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AN INTEGRATED APPROACH TO ASSEMBLY-LINE SELECTION

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Summary: *In mass production, assembly line balancing (ALB) problem has been a critical and repetitive issue for companies for long time. On the other hand, equipment selection for stations has also been another important problem at the design stage of an assembly-line system. In this paper, both problems are handled simultaneously. Therefore first, goal programming (GP) method, a well-suited technique is used to develop a preemptive formulation to joint both of the problems, when the nature of the problem consists of several conflicting objectives, and some mathematical constraints on solutions. Second, the AHP method which is incorporated with the GP is also used due to the fact that it takes both qualitative and quantitative judgments of decision-maker(s) into consideration to rank the equipment alternatives for stations by weight. But, in some cases, due to the vagueness and uncertainty on judgments of decision-maker(s), the crisp pair wise comparison in the conventional AHP seems to insufficient and imprecise to capture the right judgments of decision-maker(s). Therefore, a fuzzy logic is introduced in the pair wise comparison of AHP to make up for this deficiency in the conventional AHP, referred to as fuzzy AHP. In short, in this study, an integrated approach through fuzzy AHP and GP is proposed to evaluating assembly-line design alternatives with equipment selection. An integer GP formulation is constructed, which also uses the fuzzy AHP scores of equipment alternatives, and employs them as one of the goals. Then, the mathematical model is solved to find out the ultimate alternative in terms of the minimized equipment cost and the maximized preference measures of decision-maker(s).*

1. Introduction and literature review

In mass production, the design of an assembly-line system has been one of the major issues for companies for a long time, because the assembly-line design problem (ALDP) requires that optimal allocation of tasks of different durations to the stations, and selection of equipments of different costs for stations are made. The assembly work is completed along the line as the work pieces pass each station in sequence, with every station adding its work content to the assembly task. The work content of the workstation with the maximum workload determines the cycle time of the assembly line (Baybars, 1986; Scholl and Becker, 2003; Mcmullen and Frazier, 1998; Bukchin and Masin, 2004; Erel and Sarin, 1998; Scholl, 1999; Malakooti and Kumar, 1996).

In our study, we consider several criteria for equipment selection for stations at the design stage of an assembly-line system. Some of these criteria are qualitative (i.e. flexibility, ease of use, and level of automation), as others are quantitative (i.e. procurement cost, operational cost, production speed, and space requirement). In the presence of qualitative and quantitative criteria, a MCDM problem arises (Saaty, 1989). Therefore, for this study, we selected the AHP to evaluate the equipment alternatives under the above-defined criteria.

The AHP method, a well-known and the most commonly used MCDM method in literature and in practice was developed by Thomas Saaty, (Saaty, 1981) and the pair wise comparisons for each level with respect to the goal of the best alternative selection are conducted using a nine-point scale. This application of Saaty's AHP has some shortcomings as follows; (i) the AHP method is mainly used in nearly crisp decision applications, (ii) the AHP method creates and deals with a very unbalanced scale of judgment, (iii) the AHP method does not take into account the uncertainty associated with the mapping of one's judgment to a number, (iv) the ranking of the AHP method is rather imprecise, (v) the subjective judgment, selection and preference of decision-makers have great influence on the AHP results.

Because of the shortcomings outlined above, the crisp pair wise comparison in the conventional AHP seems to insufficient and imprecise to capture the right judgments of decision-maker(s) due to the vagueness and uncertainty on judgments of the decision-maker(s) (Ayag, 2002; Ayag, 2005a). Furthermore, it is also recognized that human assesment on qualitative criteria is always subjective and thus imprecise. Therefore, a fuzzy logic is introduced in the pair wise comparison of AHP to make up for this deficiency in the conventional AHP, referred to as fuzzy AHP (Ayag, 2005b; Ayag and Ozdemir, 2005c; Ayag, 2005d).

The fuzzy set theory is a mathematical theory designed to model the vagueness or imprecision of human cognitive processes that pioneered by Zadeh. This theory is basically a theory of classes with unsharp boundaries. What is important to recognize is that any crisp theory can be fuzzified by generalizing the concept of a set within that theory to the concept of a fuzzy set. Fuzzy set theory and fuzzy logic have been applied in a great variety of applications, which are reviewed by several authors (Zadeh, 1994).

