(REFEREED RESEARCH)

INTEGRATED CAPACITY EXPANSION AND SCHEDULING DECISIONS IN A SEWING WORKSHOP

BİR DİKİM ATÖLYESİNDE BÜTÜNLEŞİK KAPASİTE ARTIRIMI VE ÇİZELGELEME KARARLARI

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ABSTRACT

In this study, we consider the integrated problem of capacity expansion planning and job/machine scheduling in a sewing workshop. The separate problems have been studied before; however the important integrated decision has not been previously dealt with. We model the problem mathematically and develop an iterative solution approach to aid the decision maker. We demonstrate the execution of the approach on a sewing workshop example. The results are discussed together with future research directions.

Key Words: Capacity expansion problem, Workshop scheduling, Interval scheduling, Operational scheduling problem, Tactical scheduling problem.

ÖZET

Bu çalışmada bir dikim atölyesinde kapasite artırımı ve iş/makine çizelgeleme problemleri bütünleşik olarak ele alınmıştır. Literatürde bu problemler ayrı ayrı çalışılmış olsa da bütünleşik yaklaşımı içeren bir çalışmaya rastlanmamıştır. Problem matematiksel olarak modellenmiş ve karar vericiye yardımcı olacak tekrarlı bir çözüm yaklaşımı geliştirilmiştir. Geliştirilen yaklaşımın çalışma ilkeleri bir dikim atölyesi örneği üzerinde gösterilmiştir. Sonuçlar gelecek çalışma konusu öneriyle birlikte tartışılmıştır.

Anahtar Kelimeler: Kapasite artırımı problemi, Atölye çizelgelemesi, Aralık çizelgeleme, Operasyonel çizelgeleme problemi, Taktik çizelgeleme problemi.

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1. INTRODUCTION

In many industries, swift competition renders it extremely difficult to create and sustain competitive advantage. Foreign competitors and rapid technological advances are compelling firms to innovate hastily. While such industries as consumer electronics and communication technology are well-known examples, the fashion apparel industry provides an interesting case of hyper-competitive behavior (1). Competition in terms of price and quality in the fashion apparel industry has intensified over the last few decades. While low-cost manufacturing in less-developed countries initially provided an edge for the larger and aggressive fashion apparel firms, a large number of subcontractors in developing countries like Turkey have made low-cost global manufacturing accessible to even small competitors today.

The increased use of subcontracting in all stages of production brought a set of innovations in the subcontractor's side, like quick response related with timing and know-how, rapid learning, cost-cutting techniques, etc. The subcontractors are usually small companies and many in number, and the competition among them is harsh. Hence, careful management of production and operations is crucial for these small companies in order to hold their contracts.

Scheduling of the incoming jobs on the machines in the system is a very important decision in operations management, affecting the lead times, turnover rate and the utilization levels in the company. A nice literature review on scheduling in job shops is done by Jain and Meeran (2). Capacity planning is another significant decision, which influences the machine and worker utilization rates, and shapes the overall performance. Especially in small job-shop type firms, these two decisions are vitally important.

We handle the integrated problem of capacity expansion and scheduling in a sewing workshop in the fashion apparel industry. The developed approach can also be applied to other small job-shop type facilities in the industry. Such subcontractors in the fashion apparel industry, especially the smaller workshops, work with many different contracting firms in general. The utilization levels in these workshops are usually very high and a 24-hour working day may be required. Usually, the incoming orders are known in advance to allow for planning, and the processing time for the order can be estimated by experience. In this study, we combine the capacity expansion and scheduling problems for the subcontractor in such an environment, present involved mathematical models and develop an iterative algorithm to find an approximate solution. Although the scheduling and capacity planning problems have been studied, the integration of these problems has not been studied before. Our study aims to fill this important gap in the literature. The unique methodology developed in this study brings a novel contribution to the theory, and may be a pedestal for future studies and applications.

We define the problem in detail, provide related mathematical models together with the related literature, and discuss the gaps in literature in the next section. The developed solution methodology is presented in section 3. We provide a numerical example in the context of a sewing workshop, and discuss the results in section 4. Finally, we conclude with many interesting future research topics.

