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Fuzzy finish time modeling for project scheduling

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Abstract: This research aims at developing a new fuzzy activity finish time estimation model for project scheduling management. With the application of the fuzzy quality function deployment (FQFD) and fuzzy analytic hierarchy process (FAHP) methods, the degree of fuzziness for every project activity is calculated in accordance with considerations of project uncertainties. These uncertainties are measured by the risk level of such project-related characteristics as time limit, activity start time, budget, manpower, technological difficulty, and facility requirements. In this paper, rather than applying the de-fuzzification technique to obtain the crisp activity duration for project scheduling, the fuzzy finish time estimation method for every activity is proposed based on the degree of fuzziness. The corresponding fuzzy activity duration time plot is also developed in a new fuzzy Gantt chart. The proposed model can provide a reasonable fuzzy finish time estimation for every activity, while most scheduling methods only provide the finish time of the entire project. Compared to existing models, this time estimation model and its corresponding Gantt chart are predicted to have higher reliability and practical application in project management and scheduling.

Key words: Fuzzy quality function deployment (FQFD), Fuzzy analytic hierarchy process (FAHP), Fuzzy Gantt chart, Project management, Project scheduling

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1 Introduction

Project management is defined as managing time, material, personnel, and cost to meet objectives in time, resources, and technical results. The project evaluation and review technique (PERT) has been commonly applied to date, but it is known to suffer from poor time estimation and inaccurate activity durations when project-related uncertainties are considered. Banerjee and Paul (2008) studied the error of estimating mean project completion time in PERT. Genetic algorithms have also been proposed to measure uncertainty in PERT (Azaron *et al*., 2005; 2006). In practice, the operation time of activities in a project can be difficult to define and/or estimate. Project activities are subject to considerable uncertainty, which generally leads to numerous schedule disruptions. Leus and Herroelen (2004) presented a resource allocation model that protects a given baseline schedule against activity duration variability. Goren and Sabuncuoglu (2008) developed robust and stable schedules with respect to random disruptions. Kutanoglu and Wu (2004) also studied methods to improve scheduling robustness under processing time variation.

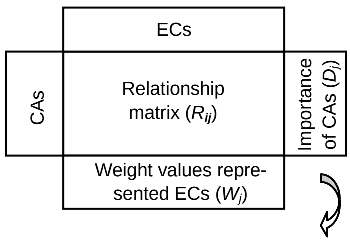
Recent works have, therefore, proposed to the combine fuzzy set theory in project management. Chen and Huang (2007) presented a fuzzy activity time evaluation method for measuring the criticality in a project network. Liu (2003) developed a solution for the critical path assumed when a project collapses. Zammori *et al.* (2009) also studied this critical path by considering duration variability, cost, shared resources, external risks, and risks of major design revisions. Liang (2009) developed a two-phase fuzzy approach for solving and managing multi-objective projects. Chen (2007) applied a linear programming formulation to calculate the lower and upper bounds of project duration, while Wang and Hao (2007) applied fuzzy linguistic probabilities to PERT. Yakhchali and Ghodsypour (2010) analyzed the possible earliest and latest start times of an activity in project networks. Shukla *et al.* (2008) considered resource-constrained project scheduling problems with the objective of minimizing the span subject to both temporal and resource constraints.

The application of the critical chain method in project management has also received considerable attention. A critical chain is the sequence of both precedence- and resource-dependent activities to complete a project. Cohen *et al*. (2004) examined the control mechanisms and alternatives of this critical chain for better project management performance. Yeo and Ning (2006) proposed to manage the time uncertainty in major equipment procurement. Ash and Pittman (2008) applied a heuristic approach to resource-constrained project scheduling. Tukel *et al.* (2006) introduced a method to determine the feeding buffer sizes in critical chain project scheduling. The above works, however, are ineffective for those projects either too complex or too similar to adequately define. Fuzzy critical chain (FCC) scheduling had been proposed as a potential solution (Chen and Hsu, 2004; Long and Ohsato, 2008). Despite the use of these fuzzy PERT or critical chain methods, scheduling processes based on either de-fuzzified activity times or resulted in a fuzzy number, are too difficult to be employed in real applications.

