtain the elasticity of the criticality index of a certain component in respect with the risk level; more rigorously we have:

$$\varepsilon = \frac{\%\Delta IC(r)}{\%\Delta r} \tag{7}$$

Grounding on this concept, a company can create its own *best practices* in which there would be a dedicated approach for each elasticity situation.

4. Industrial Application

The viability of the proposed approach is validated in a real industrial case in the machine tool sector, provided by MCM S.p.A.. MCM S.p.A. is an Italian manufacturing company that designs, produces and sells machining centers and FMS all over the world. In particular MCM S.p.A. adopts a *Make-To-Order* model for scheduling its production because it allows its costumers to customize their order. In addition, MCM S.p.A. has to design a new product and a new production process for every new order taking into account that the plant's resources (HR and space are the most important) have to be shared among several commissions. Regarding the production model, also the purchasing phase is very important because for every new order correspond a new product that has to be designed and that needs some particular components. MCM tries to buy every component it needs only when the necessity occurs, in a perfect *MTO* logic; then, for example, mandrels are ordered only when the company has an order that needs them, the same for the design of a particular element. There are, however, some elements that are stored in the company's warehouse every day in the year (stock logic), without any constraints from the orders acquired, it is the case of small components, like screws or wires that can be used for almost every product. In the considered production problem, there are some components more important than others, thus their purchasing activities can impact on the makespan of the assembly process and, if it is necessary, it could be worth changing the purchasing from a *MTO* model to a security stock model.

4.1. Formalization

The order representing our use-case is composed from a *Tank 1300* machine (basic machine model) equipped with some additional elements. This model has, by default, the turning table with torque motor; this model also use $800x800mm$ pallets during its running. It contains also a tools rack with 40 positions. In addition, the costumer, asked for a specific mandrel produced by a third part, he asked also for a multi-pallet carousel and for a cooling liquid tank different from the basic one; then the company has to design again the last element. All these requests from the costumer make the product and its production process different from all other MCM's orders. After this introduction it is possible to face the formalization that takes into account all the activities of the process, starting from negotiation and purchasing of raw materials, to the delivery to the costumer. Thus the production process is composed by 63 activities. We studied the entire process and formalize the *AoA* net shown in the Figure 2 in which there are the purchasing activities indicated with dotted arc and the *dummy* activities with a *d* before the number in the name.

For each activity we estimated a discrete distribution of different type: for the purchasing activities, we used step distributions and for operational activities we used binomial distributions by indicating the minimum and the maximum times needed for finish a certain task. In particular, when we did the study, the order was already in progress and the purchasing orders were already sent to suppliers, then we already had a delivery data. In this situation, the distribution that provides the best fitting with the reality, is the step distribution that assumes value 0 or 1 with the following rules:

- $F(t) = 1$ with $t \geq \dot{t}$;
- $F(t) = 0$ with $t < \dot{t}$;

where $\dot{t}$ represents the delivery date decided by the vendor. We use days as minimum measure unit, this means that the duration of each activity is measured in days. Some activities in our formalization have duration equal to 0. We used this formalization because the evaluation of the given process was been done in a precious date, the March 4 2014 and in that date some activi-

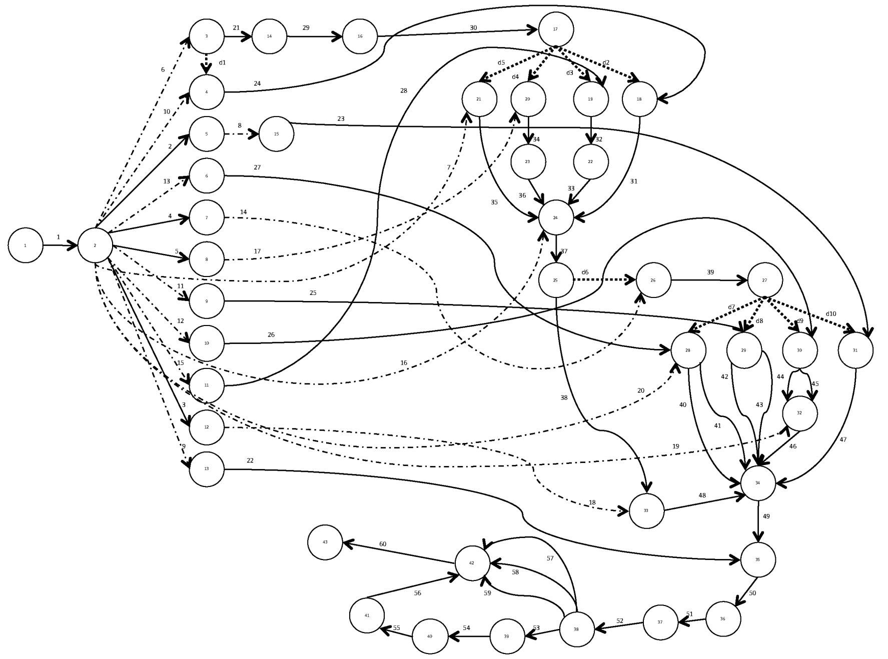

Fig. 2: MCM production process *AoA* net

ties, like *Peripheral enclosure's design* or *mandrel purchasing*, were already finished, then their duration is equal to 0. Thus it is possible to say that our evaluation on this particular process, is a picture of the process itself in a particular moment and the results are valid only for that precious moment. Anyway it is possible also to apply the proposed instrument on a process before its starting and then shoot a picture of the process for make some evaluation in advance. In this formalization we have 43 milestones (nodes) and 63 activities (arcs) including 10 *dummy activities*.