2. PROBLEM DEFINITION

We consider a sewing workshop that is employed as a subcontractor for many different companies in the fashion apparel industry. There are *m* general-purpose sewing machines in the workshop. In the upcoming foreseeable periods (the planning horizon of the workshop), *n* jobs require processing on the machines. We assume that the machines in the workshop are identical in speed and parallel, so that an incoming job can be completed on any of the machines. Foreseeable future is defined as a number of upcoming periods, during which the demand is forecasted with a desired level of accuracy. The capacity expansion plan will be valid during this period, and the length may change according to the workshop's demand structure.

For a capacity expansion plan to be technologically and economically feasible, making medium-range (3-month to 3-year) forecasts should be possible (3). This may be a very probable case for a subcontractor workshop with many employer firms and a stable demand. Another case where capacity expansion plan will work is where the machines in the workshop have high salvage values and could be replaced easily, or where the machines can be leased in and out as convenient without much difficulty. In such a case, increasing or decreasing the capacity level of the workshop will have a small cost, and can be done frequently without having to make very accurate forecasts. The sewing workshops with general-purpose sewing machines may fall into either of the above categories, depending on the demand.

In our problem we assume that a machine can process at most one job at a time. The machines are identical general-purpose machines, i.e. each machine can process each job. There are no machine breakdowns; machines are available at all times. Further, we assume that a job should be processed without any interruption on at most one machine, i.e. there is no preemption or job splitting. All parameters are known with certainty and are integer numbers, and the setup times between job changeovers are included in the processing times of jobs.

Each incoming job *j* has a ready date (r_j), and a deadline (d_j), and the processing time of a job is the difference between these two dates ($p_j = d_j - r_j$). Each job brings a profit (w_j). Based on the above assumptions and definitions, the workshop resembles a reservation system, where incoming jobs reserve time slots on the machines.

The scheduling of a subset of the incoming jobs on the current set of machines so that the total profit will be maximized is called an operational scheduling problem. With the above definitions, this problem for the defined workshop could be modeled as follows.

i, j : Job indices, $i, j = 1,\dots,n$

k: Machine index, $k = 1,\dots,m$.

$$x_{jk} = \begin{cases} 1, & \text{if job } j \text{ is processed on machine } k, \\ 0, & \text{otherwise.} \end{cases} \quad \forall j,k.$$

The binary decision variable defined above takes the value of one if job *j* is processed on machine *k*, and zero otherwise. In order to model the problem, we form a chronological sequence of ready times and deadlines. For this purpose, let $\{t_1, t_2, \dots, t_z\}$ be the sorted sequence of the r_js and d_js in chronological order with duplicates removed. Let P_a be the set of jobs that need to be processed in the interval $[t_a, t_{a+1})$ for $a=1, 2,\dots, z-1$.

Then the mathematical model for the profit maximization problem becomes:

Maximize $Z_O = \sum_{k=1}^{m}\sum_{j=1}^{n} w_j x_{jk}$ s.t.

$$\sum_{k=1}^{m} x_{jk} \le 1 \qquad j = 1,\dots,n \qquad (1)$$

$$\sum_{j\in P_a} x_{jk} \le 1 \qquad k = 1,\dots,m \qquad \forall a \qquad (2)$$

$$x_{jk} \in \{0,1\} \qquad k = 1,\dots,m \qquad j = 1,\dots,n \qquad (3)$$

The objective function Z_O of this binary programming model maximizes the total profit brought by the processed jobs. Note that some jobs may be left unprocessed since the processing times may be overlapping and we have only a limited number of machines. Constraint set 1 indicates that each job should be processed on at most one machine. Constraint set 2 assures that no machine can process more than one job at a time. The binary variable constraints 3, together with other constraint sets avoid preemption and job splitting.

The capacity planning problem can be modeled using the same assumptions and definitions. The model answers the question "In order to process all incoming jobs, how many machines should the workshop have?"

For this purpose, a new binary decision variable needs to be defined as follows:

$$y_k = \begin{cases} 0, & \text{if no job is assigned to machine } k, \\ 1, & \text{otherwise.} \end{cases} \quad \forall k.$$

The capacity planning model becomes:

Minimize $Z_T = \sum_{k=1}^{m} y_k$ s.t.

$$\sum_{k=1}^{m} x_{jk} = 1 \qquad j = 1,\dots,n \qquad (1)$$

$$\sum_{j \in P_a} x_{jk} \le 1 \qquad k = 1,...,m \qquad \forall a \qquad (2)$$

$$x_{jk} \in \{0,1\} \qquad k = 1,...,m \qquad j = 1,...,n \qquad (3)$$

$$x_{jk} \le y_k \qquad k = 1,...,m \qquad j = 1,...,n \qquad (4)$$

$$y_k \in \{0,1\} \qquad k = 1,...,m \qquad (5)$$

The objective function Z_T tries to minimize the number of machines to process all n incoming jobs. The first three constraint sets are the same as the previous model. Constraint set 4 prevents ensures the assignment of the jobs to only used machines, and constraint set 5 indicates the binary nature of the machine usage variables y_k. In this model, m is an upper bound on the number of machines in the system.