To propose a new method for estimating fuzzy activity duration, we integrate fuzzy quality function deployment (FQFD) methods that are often seen in engineering product development. The original concept of FQFD is to translate customer requirements into the technical language of engineering through the use of linguistic abstraction. The degree of fuzziness for each individual activity of a project is first defined using FQFD. Project uncertainties are measured based on the risk level of project characteristics. The fuzzy activity finish time estimation model proposed here is based on the degree of identified fuzziness. Also proposed is the fuzzy Gantt chart, which describes the fuzzy activity duration for the project network. Instead of providing the finish time of the entire project, the proposed algorithm can provide a reasonable fuzzy finish time estimation for each activity. Through the use of the proposed fuzzy estimation method, it is anticipated that project uncertainties will be analyzed more effectively and efficiently in the area of project scheduling management.

2 Degree of fuzziness by FQFD and FAHP in project scheduling application

FQFD has been applied in the translation of customer requirements into engineering specifications for product development. Lin *et al.* (2006) presented a procedure to effectively link customer requirements with design characteristics for product design. An integrated framework based on FQFD and fuzzy optimization was proposed by Kahraman *et al*. (2006). Bottani and Rizzi (2006) applied FQFD to customer management, while Chen *et al.* (2006) used it to rank technical attributes in flexible manufacturing system designs. Bottani (2009) presented an approach aimed at identifying the most appropriate enabler to be implemented on the market. Customer need is represented by the house of quality (HOQ) matrix (Fig. 1), denoting the translation of one level of design consideration into the next. Customer need is also called customer attribute (CA), and is often determined through surveys or direct questions. CAs are translated into engineering characteristics (ECs) by linguistic expressions {VL, L, M, H, VH} at different technical rankings, where VL, L, M, H, and VH represent very low, low, median, high, and very high, respectively. The weights of ECs are evaluated by



	EC_1	EC_2	EC_3	…	EC_n	
CA_1	VL	H	VH	…	L	M
CA_2	VH	VH	H	…	L	L
…	…	…	…	…	…	…
CA_n	L	M	VL	…	M	VH
	Weight1	Weight2	Weight3		Weight*n*	

Fig. 1 Example of FQFD with five fuzzy linguistic spaces {VL, L, M, H, VH}

$$W_i = \sum_j^m R_{ij} D_j,\ i = 1, 2, ..., n, \tag{1}$$

where D_j represents the jth importance factor of CA, R_{ij} is the relationship between the jth CA and the ith EC, m is the number of importance representing CA, and n is the number of weight representing EC. The relationship matrix (R_{ij}) is described in linguistic terms with a fuzzy set. For example, CAs, ECs and the relationship matrix in FQFD are all represented by five linguistic spaces {VL, L, M, H, VH}. R_{ij} indicates the relative risk level of jth CA to ith EC, and W_j represents the jth calculated total risk of ECs under the consideration of CAs and $\boldsymbol{D}$. W_j is defined as the degree of fuzziness for each activity. The linguistic value of "VH" for the relation matrix element of EC_1 to CA_2 means the relative risk level of the project characteristics CA_2 for this activity is very high (i.e., the uncertainty of EC_1 activity on the project characteristics CA_2 is significant). On the contrary, the "VL" for the relation matrix element of EC_1 to CA_1 means the relative risk level of CA_1 for this activity is very low (i.e., the uncertainty of EC_1 activity on the project characteristics CA_1 is insignificant). The importance vector of CAs shown in Fig. 1 indicates the relative importance of the project characteristics. A fuzzy set F in a specific discourse U can be defined as a set of ordered pairs:

$$F = \{(x, \mu(x)) | x \in U\}, \tag{2}$$

where $\mu(x)$ is the degree of membership function of F in [0, 1]. A fuzzy set can be defined mathematically by assigning each possible individual to a value of the membership function. To make the calculated fuzzy values useful, they must be translated back to crisp values through de-fuzzifizcation processes within the center of area method:

$$x_0 = \frac{\int_x x \cdot \mu(x) \mathrm{d}x}{\int_x \mu(x)}, \tag{3}$$

where x_0 is the de-fuzzified value. Fuzzy scheduling considers activity duration time as a fuzzy number rather than a crisp number. Using fuzzy arithmetic calculations, then the value must be translated into a crisp value via de-fuzzifizcation.