In this paper, we propose a preemptive GP formulation that considers both assignment restrictions of tasks related to equipment selection, and other constraints of precedence relations between tasks, cycle time constraint, incompatibility constraints between tasks. The GP formulation includes several system-related goals (i.e. budget goal, operational cost goal, and space requirement goal), and one more goal for satisfying the decision maker's preferences on equipment selection for stations. The last goal in the formulation, rather than the system-related those is constructed by using the results of the fuzzy AHP obtained for equipment alternatives. Naturally, the GP formulation built combines fuzzy AHP with GP through the last goal, especially defined for equipment selection for stations. In literature, some studies have been realized for various problems by combining fuzzy AHP and GP. A few of them are presented as follows; (Badri, 1999) combined the AHP and GP for global facility location-allocation problem. And he also used the combination of AHP-GP for a study, quality control systems. In another work (Yu, 2002) used a GP-AHP method for solving group decision-making. However, to the best of our knowledge, we did not come cross any study regarding the combination of fuzzy AHP and GP methods for the assembly-line design problem with equipment selection. The subsequent sections of this paper are organized as follows; Section 2 initiates the study with notation, assumptions and definition of the problem. Then in Section 3, the fuzzy AHP is introduced to solve equipment selection problem for stations in an assembly-line design. The GP formulation as a combined methodology with the fuzzy AHP is described in Section 4. Finally, Section 5 illustrates the model implementation on a case study.

2. Notation, assumptions and definition of the problem

In an assembly-line system, the allocation of tasks into various workstations is considered as the assembly line balancing problem (ALBP). In addition to the balancing issue, if the selection of equipment for each work station is considered, then the problem is converted into the assembly line design problem (ALDP). The ALDP with equipment selection requires that several conflicting objectives are considered simultaneously. Therefore, the problem of designing an assembly-line system addressed in this study is the multi-objective assembly-line design problem (MOALDP). To solve this problem, we come two popular methods; fuzzy AHP and GP together so as to utilize both subjective judgments of decision maker(s), and quantifiable objectives in finding the best assembly-line configuration. In addition, the constraints on assembly-line balancing are also considered in the model formulation. The notation used throughout the paper is given in table 1.

Table 1.Notations - Summary

i	task index
j	equipment type index
k	station index
n	number of tasks to be accomplished to make one product
m	number of equipment types available for consideration
K_{max}	maximum number of stations to be established on the line given cycle time
t_{ij}	duration of task *i* when performed by equipment *j*, $(i = 1,\ldots,n,\ \ j = 1,\ldots,m)$
f_j	fixed procurement cost of equipment type *j*, $(j = 1,\ldots,m)$
v_j	variable operational cost of using equipment type j $(j = 1,\ldots,m)$
s_j	space requirement of equipment type *j*, $(j = 1,\ldots,m)$
w_j	the preference weight of equipment type *j*, $(j = 1,\ldots,m)$
F	budget of the project, i.e., upper limit on the total procurement cost of the line
V	maximum allowed variable cost, i.e., upper limit on the total operational cost of the line
S	available space, i.e., upper limit on the total space requirement of the line
P	desired preference value, i.e., lower limit on the total preference weights of the line
c	cycle time
SIP_i	set of immediate predecessors of task *i* $(i = 1,\ldots,n)$
P_i	set of all tasks that precedes task *i* $(i = 1,\ldots,n)$
SS_i	set of all tasks that follow task *i* $(i = 1,\ldots,n)$
A_i	set of incompatible tasks of task *i* $(i = 1,\ldots,n)$
x_{ijk}	1 if task *i* is performed by equipment *j* at station *k*; 0 otherwise $(i = 1,\ldots,n,\ \ j = 1,\ldots,m,\ k = E_i$ through $L_i)$
y_{jk}	1 if equipment type j is assigned to station k, o otherwise $(\ j = 1,\ldots,m,\ k = 1,\ldots K_{max})$
d^-_{Budget}	underachievement of the budget goal
d^+_{Budget}	overachievement of the budget goal
$d^-_{\text{O\_cost}}$	underachievement of the operational cost goal
$d^+_{\text{O\_cost}}$	overachievement of the operational cost goal
d^-_{Space}	underachievement of the space requirement goal
d^+_{Space}	overachievement of the space requirement goal
$d^-_{\text{Preference}}$	underachievement of the decision maker’s preference goal
$d^+_{\text{Preference}}$	overachievement of the decision maker’s preference goal

