A study of scheduling by using the analytic hierarchy process and hierarchy consistency analysis model

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Abstract- In our company, the qualitative factor as the relationship between the company and the customers are considered when we schedule the jobs. In order to find the scheduling problem to match our multiple criteria, we apply two approaches to solve our problem. In this paper, we consider both qualitative and quantitative factors in our analysis. The analytic hierarchy process approach provides method consistency in different structure schemata. The hierarchy consistency analysis approach supports the weight-consistency by considering another different structure schemata. The basic principle of the two approaches is to implement the consistency of the different hierarchy structure to schedule the jobs. Computation results show that the improvement of using the two approaches in different structure schemata is substantial.

Keywords: Quantitative, Qualitative, Schedule, Consistency, Hierarchy

1. Introduction

The purpose of this study is to consider how to sequence jobs into a schedule when we analyze a multiple criteria problem. Usually, quantitative factors are taken into account in a scheduling issue. However, sometimes in a real-life problem, we also need to think of the qualitative factors in our schedules. For example, the job is order by my best friend. Therefore, I consider the job has the highest priority than any other jobs when it is originally scheduled at a later position. This condition usually happens in our environment. But, how to take qualitative factors into scheduling problems is seldom discussed in the related paper. In this paper, we suggest the analytic hierarchy process (AHP) approach to present experts with a set of choices so that they can decide on the trade-off all the factors.

The AHP approach is a technique of handling the problems that involve the consideration of multiple criteria simultaneously. We apply the AHP model to determinate the priority of jobs. In order to simplify the scheduling problem in this study, we only consider three factors in our analysis. The factors include the due date, the order amount of each job, and who orders the job. The attribute of who orders the job is a qualitative factor which including the relationship between the customer and the company to represent the relative importance of the qualitative weight. The relationship can be measured by the number of the years of both sides' trade.

There has been some related research discussing the AHP problem in the literature. A study concerning the usefulness of the AHP model was applied to evaluate six just-in-time techniques for improving manufacturing efficiency by Norris (1992). Leung et al. (1992) presented an AHP model for evaluation of an expert system when developed the manufacturing system. Weber (1993) modified the AHP approach for a manufacturing environment and applied it to decide the best way to automate a machine shop. Cambron and Evans (1991) used several layout design algorithms to generate candidate layouts. Chung (2016) developed assessment criteria of logistics cluster competitiveness, calculated the weight of each criterion by the AHP model. For economic integration, Hadadian et al. (2017) deal with application of AHP for selection of an appropriate country with the case study of Iran's foreign trade.

Hierarchy consistency analysis (HCA) approach is developed according to the results of the analysis of a large-scale problem. A decision maker frequently wishes to emphasize certain point or certain combination of criteria. Based on these different structures constructed in our model, the methodology is developed to combine these different structures for estimating the compromised weights so that all different hierarchy structures have the same aggregated index. Guh (1996) proved the HCA theory and the algorithm.

2. AHP Model

The multi-criteria technique, AHP, was developed by Saaty (1980). The AHP approach is a robust and flexible multi-criteria method when we deal with the scheduling jobs. Although, AHP model can not verify which structure is more appropriate, but according to statistics or group decision theories the more objective results will be obtained if we can comprise several estimates. The most important step in AHP model is how we can formulate the scheduling problem in a hierarchical structure. The hierarchy should be constructed such that jobs at the same level of magnitude must be related to some or all jobs in the next higher level. In a typical hierarchy, the top level reflects the overall objective of the scheduling problem. The jobs affecting decisions are represented in the intermediate levels. The lowest level comprises the decision options. This type of hierarchy provides a clear and simple illustration of all the factors affecting the decision and their relationships. Prioritization of the jobs in each level is pairwise compared with respect to their importance in making the decision under consideration. In the AHP technique, pairwise comparison should be made at criteria level and alternative level. The pairwise comparison of criteria level is done based on authors' interview with experts on scheduling systems.

3. Comparison and consistency ratio

In this paper we find the trade-off criteria among three conflicting objectives, which are the due date, the order amount of each job, and who orders the job. The character of AHP model is the consistency of pairwise comparison. It can be used to check the error judgement of decision and indicates the preference of user. Saaty (1980) suggested that the consistency ratio (*C.R.*) less equal to or less than 0.1 is acceptable. Otherwise, it may be in conflict between the comparisons. If the value of *C.R.* is greater than 0.1, we need to establish a new architecture from the initial structure. Before considering the AHP approach, the designer needs to understand the following procedure:

1. Reciprocal condition: if the preference of A is equal to n times B, then the preference of B is equal to 1/n times A.
2. Homogeneity: comparison between two elements must be significant.
3. Independence: the relative importance between two elements can not depend on any other elements.
4. Expectations: the levels need to show the whole structure integrality and they can not miss the alternative data or the criteria in each

level.