The demand to finish a project in a shorter time is increasing in today's competitive environment. Moreover, challenges to or difficulties in project management also increase by the disturbance of many delays/interruptions, as well as uncertainties stemming from many unidentifiable environmental factors. When applying FQFD to a project management, the risk level of such project characteristics as project time limit (PTL), project activity begin time (PABT), project budget (PB), manpower (MP), technological difficulty (TD), and facility requirements (FRs) are considered as CAs, while the project activities are defined as ECs.

Up to now, the analytic hierarchy process (AHP) has been commonly used for determining the rank of CAs in QFD by filling in the crisp values for the ratio of CAs toward one another (Franceschini and Rupil, 1999). However, what if the project manager fails to determine accurate ratios while ranking? This case identifies a legitimate need for using qualitative assessment in defining the relationship of one CA to another. Taking qualitative assessment into consideration, Vanegas and Labib (2001) applied the fuzzy analytic hierarchy process (FAHP) to rank CAs with the outcome of the weighted values, which are in the form of a fuzzy number (Vanegas and Labib, 2001). The membership function of FAHP is the same as that of the proposed FQFD as shown in Fig. 2.

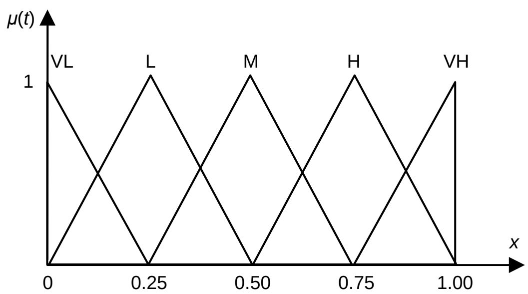


Fig. 2 Relationship membership function of FQFD

To determine the weighted values of CAs, the fuzzy relationship matrix of CAs (Fig. 3) will be used to determine the eigenvector of the weighted values in the form of a fuzzy number (Cheng and Mon, 1994). In the process of completing the fuzzy relationship matrix of CAs to determine the ranking, this study used ten fuzzy numbers to represent the relationship of one CA to another. A definition for each fuzzy number is provided in Table 1.

	PTL	PABT	PB	MP	TD	FR
PTL	*I*	VL	M	M	VH	VH
PABT	Inverse VL	*I*	L	M	H	VH
PB	Inverse M	Inverse L	*I*	L	M	H
MP	Inverse M	Inverse M	Inverse L	*I*	M	H
TD	Inverse VH	Inverse H	Inverse M	Inverse M	*I*	L
FR	Inverse VH	Inverse VH	Inverse H	Inverse H	Inverse L	*I*

Fig. 3 Fuzzy relationship of CAs

Table 1 Fuzzy number definition for CAs

	Triangular membership function	Degree of impact with respect to project duration
VL	(1, 1, 3)	Equal impact as compared with the others
L	(1, 3, 5)	A little more impact over the others
M	(3, 5, 7)	More impact over the others
H	(5, 7, 9)	Much more impact over the others
VH	(7, 9, 9)	Overwhelming impact over the others

As defined in Fig. 3, the project duration is greatly affected by the PTL and PABT, indicating that this is a long-period project with an actual PABT commencing much later than expected. This project also requires significant MP and has an elevated PB, indicating that MP and PB could be factors that increase project duration, while its TD and FRs pose no issue for project duration. Using the FAHP to prioritize the CAs, a ranking of CAs with weighted values in fuzzy number form is generated. The average triangular membership function is the largest weighted value of PTL; thereby identifying it to be the factor that will most increase project duration. The mean weighted value of FR is the smallest, indicating this to be the factor that least affects project duration and hence, poses no issue for this case project.

As for the example of a project activity network shown in Fig. 4, there are 11 project activities (A–K) with a possible duration time range when uncertainties considered. The fuzzy model is independent on the activity duration and can be in any membership. The trapezoidal fuzzy model is adopted because of its simplicity. The fuzzy model $\mu(t)$ is used to express the degree of an element belonging to a fuzzy set. The trapezoidal fuzzy model as shown in Fig. 5 can be defined as

$$\mu(t)=\begin{cases}(t-a)/(b-a), & \text{for } t\in[a,b],\\ 1, & \text{for } t\in[b,c],\\ (d-t)/(d-c), & \text{for } t\in[c,d],\\ 0, & \text{for } t\notin[a,d].\end{cases} \tag{4}$$

