Correspondence

Comments on “A Practical Approach to Job Shop Scheduling Problems”[1]

S. Ramaswamy

In the above paper,[1] the model formulation (p. 4) of the scheduling problem is highly irregular. If one were to consider the formulation by itself it would seem that since neither the precedence nor processing time constraints are linked to time, we could set all

$$\delta_{ijkh} = 0$$

and obtain a feasible solution with jobs overlapping on machines.

I note that in the subsequent relaxation of the capacity constraint, the binary variables have been set to 1 from start to finish time of the corresponding operation to account for capacity, but still feel that the model formulation should include such constraints explicitly.

More interestingly, I would like to make reference to [1] where a discrete time formulation of a similar problem has been presented along with a Lagrangian relaxation heuristic obtained by dualizing the capacity constraint.

Authors' Reply by Debra J. Hoitomt and Peter B. Luh

In the comments, the precedence and processing time constraints are “linked to time” since these constraints take on values in the time domain. Also, if $\delta_{ijkh}= 0$, no operations would be scheduled by definition of δ, since no operations could be active on the machines. The logical connection between machine activity and the beginning/completion times of an operation is illustrated in Figs. 2 and 3 of the paper.

There is a similarity in the capacity constraint formulation and its relaxation in our paper and Sherali *et al.* [4], and also Hoitomt *et al.* [2], and Luh *et al.* [3]. However, none of those papers address job shop scheduling, a common but very complicated manufacturing environment. In addition, the precedence constraints in our job shop scheduling paper are handled by using a decomposition approach, another aspect which sets the paper apart. This decomposition approach makes the algorithm practical for jobs with generic precedence structures, where the coordinated production and assembly of many parts may be considered. It is currently being utilized in the daily scheduling of Pratt & Whitney's Development Operations shop to schedule jobs represented by complex bills of material. Also, the decomposition structure is being further explored as part of an Intelligent Manufacturing Systems (IMS) test case entitled “Holonic Manufacturing Systems.”

Additional Comments by S. Ramaswamy

The authors seem to have missed the point of my previous letter. The simple idea is that a standard mathematical programming formulation should unambiguously describe the feasible region and objective so as to decouple further manipulations or the solution process from any reference to the context of the original problem (for obvious benefits). It is clear that Hoitomt et al. have failed to do the same. This is well evidenced by the fact, that in defense of the formulation, they refer me to "definitions" and "figures" *outside* the mathematical model, when in fact, they should be pointing out constraints *within* the formulation that disallow such a variable setting. Needless to say, no such constraints exist. Note that this is not the case with the formulation in [4], where the additional constraints to set the required number of δ_{ijkh} for each job operation to one, and also to ensure that these are contiguous are included.

Secondly, and more importantly, the statement of the authors in their reply that [4] does not address the problem of job shop scheduling is not true. In addition to the standard constraints of operation precedence, and variable machine routings for each job which characterize the general job shop problem as discussed in [5], [4] also considers alternative routings. As clearly mentioned in [4] (pg. 441, paragraph 1), given a selected set of jobs and their choice of routings, the problem they solve is that of job-shop scheduling.

Additional Reply by Debra J. Hoitomt and Peter B. Luh

The model, as provided in the aforementioned paper, is self-contained. The purpose of the illustration in the text is additional clarity, not because it is required as a part of the formulation. The processing time requirements are fully and completely defined in the paper and serve the purpose of assuring that the variables δ in question are both contiguous and properly represent the processing time. Certainly, there is a relationship between δ and b which could be mathematically defined (see, for example, some useful concepts from [6]). However, it is not necessary to do so in order to solve the problem. This decision makes the model neither incomplete nor incorrect since many other extraneous relationships may exist among variables that are not necessary to define in order to solve the problem.

We concur that there are some correspondences between scheduling in a flexible manufacturing system and job-shop scheduling, which allow useful interchange of solution strategies. We apologize for our failure to recognize the subsection in Sherali *et al.* [4] devoted to job-shop scheduling. There are, however, considerable differences in both the model and the methodology presented in that paper and that provided in our paper. Sherali *et al.* uses a makespan cost function as opposed to the job tardiness function used in our paper. Sherali *et al.* does not provide for parallelism in the routing, whereas our formulation and algorithm can handle complex bills of materials involving parallel processing of parts.

Finally, it is interesting to note, on p. 446 of the article by Sherali *et al.*, the statement that their dynamic programing algorithm is “very time consuming, and [that] some other relaxation is necessary for large-sized problems,” The reason is that the precedence constraints

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Manuscript received September 3, 1993.

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IEEE Log Number 9404607.

[1] D. J. Hoitomt and P. B. Luh, *IEEE Trans. Robot. Automat.*, vol. 9, no. 1, pp. 1–13, Feb. 1993.

Manuscript received October 7, 1993.

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IEEE Log Number 9404608.

Manuscript received September 3, 1993.
IEEE Log Number 9412450.
Manuscript received October 7, 1993.
IEEE Log Number 9412449.

needed to properly manufacture a part are not relaxed, similar to our previously published paper [2]. In fact, our current algorithm is designed to address exactly this problem, and thus generate high-quality schedules efficiently when products and parts have complex manufacturing requirements. This decomposition approach is currently being utilized for the daily scheduling of Pratt & Whitney.