The profit maximization model described above is identical to the model of operational interval scheduling, and the number minimization model is identical to the tactical interval scheduling model, both of which are well-known and well-studied models in literature.

Interval Scheduling is an important problem in scheduling that is frequently encountered in manufacturing and service sectors. The problem considers the scheduling of jobs with predetermined ready times and deadlines on identical parallel machines. Besides its broad application areas in various manufacturing systems, the problem has important applications in the service sector, especially in reservation systems (where resource times are reserved in advance, such as hotel reservation, vehicle rental/repair systems, classroom scheduling etc.). The interval scheduling problem has been studied under different names in literature such as fixed job scheduling (4, 5, 6, 7, 8, 9), scheduling jobs with fixed start and end times (10) or class scheduling (11, 12). Kovalyov et al. (13) and Kolen et al. (14) provide recent reviews on interval scheduling problems and applications. The problem can be applied to almost any reservation system.

Bouzina and Emmons (15) formulate the operational interval scheduling problem as a Minimum Cost Network Flow (MCNF) problem with n+1 nodes and 2n arcs. Hence, the profit maximization problem described in this section is polynomially solvable. Operational interval scheduling has been studied under eligibility and time limitations by Eliiyi and Azizoğlu (4-7). The authors have shown that the problem becomes NP-hard under these limitations, and provided effective exact and approximate solution procedures for the problem. Other studies on the problem under different sets of constraints include (8, 11, 16).

The tactical interval scheduling described above as the capacity planning problem was studied by Hashimoto and Stevens (17). The problem is shown to be polynomially solvable, but the problem becomes hard to solve as different constraints are added. The problem with time limitations has been studied by Fischetti et al. (18- 20), and several algorithms are proposed by the authors for optimal and near-optimal solutions. The problem with eligibility and availability constraints has been studied in (9, 12).

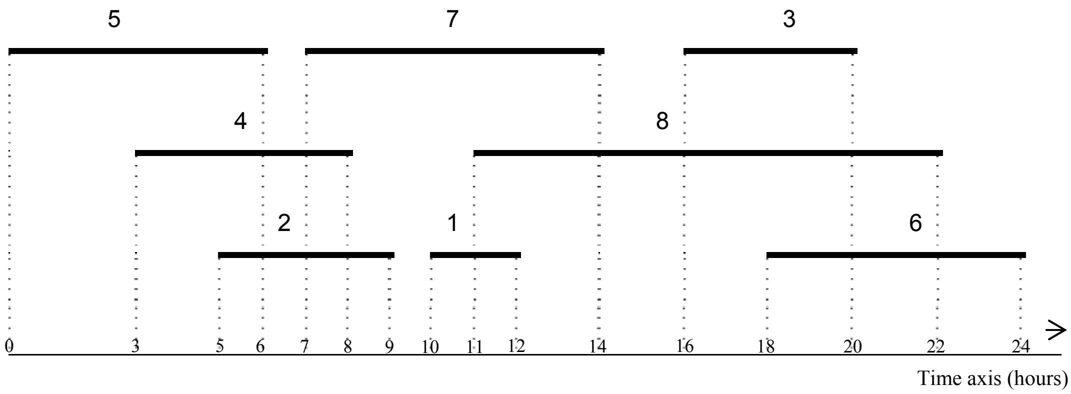
It is obvious from the above analysis that the operational and tactical problems have been popular study topics separately. However, to the best of our knowledge, there has been no attempt to combine these two models in order to reach an integrated decision of incremental capacity expansion and scheduling. The integrated problem is a very important one, answering the following question: "How many extra machines should the workshop include in order to increase the profit to a desired level, and how should the incoming jobs be scheduled on these extra machines?". Thus, we intend to fill this gap in literature by providing an iterative solution approach for the mentioned decision. The specifics of the approach are provided in the next section.