The following assumptions are also stated to explain the situation in which the problem addressed in this paper arises; (i) there is a given set of equipment types; each type is associated with specific features (i.e. procurement cost, operational cost, space requirement, production speed, flexibility, ease of use, level of automation). These features are also accepted as criteria used for evaluating equipment types, (ii) the precedence relation between assembly tasks is known, and the assembly tasks cannot be further subdivided, (iii) the duration of a task is deterministic, but depends on the equipment selected to perform the task, (iv) a task can be performed at any station of the assembly-line, provided that the equipment selected for this station is capable of performing the task, and that precedence relations are satisfied, (v) a single equipment is assigned to each station, and a single product is assembled on the line, and (vi) material handling, loading/unloading, set up and tool changing times are negligible or included in the task's duration. The maximum number of stations, K_{max}, can be approximated by a heuristic procedure, or the simple upper bound on K_{max}, (i.e. number of tasks, n) can be used.

3. Steps of fuzzy AHP approach

The fuzzy AHP is realized by using both the above-defined tangible and intangible criteria to evaluate equipment alternatives for workstations. These criteria and alternatives are taken into consideration using the triangular fuzzy numbers by the decision-maker(s) in order to reach the ultimate assembly-line design alternative.

The AHP method developed by Saaty is known as an eigenvector method. It indicates that the eigenvector corresponding to the largest eigenvalue of the pair wise comparisons matrix provides the relative priorities of the factors, and preserves ordinal preferences among the alternatives. This means that if an alternative is preferred to another, its eigenvector component is larger than that of the other. A vector of weights obtained from the pair wise comparisons matrix reflects the relative performance of the various factors. In the fuzzy AHP triangular fuzzy numbers are utilized to improve the scaling scheme in the judgment matrices, and interval arithmetic is used to solve the fuzzy eigenvector (Cheng and Mon, 1994).

In this study, the 4-step-procedure of this approach is given as follows;

*Step 1.*Comparison of the performance score; Triangular fuzzy numbers $(\tilde{1},\ \tilde{3},\ \tilde{5},\ \tilde{7},\ \tilde{9})$ are used to indicate the relative strength of each pair of elements in the same hierarchy.

*Step 2.*Building the fuzzy comparison matrix; by using triangular fuzzy numbers, via pair wise comparison, the fuzzy judgment matrix $\tilde{A}\ (a_{ij})$ is constructed as given below;

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & .. & .. & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & .. & .. & \tilde{a}_{2n} \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ \tilde{a}_{n1} & \tilde{a}_{n2} & .. & .. & 1 \end{bmatrix}$$

where,

$\tilde{a}_{ij}^{\alpha} = 1$, if i is <u>equal</u> j, and $\tilde{a}_{ij}^{\alpha} = \tilde{1},\ \tilde{3},\ \tilde{5},\ \tilde{7},\ \tilde{9}$ or $\tilde{1}^{-1},\ \tilde{3}^{-1},\ \tilde{5}^{-1},\ \tilde{7}^{-1},\ \tilde{9}^{-1}$, if i is <u>not equal</u> j