4. Establish procedure

The AHP approach can be used to establish level architecture by combining criteria, sub-criteria, and alternative. The level relationship can be easily accepted and communicated by people's cognition. Now the AHP procedures are stated as follows:

Step 1. Decision maker selects criteria from the bottom level of the problem. In our example, Job 1, Job 2, and Job 3 are selected. (See figure 1)

Step 2. Decision maker establishes different architectures from different view points.

Step 3. For each architecture, we can establish the different relative weight matrixes by using different criteria. We utilize such criteria of the relative weight matrixes to generate an eigenvector and calculate the maximum eigenvalue. Sum of the weight must equal to 1. To evaluate the consistency of the relative matrix, the consistency index is used to verify the results.

Step 4. From all of the relative weight matrixes, we can produce the combined matrix.

Step 5. The goal of relative weight matrix is produced as Step 3.

Step 6. The decision matrix is established by the goal of the relative weight matrix product the combined matrix.

Step 7. Decision maker selects the priority of the jobs from the decision matrix.

An importance benefit of the approach is the AHP process considers the inconsistency in the relative matrix. The inconsistency exists when redundant information is presented in each matrix. The AHP approach adopts the preference scaling to show the degree of the preference. In table 1, the numerical scaling (1 to 9) displays the preference of the different jobs.

Example 1. Considering three jobs are scheduled to comply with three criteria in the architecture 1. We define the weight of the job difference in the criteria of the due date, the relationship and the order amount as presented in table 2.

Comparison of the criteria with respect to the goal in the architecture 1 is shown in table 3. The preference for the alternative jobs with respect to the due date, the relationship and the order amount is shown in tables 4, 5 and 6 respectively. Form table 4, the matrix A can be generated as the following:

$$A=\begin{bmatrix} 0.286 & 0.294 & 0.250 \\ 0.570 & 0.588 & 0.625 \\ 0.144 & 0.118 & 0.125 \end{bmatrix}$$

From the matrix A, we can calculate the relative weight matrix W as follow:

$$W=\begin{bmatrix} 0.277 \\ 0.595 \\ 0.128 \end{bmatrix}$$

According to the following equations, if W is not a zero matrix for the n jobs, we can derive the eigenvalue $\lambda_{\max}$, where I is an unit matrix.

$$A\times W=n\times W \quad (1)$$

$$(A-n\times I)\times W=0 \quad (2)$$

$$(A-\lambda_{\max})\times W=0 \quad (3)$$

The final value of

$$\lambda_{\max}=\frac{1}{3}\left[\frac{0.832}{0.277}+\frac{1.793}{0.594}+\frac{0.387}{0.129}\right]=3.005$$

A consistency index ($C.I.$) is used to evaluate the consistency of each matrix. A $C.R.$ is adopted to verify whether the related matrixes are paradox. To generate the $C.R.$, the random index ($R.I.$) can be simplified as a random index table. (For example, for level 3, $R.I.$=0.58.)

From the following equation (4)-(5), we can derive the $C.I.$ and the $C.R.$ as follows:

$$C.I.=\frac{\lambda_{\max}-n}{n-1} \quad (4)$$

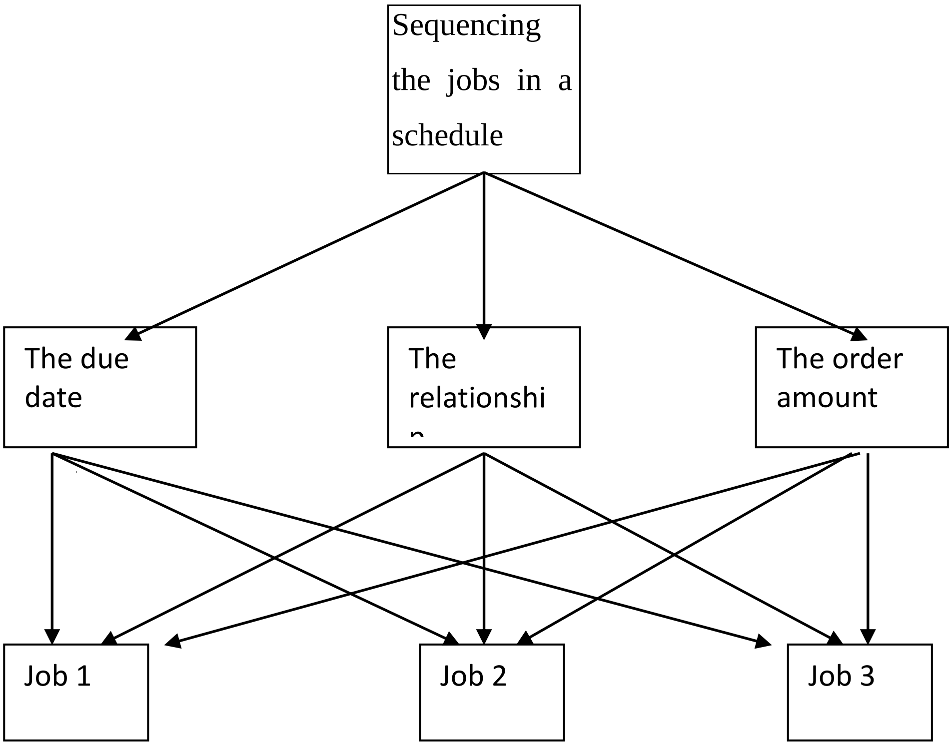


Figure 1. The AHP structure schema for architecture 1.

Table 1. The preference scaling.

scaling	Definition	Remark
1	Equal Importance	Equal preference of some jobs
3	Weak Importance	Slight preference of some jobs
5	Essential importance	Strong preference of some jobs
7	Very Strong Importance	Very Strong preference of some jobs
9	Absolute Importance	Extreme preference of some jobs
2,4,6,8	Intermediate Value	Mediate preference of above scaling

Table 2. The weight of job difference in the three criteria.

Weight	The due date	The relationship	The amount
1	Within one week	Within one year	Within one million
2	1~2 weeks	1~2 years	1~2 millions
3	2~3 weeks	2~3 years	2~3 millions
4	3~4 weeks	3~4 years	3~4 millions
5	4~5 weeks	4~5 years	4~5 millions
6	5~6 weeks	5~6 years	5~6 millions
7	6~7 weeks	6~7 years	6~7 millions
8	7~8 weeks	7~8 years	7~8 millions
9	Above 8 weeks	Above 8 years	Above 8 millions

Table 3. Comparison of the goal. ($\lambda_{\max}$=3.000 C.R.=0.0)

	The due date	The relationship	The order amount
The due date	1	2	1/2
The relationship	1/2	1	1/4
The order amount	2	4	1

Table 4. Preference of the due date. ($\lambda_{\max}$=3.005 *C.R.*=0.0043)

	Job 1	Job 2	Job 3
Job 1	1	1/2	2
Job 2	2	1	5
Job 3	1/2	1/5	1

Table 5. Preference of the relationship. ($\lambda_{\max}$=3.0044 *C.R.*=0.0038)

	Job 1	Job 2	Job 3
Job 1	1	1/5	1/2
Job 2	5	1	3
Job 3	2	1/3	1

Table 6. Preference of the order amount. ($\lambda_{\max}$=3.000 *C.R.*=0.0)

	Job 1	Job 2	Job 3
Job 1	1	3	1/3
Job 2	1/3	1	1/9
Job 3	3	9	1

$$C.R.=\frac{C.I.}{R.I.} \qquad (5)$$

The same procedure is repeated by using the data in table 5 and table 6. We combine the three different *W* matrixes to produce the relative weight matrix α.

$$\alpha=\begin{array}{c} \\ job\ 1 \\ job\ 2 \\ job\ 3 \end{array}\begin{array}{c} \begin{array}{ccc} \text{Due date} & \text{Relationship} & \text{Order amount} \end{array} \\ \begin{bmatrix} 0.277 & 0.122 & 0.231 \\ 0.595 & 0.648 & 0.077 \\ 0.128 & 0.230 & 0.692 \end{bmatrix} \end{array}$$

Using the data in table 3 and following the same aforementioned procedure, we produce the goal of the relative weight matrix β as follows:

$$\beta=\begin{array}{c} job\ 1 \\ job\ 2 \\ job\ 3 \end{array}\begin{bmatrix} 0.286 \\ 0.143 \\ 0.571 \end{bmatrix}$$

The decision matrix ($\alpha\times\beta$) is computed as follows:

$$\alpha\times\beta=\begin{array}{c} job\ 1 \\ job\ 2 \\ job\ 3 \end{array}\begin{bmatrix} 0.229 \\ 0.306 \\ 0.465 \end{bmatrix}$$

According to the weights of ($\alpha\times\beta$), we schedule the jobs as the sequence job3, job2, and job1. From the above results, we find that the *C.R.* in the related tables is less than 0.1. We conclude that the consistency exists in the related matrixes without revising our judgement. (See tables 3- 6).