3. SOLUTION METHODOLOGY

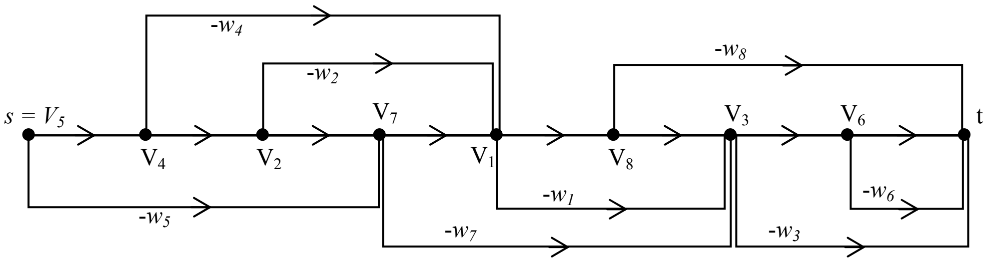
In this section, we first present the existing solution procedures for the operational and tactical interval scheduling problems, and then we provide the developed solution approach for the integrated capacity expansion and scheduling problem.

Bouzina and Emmons (15) formulate the operational interval scheduling problem as a Minimum Cost Network Flow (MCNF) problem with n+1 nodes and 2n arcs as follows: The jobs are sorted in chronological order of ready times, and nodes $s = V_1, V_2, \ldots, V_n$ for each job, and a dummy node $t = V_{n+1}$ are created. Each node is connected to the next with arc cost zero and capacity m, j=1,…,n. Besides, node V_j is connected to node V_k, where k is the first job not overlapping with job j, j=1,…,n. If no such job exists, we create the arc (V_j, t). Each of these arcs has cost $-w_j$ and capacity 1. Then, a flow of m from s to t is required and the resulting MCNF problem is solved.

The conversion procedure is depicted in Figure 1. The jobs in Figure 1(a) are to be scheduled on two parallel identical machines. Labels correspond to job numbers. Assume $w_j = p_j$, for j=1,…,8, i.e. the profit is charged per unit time, as may be possible in a sewing workshop. The network structure is given in Figure 1(b), where each arc is labeled with its cost $-w_j$, and capacity 1, except for the arcs on the straight line from s to t, whose costs and capacities are 0 and 2, respectively. When solved, the optimal profit becomes 35 and the corresponding to processed job set is {4-8}.



(a) **Instance of the OFJS problem**



(b) **Corresponding network structure**

Figure 1. Instance of the operational interval scheduling problem [Eliiyi (4)]

An optimal solution to the tactical interval scheduling problem can be found very easily by finding the maximum job overlap of the jobs (17). According to our notation, the maximum job overlap is $\text{Max}_a\{|P_a|\}$, where $|P_a|$ is the cardinality of set P_a. For the example in Figure 1, the minimum number of machines required to carry out all jobs equals 3 as the maximum job overlap at any time equals 3, as well.

There are currently *m* machines in the sewing workshop, and a total of *n* jobs are expected in the upcoming planning horizon. Then, the optimal schedule of the workshop with the existing machines could easily be determined by converting the structure into a network as shown in Figure 1, and solving the obtained MCNF problem. Given this solution, the decision maker aims to determine the number of additional machines for the workshop (the level of capacity expansion), and the scheduling of jobs on these machines. In other words, he/she wants to know the extra contribution brought by each level of capacity expansion, and make a decision accordingly. For solving this integrated decision, the iterative approximation approach developed in this study makes use of the above solution procedures.

We assume that the schedule in the current state of the workshop is already determined (if not, this can be found by solving the operational problem once). At this point, some jobs are scheduled, and some are left unprocessed due to limited number of machines. The set of processed jobs is called set *S*. Then, we have $n - |S|$ jobs left unscheduled. We first solve a tactical problem with $n - |S|$ jobs to find the minimum number of machines to process all of the jobs. The optimal solution of this problem gives us the upper limit of economically-efficient capacity expansion, that is, an upper bound *A* on machines. In order not to let any machine stay idle, there may be at most $m+A$ machines in the system. Next, we solve subproblems with 1, 2, …, *A* machines. If the initial schedule is not known, $A+2$ problems are solved in total, one of which is the tactical problem.