4.2. Application

After the formalization and the distribution evaluation already mentioned, we slavishly follow the procedure presented in Section 3 and obtain some evaluation results for the first criticality indicator and the second one as well. The first step is the isolation of a sub-net with the characteristic presented in Section 3 and, after that, it is possible to calculate the criticality indexes and make some evaluations on all components under study.

4.3. Results

Regarding the first index, $IR(t)$, for all the considered elements but the *table*, the index assumes value 0 in all the time intervals. This is due to the fact that the time span considered is greater than the time needed for the purchasing plus the pre-assembly operation (if needed), hence, no criticality foreseen. For the element *table*, the indicator assumes value 1 for all the extensions of the distribution and, consequently, it is necessary to investigate the shape of the function provided. We will focus the analysis on this issue later on. For the second criticality index, $IC(r)$, we present the Table 1 containing the elasticity calculated with eight different risk values, from 1% to 50%.

Element	Elasticity
Electrical cabinet	0,137
Peripheral Protection	0,136
Machine Border	-
Option Group	0,129
Mandrel	-
Peripheral Enclosure	0,135
Pallet Warehouse	-
Tools Changer	0,123
Multi-pallet	0,123
Table	0,000
Pneumatic Cabinet	0,230
Swarf Conveyor	0,123
Tools Rack	0,123
Structures	-
Pallet	0,106

Table 1: Elasticity evaluated on the MCM use-case with eight different risk values, from 1% to 50%

The results provided from this second analysis are similar to the previous one. First of all, the elasticity is always smaller than 1, then the index is *inelastic* and, thus, it increases slowly with the increasing of the risk; moreover, all the $IC(r)$ index provided (not reported), except the ones for the *table*, are higher than 1, hence, no criticality. At least for some elements (i.e., *machine border*, *mandrel*, *pallet warehouse* and *structures*) we have no value because the components were already available at the moment the analysis was done. Concerning the *table*, we

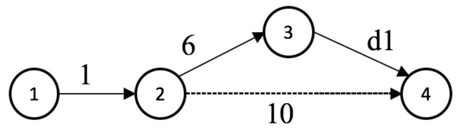

Fig. 3: Table component sub-net

already said that all the values are equal to 0: all the $\hat{t}$ estimated assume value *null* because of the sub-net evaluation shape, reported in Figure 3. In this sub-net we have only one path from the source to the sink node, without the purchasing arc (number 10), that is the the path that follows activities $1, 6, d1$. The makespan obtained from this path is, obviously, 0 because all the activities have duration *null* for the reasons reported in Section 4.1. As described in Section 3, when the *IC* is smaller than 1, we have a critical situation, a risk in the purchasing of that element. In relation to the table, we have the criticality indicator constantly lower than 1, equal to 0. This means that the situation is really critical, indeed, at the date of the analysis, activities named 1, 6 and $d1$ were already in execution, hence the production process was waiting for the arriving of the component *table*.

Finally, we present the elasticity indexes included in Table 1 It is possible to see that the element with the highest elasticity, and then with the highest probability to become critical with the increasing of the risk, is the *pneumatic cabinet*, with elasticity value equal to 0.23; then we have the *electric cabinet* and the *peripheral protection* with 0.137 and 0.136 respectively.

5. Conclusions

In this article we proposed a new approach to evaluate the criticality of the lack of a component in a *MTO* production environment by addressing the coordination between the need of a particular element from the production (or assembly) line and the presence of that component in the warehouse of the plant. Our approach could be used to assess the available inventory (e.g., setting a threshold for the considered indexes), or to analyze the criticality of a single component and/or to select a proper different supply strategy and assess it in terms of the associated risk. In the application to the real case we made an evaluation regarding a precise instant of the production (specifically March 4th 2014). At that time, some operational activities were already completed and all the purchasing activities were already decided (with deterministic arrival time), hence we took a picture of that situation and analyzed it from the point of view of the developed methodologies. Notice that it could be also possible to work with an *ex ante* approach, i.e., before the production of a given product has started, even if this entails the difficulty of estimating the time distributions of the delivery time for the considered inventory items. To estimate these distributions, historical data associated to the specific component and vendor are needed. Finally, a possible future research will address the extension of the approach to the system dimension, i.e., considering multiple product being processes at the same time sharing the same resources and, in addition, addressing an optimization of the inventory.

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