5. The model of formulation

The different weights in table 3 can produce different β. It may establish the different schema of decision matrix ($\alpha \times \beta$) by changing the original weights. Thus, the different results appear according to the weights in table 3.

Now we replace one of the criteria, the order amount, with the other criteria, the system time (including processing time, waiting time, setup time etc.), in our consideration. The revised architecture for this case is shown in figure 2. The revised architecture may create a different structure schema and generate different results. If we append the criteria such as the manpower, the machine, the cost and the material supply in our consideration. The new system induced from such a complicated architecture becomes difficult to integrate and understand. On the contrary, the more the criteria we consider the more the rational results we can reach.

If the jobs under consideration are more than three, say four jobs, in the original architecture, another different structure schema can be established. (See figure 3). If we append the above criteria in our analysis, such complicated system needs to be aided by using the Expert Choice software, which is developed by Forman and Saaty (1991).

From above discussion, we found that the AHP approach is a robust and flexible multi-criteria method that is useful for scheduling problems in different kinds of companies.

6. The hierarchy consistency analysis

We also propose another approach, the hierarchy consistency analysis (HCA), in the following discussion. Based on the fact that in the analysis of a complex system, a decision maker frequently favors a certain combination of criteria. As the result of these different combinations, different hierarchy structure models in above discussion can be obtained. The HCA approach can be utilized in these different hierarchy models. An important assumption in the HCA approach is to consider the jobs in the bottom level of the hierarchies are the same; when we require the same overall performance index for the different hierarchies. The most important advantage of the HCA is that it does not require any pairwise comparison in determining the weights of the criteria. Therefore, no transitivity requirement is needed. The second advantage comes from the introduction of the rational index, which offers a natural and simple way to judge as well as improve the assigned weights from the decision maker. Another advantage includes that the analyses of these different structures give more insights to the problem being considered, hence it is useful to assist the decision maker to understand and to audit the performance status of the system from various viewpoints.

Example 2. We consider two decision makers constructing their architectures from their own viewpoints. We assume that the four jobs are scheduled by the product and the sale managers. The combined architecture is established by the two managers. (See figure 4). From the sale manager's viewpoint, the jobs J_{11} and J_{12} belong to the order 1, and the jobs J_{21} and J_{22} to the order 2. From the product manager's viewpoint, the jobs J_{11} and J_{21} belong to the product 1, and the jobs J_{12} and J_{22} belong to the product 2. Let ${}_i w_{jk}^0$ be the assigned weight, where the subscript *j*, *k* and *i* indicate the level, the position and the particular hierarchy structure respectively. The number of the iterations 0 presents the initially assigned value or the prior value. In figure 4, the assigned weights must obey the following equations: $(0 \le {}_i w_{jk}^0 \le 1)$