*Step 3.*Solving fuzzy eigenvalues; A fuzzy eigenvalue, $\tilde{\lambda}$ is a fuzzy number solution to

$$\tilde{A}\tilde{x} = \tilde{\lambda}\tilde{x} \tag{1}$$

where is a nxn fuzzy matrix containing fuzzy numbers $\tilde{a}_{ij}$ and $\tilde{x}$ is a non-zero $nx1$ fuzzy vector containing fuzzy numbers $\tilde{x}_i$. To perform fuzzy multiplications and additions using the interval arithmetic and $\alpha - cut$, *Equation 1* is equivalent to

$$\left[a_{i1l}{}^{\alpha} x_{1l}{}^{\alpha}, a_{i1u}{}^{\alpha} x_{1u}{}^{\alpha}\right] \oplus ..... \oplus \left[a_{inl}{}^{\alpha} x_{nl}{}^{\alpha}, a_{inu}{}^{\alpha} x_{nu}{}^{\alpha}\right] = \left[\lambda x_{il}{}^{\alpha}, \lambda x_{iu}{}^{\alpha}\right]$$

where,

$$\tilde{A} = \left[\tilde{a}_{ij}\right], \tilde{x}^t = \left(\tilde{x}_1, ..., \tilde{x}_n\right),$$

$$\tilde{a}_{ij}{}^{\alpha} = \left[a_{ijl}^{\alpha}, a_{iju}^{\alpha}\right], \tilde{x}_i{}^{\alpha} = \left[x_{il}^{\alpha}, x_{iu}^{\alpha}\right], \tilde{\lambda}^{\alpha} = \left[\lambda_l^{\alpha}, \lambda_u^{\alpha}\right] \tag{2}$$

for $0 < \alpha \leq 1$ and all *i, j*, where *i=1,2,….,n, j=1,2,…,n*

$\alpha - cut$ is known to incorporate the experts or decision maker(s) confidence over his/her preference or the judgments. Degree of satisfaction for the judgment matrix $\tilde{A}$ is estimated by the index of optimism μ. The larger value of index μ indicates the higher degree of optimism. The index of optimism is a linear convex combination [44] defined as;

$$\tilde{a}_{ij}^{\alpha} = \mu a_{iju}^{\alpha} + (1 - \mu) a_{ijl}^{\alpha}, \qquad \forall \mu \in [0,1] \tag{3}$$

While α is fixed, the following matrix can be obtained after setting the index of optimism, μ in order to estimate the degree of satisfaction.

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & .. & .. & \tilde{a}_{1n}^{\alpha} \\ \tilde{a}_{21}{}^{\alpha} & 1 & .. & .. & \tilde{a}_{2n}^{\alpha} \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ \tilde{a}_{n1}^{\alpha} & \tilde{a}_{n2}^{\alpha} & .. & .. & 1 \end{bmatrix}$$

The eigenvector is calculated by fixing the μ value and identifying the maximal eigenvalue. $\alpha - cut$; will yield an interval set of values from a fuzzy number (for example, $\alpha = 0.5$ will yield a set $\alpha_{0.5} = (2,3,4)$.

Normalization of both the matrix of paired comparisons and calculation of priority weights (approx. criteria weights), and the matrices and priority weights for alternatives are also done before calculating $\lambda_{\max}$. In order to control the result of the method, the consistency ratio for each of the matrices and overall inconsistency for the hierarchy calculated. The deviations from consistency are expressed by the following equation consistency index and the measure of inconsistency is called the consistency index (CI);

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{4}$$

The consistency ratio (CR) is used to estimate directly the consistency of pair wise comparisons. The CR is computed by dividing the CI by a value obtained from a table of Random Consistency Index (RI);

$$CR = \frac{CI}{RI} \tag{5}$$

If the CR less than 10%, the comparisons are acceptable, otherwise they should be repeated until reached to the CR, less than 10%. RI is the average index for randomly generated weights [21].

*Step 4.*The priority weight of each alternative can be obtained by multiplying the matrix of evaluation ratings by the vector of criterion weights and summing over all criteria. Expresses in conventional mathematical notation [21];

$$\text{Weighted evaluation for alternative } k = \sum_{i=1}^{t} \left(criterion\,weight_i * evaluationrating_{ik} \right) \tag{6}$$

for *i=1,2,..,t* (*t :* total number of criteria)

After calculating the weight for each alternative, the overall consistency index is also calculated that it should be less than 10% for consistency on all judgments.