After this point, the decision as to determining the preferable expansion scheme has to be made. In other words, how many extra machines should be added to the workshop: 1, 2, …, or *A*? In order to make this selection, many criteria are to be considered. Some of these may be the cost of the new machines, technological capabilities of the new machines (speed, personnel skill requirements, etc.), cost of to-be-hired personnel and the marginal profit contribution of each added machine (economic analysis).

Additional criteria may exist depending on the characteristics of the workshop, contracting firms and other environmental factors. Hence the selection problem is a multi-criteria decision problem. In order to help the decision maker in making the capacity expansion decision, we may draw a function of marginal profits brought by each capacity level. The curve of the function will help in choosing the desired expansion level. This is demonstrated through the example in the next section.

Once the decision maker chooses the level of expansion, the schedule of the jobs on the new machines is automatically determined by the corresponding solution of the operational subproblem. That is, if the decision maker decides that *r* additional machines will be included in the workshop, the solution of the subproblem with *r* machines will yield the schedules on those machines. The total profit of the workshop (excluding the investment costs) can be calculated by adding the objective function values of the initial solution with *m* machines, and the subproblem solution with *r* machines.

Maintenance planning of the machines may be done according to the obtained schedules. This may be handled by scheduling the maintenance of each machine during the idle intervals.

4. NUMERICAL EXAMPLE

We illustrate the execution of our iterative solution approach on an example in a sewing workshop. For demonstration purposes, and for evaluating several capacity expansion levels, we take a moderate size problem with 200 jobs and 2 general purpose sewing machines. The jobs may be defined as actual pieces to be processed (i.e. sewn), or they may be aggregated products corresponding to order lots. Assume that there are 200 time intervals in the planning horizon. The time intervals do not need to correspond to actual days or hours; they may be conveniently determined by the decision maker, possibly as a multiple of job processing times. The jobs arrival times follow a uniform distribution in the 200-time-unit horizon. The processing times and the weights (profit contributions) are coming from uniform distributions U(1,10) and U(1,40), respectively.

The entire approach is coded in Visual C++ on a MS Visual Studio platform, calling the ILOG CPLEX 9 library for solving the MCNF problem. The codes are run on a PC with 1 GB Ram and 2.20 GHz Core2Duo processor configuration.

At first, the operational problem (i.e. the profit maximization problem) is considered for 200 jobs and 2 machines in order to find the current schedule of the workshop; let's call this initial problem as P0. The objective function value (the total profit) becomes 2086, and 117 of the 200 jobs are left out of the schedule; namely they cannot be processed with the current capacity.

Next, the tactical problem (i.e. capacity planning problem) is solved, which finds the minimum number of machines that have to be in the workshop to process all incoming jobs. The solution to the problem yields 12 machines. Recall that this number is an upper bound on the capacity expansion level; acquiring 12 machines will never be economically feasible, but it gives us the maximum number of capacity levels that we have to evaluate. Since the workshop already has 2 sewing machines, 10 incremental levels of capacity expansion are considered, one for each machine, up to 12 machines. Then, 10 operational subproblems are solved incrementally with the unscheduled 117 jobs and 1, 2, …, 10 machines. Call these subproblems as P1, P2, …, P10.

The results of the solutions for the subproblems are summarized in Table 1. Note that the capacity level corresponding to P1 is 3 machines (2 existing and 1 additional), level corresponding to P2 is 4 machines, and so on. The *Objective Function Value* (OFV) column presents the total profit found by the subproblem, the *Cum. OFV* column shows the cumulative profit found by adding the corresponding subproblem's profit to the profit found by P0. *Marginal contribution per machine* column shows the extra profit brought by each additional sewing machine. *#Jobs Unscheduled* column provides the number of jobs left undone at each capacity level.

It is obvious from the table that the marginal profit decreases as the capacity level increases, as expected. The number of jobs unscheduled decreases rapidly for the first few added machines, but after that it seems that the expansion becomes economically infeasible. This result is also depicted in Figure 2.

Table 1. Results for the sewing workshop example.