$${}_1 w_1^0 + {}_1 w_2^0 = 1,\quad {}_2 w_1^0 + {}_2 w_2^0 = 1$$

$${}_1 w_{11}^0 + {}_1 w_{12}^0 = 1,\quad {}_1 w_{21}^0 + {}_1 w_{22}^0 = 1$$

$${}_2 w_{11}^0 + {}_2 w_{12}^0 = 1,\quad {}_2 w_{21}^0 + {}_2 w_{22}^0 = 1$$

Let the calculated weight $\Phi({}_i w_{jk}^0)$ be determined

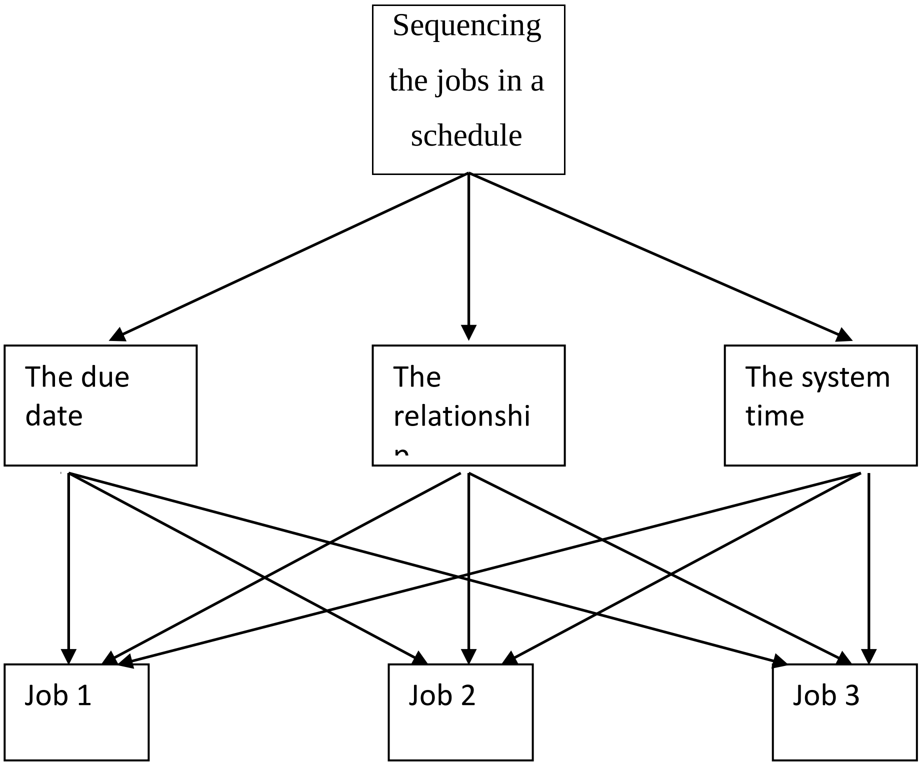


Figure 2. The AHP structure schema for architecture 2.