4. GP formulation

In the GP formulation to find out the best assembly-line design with equipment selection, the objective functions are described as goal constraints. The formulation is constructed to optimize the objective functions. This optimization is carried out to satisfy all goals by considering highly prioritized those first. The goals could be prioritized according to their relative importance. The result of this ordering process is a goal structure. The goal structure will differ depending on the situation and preferences of the decision maker(s). *Equation 7* represents the lexicographical order of deviational variables to be minimized.

$$\text{Lexmin} \left\{ d^{+}_{\text{Budget}}, d^{+}_{\text{O\_cost}}, d^{+}_{\text{Space}}, d^{-}_{\text{Preference}} \right\} \tag{7}$$

The positive deviations from these goals are minimized with respect to their priorities. In *Equation 7*, the budget goal is prioritized as the first goal to be achieved. The second, third, and fourth priorities are given to the goals of operational cost goal, space requirement goal, and decision maker’s preferences goal respectively. However these given priorities could be different for another decision-maker.

4.1. Budget goal constraint

Total procurement cost of the equipments assigned to the stations in an assembly-line depends on equipment types at different costs, and the number of the stations. Since there is a certain investment budget, *F*, positive deviation from the goal of total procurement cost represents the excess of budget, and this situation is undesirable. Therefore, the positive deviation, d^{+}_{Budget} from the budget goal is minimized as the first objective function and shown as below;

$$\sum_{j=1}^{m}\sum_{k=1}^{K_{\max}} f_j y_{jk} + d^{-}_{\text{Budget}} - d^{+}_{\text{Budget}} = F \tag{8}$$

4.2. Operational cost goal constraint

There is an operational cost associated with each type of equipment. Thus, equipment types and their numbers determine the number of stations in the line, and influence the total operational cost of the line, and hence the unit production cost. Similar to the budget goal constraint, there is certain goal on the total operational cost, and it is not desired that the equipments in the line lead to the excess of this goal. Therefore, the positive deviation, $d^{+}_{\text{O\_cost}}$, from the operational cost goal is minimized as the second objective function as follows;

$$\sum_{j=1}^{m}\sum_{k=1}^{K_{\max}} v_j y_{jk} + d^{-}_{\text{O\_cost}} - d^{+}_{\text{O\_cost}} = V \tag{9}$$

4.3. Space requirement goal constraint

Total space requirement of an assembly-line should be also critical and restricted to a certain value, available space *S*, and excess of space restriction or positive deviation, d^{+}_{Space} from space requirement goal is minimized as the third objective function as follows;

$$\sum_{j=1}^{m}\sum_{k=1}^{K_{\max}} s_j y_{jk} + d^{-}_{\text{Space}} - d^{+}_{\text{Space}} = S \tag{10}$$

4.4. Decision maker's preferences goal constraint

The preference weights of equipments obtained from the fuzzy AHP are imposed to the model formulation as the fourth objective function. The decision maker's preference value is set to *P*, and underachievement of this goal, $d^{-}_{\text{Prefeence}}$ is minimized. This 4$^{\text{th}}$ goal constraint is formulated as follows;

$$\sum_{j=1}^{m}\sum_{k=1}^{K_{\max}} w_j y_{jk} + d^{-}_{\text{Prefeence}} - d^{+}_{\text{Preference}} = P \tag{11}$$

4.5. Hard constraints

In GP formulation, hard constraints define the feasible area for optimal solution of an assembly-line design with equipment selection. The satisfaction of these constraints is compulsory.