Problem ID	*Objective Function Value*	*Cum. OFV*	*Marginal Contribution per Machine*	*#Jobs Unscheduled*
P0	2086	2086	1043	117
P1	653	2739	653	91
P2	1081	3167	428	69
P3	1435	3521	354	50
P4	1707	3793	272	33
P5	1868	3954	161	22
P6	1976	4062	108	12
P7	2030	4116	54	7
P8	2059	4145	29	3
P9	2082	4168	23	1
P10	2084	4170	2	0

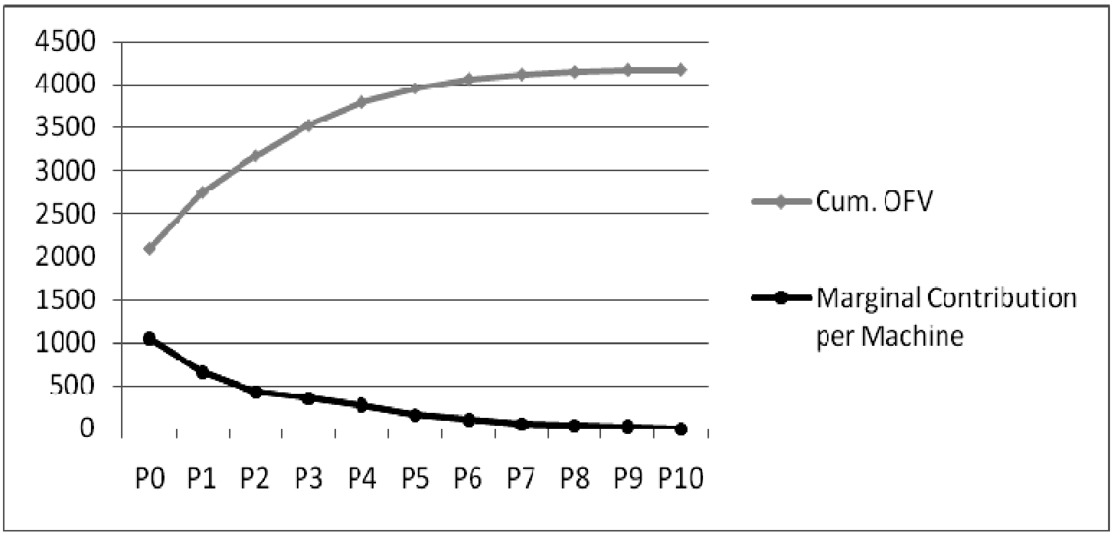


Figure 2. The marginal profit contribution of capacity expansion levels for the example.

The analysis and approach presented here provides a very useful guide to the decision maker. For example, we can argue that considering a capacity expansion of more than 5 machines will not be economical for this workshop, considering the results of the analysis. But other factors might also be included in the decision making process, as it was stated in the previous section.

5. RESULTS AND CONCLUSION

With this study, we intend to break new ground in the integration of scheduling and capacity expansion problems in interval scheduling. The applications are not limited to sewing workshops but may be applied to a great number of situations, such as car repair shops, car rental systems, hotel reservation systems, etc. The study offers an analytical guide for the decision maker for taking this important decision.

Future research directions that may be worth studying include (but not limited to) the following:

1. More efficient solution approaches may be developed in solving the incremental operational interval scheduling problem. Especially, once the solution is known with a certain number of machines, how can we generate all incremental solutions without actually having to solve the problem repeatedly? The answer to this question may be a nice theoretical contribution and may be applied to a great number of real-life cases.
2. Making the maintenance plan according to the current schedule may involve risks of unwanted breakdowns. In order to prevent such cases, regular maintenance should also be dealt with. For this purpose, we may ensure time limitations on the processing time of each sewing machine, in order to fit the regular maintenance into the schedule. Optimal and approximation algorithms may be investigated, as those developed in (5, 7).
3. Identical general-purpose sewing machines are assumed in the workshop. However, this may not be the case due to rapidly changing technology. Especially in case of a capacity expansion decision, the newly-acquired machines may be of a different generation. In such a case, the speed of the new sewing machines will be faster. This corresponds to a uniform-machines problem, which may be a nice generalization of the problem.
4. In the existence of different types of sewing machines, the machines may require different setup times. Then, the inclusion of setup times in the job processing times will not be possible in modeling the problem. Separately considering the setup times will bring an additional complexity.
5. Finally, the selection of the expansion level, which is a multi-criteria decision problem, is certainly worth studying. We have demonstrated possible criteria that may be used in the selection process, and developed a useful and simple tool for identifying the marginal profit contribution of each machine for the decision maker. The inclusion of all (and possibly opposing) criteria, and systematically coming up with the best decision requires extra effort. For this purpose, the inclusion of a multi-criteria decision making method, such as Analytical Hierarchy Process (AHP) or Analytic Network Process (ANP) may prove very useful.

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