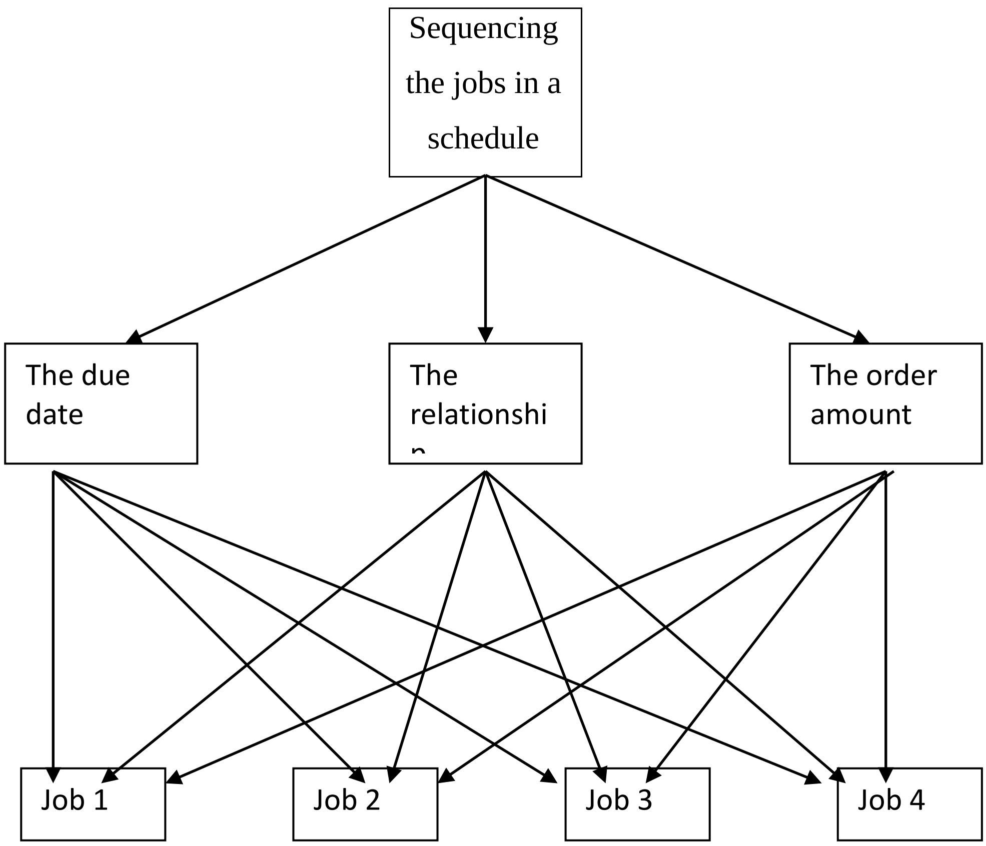
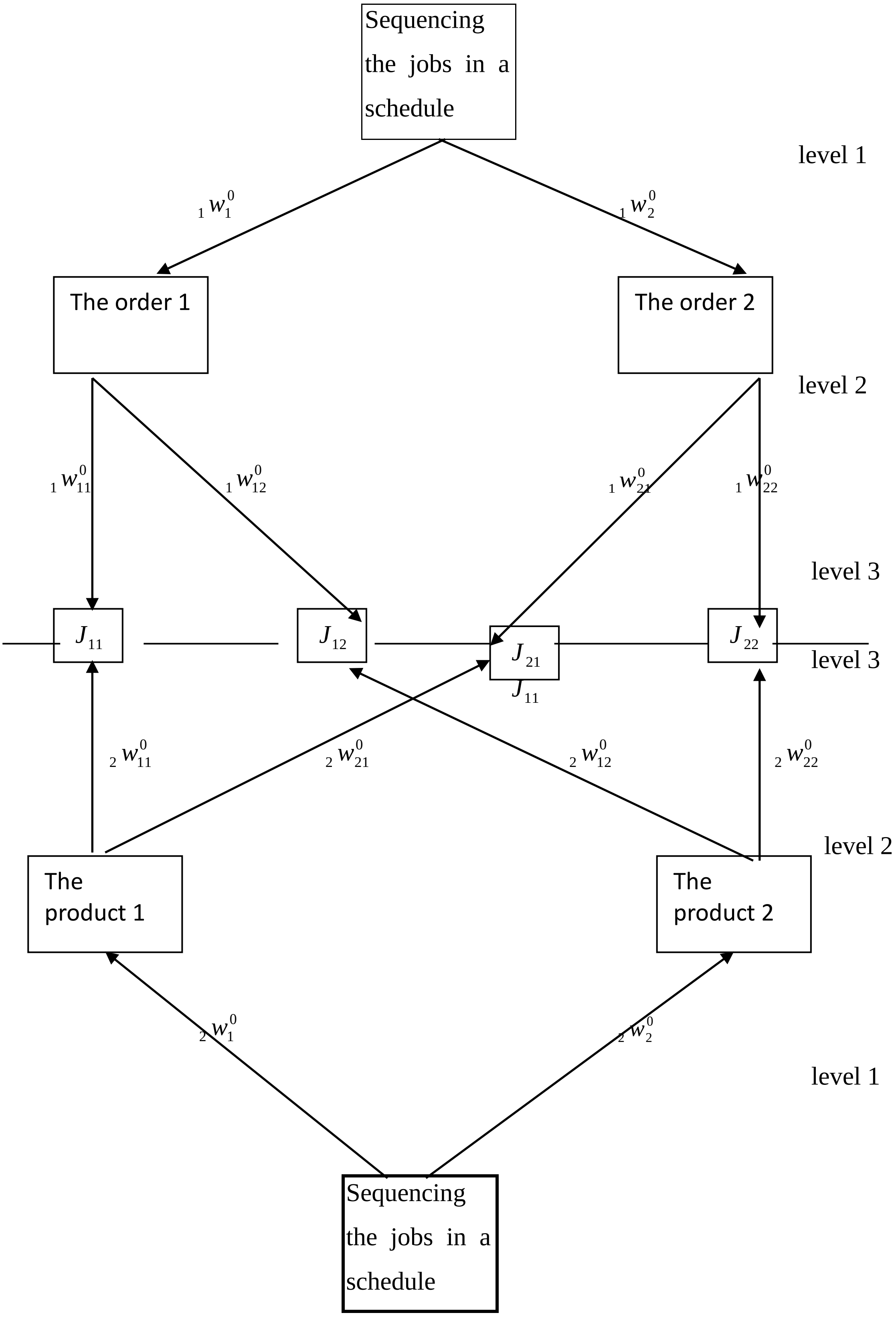


Figure 3. Four jobs are considered in AHP structure schema.

Hierarchy 1



Hierarchy 2

Figure 4. Combing hierarchy structure for the different orders and the products.

from the other hierarchy of the assigned weight. If the sale manager coordinates ${}_i w_{jk}^0$ to include the effect of the calculated weight $\Phi({}_i w_{jk}^0)$. We can derive $\Phi({}_1 w_{jk}^0)$ by using the following equations:

$$\Phi({}_1 w_1^0)={}_2 w_1^0 \; {}_2 w_{11}^0 + {}_2 w_2^0 \; {}_2 w_{12}^0 ,$$

$$\Phi({}_1 w_2^0)={}_2 w_1^0 \; {}_2 w_{21}^0 + {}_2 w_2^0 \; {}_2 w_{22}^0$$

$$\Phi({}_1 w_{11}^0)=\frac{{}_2 w_1^0 \; {}_2 w_{11}^0}{{}_2 w_1^0 \; {}_2 w_{11}^0 + {}_2 w_2^0 \; {}_2 w_{12}^0}$$