REFERENCES

[1] H. D. Sherali, S. C. Sarin, and R. Desai, "Models and algorithms for job selection, routing, and scheduling in a flexible manufacturing system," *Annals Operat. Res.*, vol. 26, pp. 433–453, 1990

[2] D. J. Hoitomt, P. B. Luh, E. Max, K. R. Pattipati, "Scheduling jobs with simple precedence constraints on parallel machines," *IEEE Cont. Syst. Mag.*, vol. 10, no. 2, pp. 34-40, also in *Dynamics of Discrete Event Systems*, Y. C. Ho, Ed. New York: IEEE Press, 1992, pp. 271-277.

[3] P. B. Luh, D. J. Hoitomt, E. Max, and K. R. Pattipati, "Schedule generation and reconfiguration for parallel machines,"*IEEE Trans. Robot. and Automat.*, vol. 6, no. 6, pp. 687-696, Dec. 1990.

[4] N. D. Sherali, S. C. Sarin, and R. Desai, "Models and algorithms for job selection, routing and scheduling in a flexible manufacturing system,"*Annals Operat. Res.*, vol. 26, pp. 433-453, 1990.

[5] K. R. Baker, *Introduction to Sequencing and Scheduling*. New York: Wiley, 1974.

[6] N. T. Bruvold and J. R. Evans, "Flexible mixed-integer programming formulations for production scheduling problems,"*IIE Trans.*, vol. 17, no. 1, pp. 2–7, Mar. 1985.

A Note on "On Single-Scanline Camera Calibration"[1]

Hanqi Zhuang

Abstract— **In this correspondence, the single-scanline camera model proposed in the above paper[1] is modified to include a lens distortion coefficient. By this modification, the calibration approach presented in the above paper will become more practical.**

I. INTRODUCTION

Single-scanline cameras may be used for dimensional measurement and inspection. In such cases, the accuracy performance of such cameras is very important. To be able to perform dimensional measurement, parameters of a camera model that relates image measurements to 3-D measurements have to be estimated through calibration.

Horaud *et al.* in the above paper[1] presented a linear method for the calibration of single-scanline cameras. Their approach is very easy to implement due to its simplicity. However, the camera model they used is basically a pin-hole model that does not account for any geometric distortions of the camera lens. Lens distortion is a dominant factor that influences the accuracy performance of the camera system.

Lens distortion may be corrected by a separate procedure before applying the method proposed in the above paper. It can also be compensated by a more elaborate camera model. In this correspondence, the camera model given in the above paper is modified to include a lens distortion coefficient that represents geometric distortion of the camera lens.

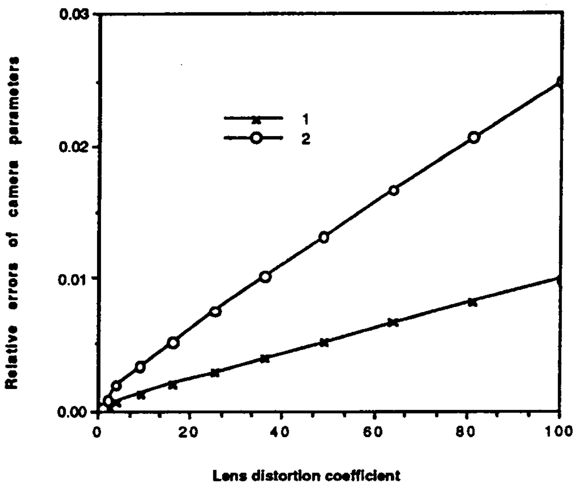

Fig. 1. Relative errors in some of the camera parameters versus lens distortion coefficient. Note: 1) O denotes relative errors of n_1, and × denotes those of n_2. 2) Lens distortion coefficient is scaled by 10^{-10}.

II. A SINGLE-SCANLINE CAMERA MODEL

The model presented here modifies the one given in the above paper by adopting some techniques for modeling array cameras [2]. Let X, Y, Z be world coordinates of a 3-D point, and u, v be the undistorted image coordinates of its projection. Let x, y be its distorted image coordinates. Then from the above paper ,

$$u = \frac{n_1 Y + n_2 Z + n_3}{n_4 Y + n_5 Z + 1} \tag{1}$$

where $n_1, \cdots n_5$ are camera parameters.

The distorted image coordinate x is related to the undistorted image coordinate u by

$$u = x(1 + kx^2) \tag{2}$$

where the high order terms have been dropped. In (2), k is the distortion coefficient. Combining (1) and (2) yields

$$x(1 + kx^2) = \frac{n_1 Y + n_2 Z + n_3}{n_4 Y + n_5 Z + 1}. \tag{3}$$

Moreover, the world coordinates of the object point are constrained by the following viewing-plane from the above paper,

$$X = pY + qZ + r. \tag{4}$$

Equations (3) and (4) relate world coordinates of an object point to its image coordinates. The parameters to be calibrated in this model are $n_1, \cdots, n_5, k, p, q$, and r.

The model given in (4) is nonlinear, therefore the linear algorithm given in the above paper cannot be used to compute $n_1, \cdots, n_5$ and k. The calibration problem can however be solved by using a nonlinear optimization procedure. Let $g = [n_1, \cdots, n_5, k]^T$, and let

$$\begin{aligned} f(x, Y, Z, g) = {} & x(1 + kx^2)(n_4 Y + n_5 Z + 1) \\ & - (n_1 Y + n_2 Z + n_3). \end{aligned} \tag{5}$$

Manuscript received February 11, 1994.

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IEEE Log Number 9404605.

[1] R. Horaud, R. Mohr, and B. Lorecki, *IEEE Trans. Robot. Automat.*, vol. 9, no. 1, pp. 71–75, Feb. 1993.