The constraint sets (12) and (13) are constructed as follows: to ensure that each task and equipment is assigned to only one station.

$$\sum_{j=1}^{m}\sum_{k=E_i}^{L_i} x_{ijk} = 1, \qquad \forall i \qquad (12)$$

$$\sum_{j=1}^{m} y_{jk} \leq 1, \qquad \forall k \qquad (13)$$

The constraint sets (14) and (15) are constructed as follows: to ensure that the precedence and the incompatibility relations between tasks are satisfied, respectively.

$$\sum_{j=1}^{m}\sum_{k=E_h}^{L_h} k \cdot x_{hjk} - \sum_{j=1}^{m}\sum_{r=E_g}^{L_g} r \cdot x_{gjr} \leq 0, \quad \forall h,g \text{ subject to } h \in SIP_g \text{ and } L_h \geq E_g \qquad (14)$$

$$\sum_{j=1}^{m}\sum_{k=E_h}^{L_h} k \cdot x_{hjk} - \sum_{j=1}^{m}\sum_{r=E_g}^{L_g} r \cdot x_{gjk} \geq 1, \quad \forall h,g \text{ subject to } h \in A_g,\ h \in SS_g \text{ and } L_h \geq E_g \qquad (15)$$

Furthermore, the constraint set (16) ensures that stations are open sequentially, while allocating tasks and equipments. The constraint set (17) ensures that the total station time can not exceed the cycle time, and if equipment is not assigned to any station, this constraint set does not allow any task to be performed by that equipment at any station.

$$\sum_{j=1}^{m} y_{jk} - \sum_{j=1}^{m} y_{j,k+1} \geq 0, \qquad \text{for } k=1,\ldots,(K_{max}-1) \qquad (16)$$

$$\sum_{i=1}^{n} t_{ij} \cdot x_{ijk} - c \cdot y_{jk} \leq 0, \qquad \forall j, k \qquad (17)$$

The constraint sets (18) and (19) are constructed as follows: to define the assignment variables, x_{ijk} and y_{jk}, to be binary integer, as the constraint (20) is constructed to define the deviational variables to be non-negative.

$$x_{ijk} = 0,1 \qquad \forall i, j, k \qquad (18)$$

$$y_{jk} = 0,1 \qquad \forall j, k \qquad (19)$$

$$d^-_{\text{Budget}}, d^+_{\text{Budget}}, d^-_{\text{O\_cost}}, d^+_{\text{O\_cost}}, d^-_{\text{Space}}, d^+_{\text{Space}}, d^-_{\text{Preference}}, d^+_{\text{Preference}} \geq 0 \qquad (20)$$

6. Concluding remarks

In this paper, a combined fuzzy AHP-GP approach has been proposed to evaluating assembly-line design alternatives with equipment selection. An integer GP formulation was constructed, which also uses the fuzzy AHP scores of equipment alternatives, and employs them as one of the goals. Then, the constructed model was solved to reach to the ultimate assembly-line design alternative in terms of the minimized equipment cost and the maximized preference measures of decision-maker(s).

The fuzzy AHP is a popular method for tackling MCDM problems involving both quantitative and qualitative data, and has successfully been applied to many actual decision situations so far. Therefore, to exploit the advantages of this method, we considered both quantitative criteria (i.e. procurement cost, operational cost, space requirement) and qualitative criteria (i.e. flexibility and ease of use and level of automation). In this approach, triangular fuzzy numbers were introduced into the conventional AHP in order to improve the degree of judgments of decision maker(s). The central value of a fuzzy number is the corresponding real crisp number. The spread of the number is the estimation from the real crisp number. *Equation 3* defines how the real crisp number, $\tilde{a}_{ij}$ reacts to the real crisp number by adjusting the index of optimism, μ. The μ indicates the degree of optimism, which could be determined by a manufacturing engineering team, who is responsible to design an assembly-line system.

Using of fuzzy AHP approach to evaluating equipment alternatives at the ALD results in the following two major advantages; (i) fuzzy numbers are preferable to extend the range of a crisp comparison matrix of the conventional AHP method, as human judgment in the comparisons of selection criteria and equipment alternatives is really fuzzy in nature, (ii) adoption of fuzzy numbers can allow decision maker(s) to have freedom of estimation regarding the ALD selection.

In the GP formulation includes four goals, the fourth of which is constructed by using the results of the fuzzy AHP for equipment alternatives. The first three goals are also as follows; budgeted procurement cost, operational cost, and space requirement. We also presented a case study to demonstrate the proposed approach on how the best set of equipment types could be selected for workstations at the design stage of an assembly-line system.

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