$$\Phi({}_1 w_{12}^0)=\frac{{}_2 w_2^0 \; {}_2 w_{12}^0}{{}_2 w_1^0 \; {}_2 w_{11}^0 + {}_2 w_2^0 \; {}_2 w_{12}^0}$$

$$\Phi({}_1 w_{21}^0)=\frac{{}_2 w_1^0 \; {}_2 w_{21}^0}{{}_2 w_1^0 \; {}_2 w_{21}^0 + {}_2 w_2^0 \; {}_2 w_{22}^0}$$

$$\Phi({}_1 w_{22}^0)=\frac{{}_2 w_1^0 \; {}_2 w_{21}^0}{{}_2 w_1^0 \; {}_2 w_{21}^0 + {}_2 w_2^0 \; {}_2 w_{22}^0}$$

$\Phi({}_2 w_{jk}^0)$ can also be derived from the same procedure.

The following convex combination was created by Guh et al. (1996) that can induce the iteration (n +1), where *k* is a combination parameter. $(0 \leq k \leq 1)$

$${}_1 w_j^{n+1}=k({}_i w_j^n)+(1-k)\Phi({}_i w_j^n)$$

Example 3. The two hierarchy structures have the same schema as shown in example 2. Two decision makers list the initial weights as follows:

$${}_1 w_1^0=0.3, \quad {}_2 w_1^0=0.6$$

$${}_1 w_2^0=0.7, \quad {}_2 w_1^0=0.4$$

$${}_1 w_{11}^0=0.8, \quad {}_2 w_{11}^0=0.5$$

$${}_1 w_{12}^0=0.2, \quad {}_2 w_{12}^0=0.7$$

$${}_1 w_{21}^0=0.6, \quad {}_2 w_{21}^0=0.5$$

$${}_1 w_{22}^0=0.4, \quad {}_2 w_{22}^0=0.3$$

We randomly assign *k* to be 0.5. The computed weights are calculated below:

$$\Phi({}_1 w_1^0)=0.580, \; \Phi({}_2 w_1^0)=0.660$$

$$\Phi({}_1 w_2^0)=0.420, \; \Phi({}_2 w_2^0)=0.340$$

$$\Phi({}_1 w_{11}^0)=0.517, \; \Phi({}_2 w_{11}^0)=0.364$$

$$\Phi({}_1 w_{12}^0)=0.483, \; \Phi({}_2 w_{12}^0)=0.176$$

$$\Phi({}_1 w_{21}^0)=0.714, \; \Phi({}_2 w_{21}^0)=0.636$$

$$\Phi({}_1 w_{22}^0)=0.286, \; \Phi({}_2 w_{22}^0)=0.824$$

This process of iteration can be continued until the results are converged to the acceptable range. The process and the results are summarized in table 7.From table 7, the sale manager schedules the jobs as the sequence J_{21}, J_{22}, J_{11}, and J_{12} originally. After considering the product structure schema, the sale manager reschedules the jobs in the following sequence J_{21}, J_{11}, J_{22} and J_{12}.

The weights in table 7 are computed from a personal computer. After three iterations, the computed weights converge to the assigned weight. The differences are in the acceptable range, less than 0.001. (See table 7). The program stops running and the new schedule is generated. In the example, we assign *k* equal to 0.5. It means that, the new weights are generated equally by the assigned weights and the calculated weights. If *k* closer to 0.5, the number of iteration *n* converges more quickly. (See table 8).

7. Conclusion

In the past years, a group decision is determined by only one architecture. Now the AHP methodology provides us a comprehensive framework for solving qualitative scheduling problems. It’s merits including being simpler in calculating the weight of criteria, offering a rational index to monitor the consistency when a decision maker makes his or her judgement, providing more type of AHP model to aid decision maker to understand and audit the performance status of system etc.

Table 7. The compromise process of determining weights.

1^{st} iteration		2^{st} iteration		3^{st} iteration	
${}_1w_1^0$=0.300	$\Phi({}_1w_1^0)$=0.580	${}_1w_1^1$=0.440	$\Phi({}_1w_1^1)$=0.434	${}_1w_1^2$=0.437	$\Phi({}_1w_1^2)$=0.437
${}_1w_2^0$=0.700	$\Phi({}_1w_2^0)$=0.420	${}_1w_2^1$=0.500	$\Phi({}_1w_2^1)$=0.491	${}_1w_2^2$=0.563	$\Phi({}_1w_2^2)$=0.563
${}_1w_{11}^0$=0.800	$\Phi({}_1w_{11}^0)$=0.517	${}_1w_{11}^1$=0.659	$\Phi({}_1w_{11}^1)$=0.627	${}_1w_{11}^2$=0.643	$\Phi({}_1w_{11}^2)$=0.643
${}_1w_{12}^0$=0.200	$\Phi({}_1w_{12}^0)$=0.483	${}_1w_{12}^1$=0.341	$\Phi({}_1w_{12}^1)$=0.373	${}_1w_{12}^2$=0.357	$\Phi({}_1w_{12}^2)$=0.357
${}_1w_{21}^0$=0.600	$\Phi({}_1w_{21}^0)$=0.714	${}_1w_{21}^1$=0.657	$\Phi({}_1w_{21}^1)$=0.633	${}_1w_{21}^2$=0.645	$\Phi({}_1w_{21}^2)$=0.645
${}_1w_{22}^0$=0.400	$\Phi({}_1w_{22}^0)$=0.286	${}_1w_{22}^1$=0.343	$\Phi({}_1w_{22}^1)$=0.367	${}_1w_{22}^2$=0.355	$\Phi({}_1w_{22}^2)$=0.355
${}_2w_1^0$=0.600	$\Phi({}_2w_1^0)$=0.660	${}_2w_1^1$=0.630	$\Phi({}_2w_1^1)$=0.658	${}_2w_1^2$=0.644	$\Phi({}_2w_1^2)$=0.644
${}_2w_2^0$=0.400	$\Phi({}_2w_2^0)$=0.340	${}_2w_2^1$=0.370	$\Phi({}_2w_2^1)$=0.342	${}_2w_2^2$=0.356	$\Phi({}_2w_2^2)$=0.356
${}_2w_{11}^0$=0.500	$\Phi({}_2w_{11}^0)$=0.364	${}_2w_{11}^1$=0.432	$\Phi({}_2w_{11}^1)$=0.441	${}_2w_{11}^2$=0.436	$\Phi({}_2w_{11}^2)$=0.436
${}_2w_{12}^0$=0.700	$\Phi({}_2w_{12}^0)$=0.176	${}_2w_{12}^1$=0.438	$\Phi({}_2w_{12}^1)$=0.439	${}_2w_{12}^2$=0.439	$\Phi({}_2w_{12}^2)$=0.439
${}_2w_{21}^0$=0.500	$\Phi({}_2w_{21}^0)$=0.636	${}_2w_{21}^1$=0.568	$\Phi({}_2w_{21}^1)$=0.559	${}_2w_{21}^2$=0.564	$\Phi({}_2w_{21}^2)$=0.564
${}_2w_{22}^0$=0.300	$\Phi({}_2w_{22}^0)$=0.824	${}_2w_{22}^1$=0.562	$\Phi({}_2w_{22}^1)$=0.561	${}_2w_{22}^2$=0.561	$\Phi({}_2w_{22}^2)$=0.561

Table 8. The convergence of iteration *n* of different *k*.

k	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
n	16	8	5	4	3	3	4	8	16

The contribution of HCA approach is providing a new evaluation methodology. The HCA approach deals with the multiple-criteria and the multiple-level evaluation problem. It supports us with a framework for solving the different weights of scheduling problems. It is especially suited for large complex problems where different hierarchy structures occur frequently and naturally.

The differences between the AHP approach and the HCA approach is that the former provides us the method consistency while the later shows us the weight can be coordinated with another architecture. Using the above approaches, managers who are responsible for scheduling jobs can make their decisions more rationally.

In the real environment, many companies face many qualitative factors when they schedule their jobs. A useful and relevant model is difficult to establish or formulate. However, in our research, scheduling problems can be constructed as a hierarchy model, which include both qualitative and quantitative factors. They provide us new methods for solving scheduling problems. These approaches can be applied in many fields.

In the near future, we plan to improve our above model with simulation method and to solve a large complex system with different structure schema.

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應用層級分析程序與層級一致性分析模式之排程研究

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摘要

在我們的公司中，公司與顧客間的關係，這樣的定性因素會在工件排程中被考量。為了要尋求能符合多準則的排程問題，我們應用兩種方法來解決我們的問題。在本研究中，我們的分析考量到定性與定量兩種因素。層級分析程序法可在不同的架構中，提供了一致性的準則。層級一致性分析法則在考量另一不同架構中，證實了權重的一致性。在排程工件時，這兩種方法的基本準則可在不同層級的一致性上得到執行。演算的結果說明在不同的架構中，採用此兩種方法來改善是很有實際價值的。

關鍵字：定量，定性，排程，一致性，層級。