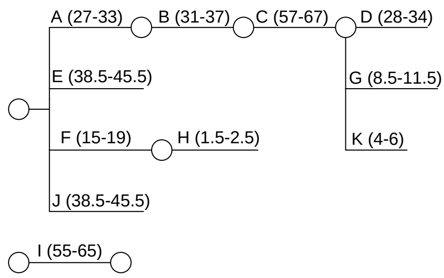


Fig. 4 Activity network of a project containing 11 project activities (A–K)
Activity A (27–33) can be completed in 27–33 d. A, B, C, and D are conducted sequentially, while D, G, and K concurrently

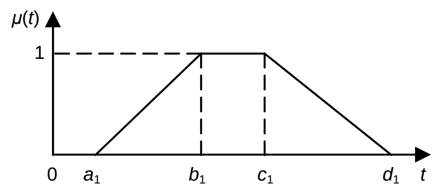


Fig. 5 Trapezoidal fuzzy model for project network activity

For a project activity with duration of (T_1, T_2), the trapezoidal fuzzy model of activity duration time can be defined as $a=T_m-T_s$, $b=T_m-T_s/2$, $c=T_m+T_s/2$, $d=T_m+T_s$, where the mean duration $T_m=(T_1+T_2)/2$ and duration span $T_s=T_2-T_1$. Table 2 shows the results of the fuzzy model for every activity. The project characteristics considered in this work including the PTL, PABT, PB, MP, TD, and FR. The risk levels are all in 5 fuzzy spaces: {very long/large/hard, long/large/hard, medium, short/small/easy, very short/small/easy}. Longer project time such as project activity C can induce unexpected events and cause delay, and in that way the project duration will be increased. Thus, the risk level of activity C is defined as "VH". For the case of very short project time, such as project activity H, the risk level can be defined as "VL" because there is little chance for uncertainties. Table 3 shows the relationship matrix in the fuzzy set for every activity with respect to the six project characteristics. The linguistic space of fuzzy set {VL, L, M, H, VH} shown in Fig. 2 is defined according to engineers' experience (Liu *et al*., 2008). The calculated weighting W_i from Eq. (1) is also listed in Table 3. Consider a_i is the normalized weight, $\bar{W}$ is the mean and σ is the standard deviation of the weights calculated from Table 3.

$$a_i = \frac{W_i}{\bar{W} + 3\sigma}, \tag{5}$$

where $\bar{W} + 3\sigma$ stands for the span of mean value with three times of standard deviation for the Gaussian distribution case. Most of the weights (99.5%) will be included in this region to make $a_i \leq 1$. From the definition of the relation matrix (R_{ij}), a_i can be considered as the relative degree of fuzziness for every activity of the project. Those activities with larger a_i, such as project activity C, indicate higher fuzziness, i.e., the uncertainties are more likely to occur. Those with smaller a_i, such as activities H and K, can be considered less fuzzy, with lower uncertainties.

Table 2 Fuzzy models for every activity of the project

Activity	Fuzzy model
A (27–33)	(24, 27, 33, 36)
B (31–37)	(28, 31, 37, 40)
C (57–67)	(52, 57, 67, 72)
D (28–34)	(25, 28, 34, 37)
E (38.5–45.5)	(35, 38.5, 45.5, 49)
F (15–19)	(13, 15, 19, 21)
G (8.5–11.5)	(7, 8.5, 11.5, 13)
H (1.5–2.5)	(1, 1.5, 2.5, 3)
I (55–65)	(50, 55, 65, 70)
J (38.5–45.5)	(35, 38.5, 45.5, 49)
K (4–6)	(3, 4, 6, 7)

3 Fuzzy activity duration estimation based on the degree of fuzziness

Fuzzy project scheduling methods, such as fuzzy PERT or FCC, need de-fuzzification when calculating the project duration and scheduling. In this study, we developed a method of using degree of fuzziness to estimate each activity's finish time. After applying FQFD and FAHP to determine the weight of every activity, W_i, we can determine a_i, the normalized degree of fuzziness of every activity. The range of the normalized degree of fuzziness is from 0 to 1. The larger the number, the fuzzier the activity. And we defined that the earliest finishing time of an activity is at b_1 in Fig. 5, while the latest finishing time is at d_1. If a_i equals 1 means this work is extremely fuzzy, we say it will be finished at its latest time, which is at d_1 in Fig. 5. If a_i equals 0 means this work is not fuzzy at all, and one can declare that it will be done at the earliest time, which is at b_1 in Fig. 5. Using the method of interpolation, we can derive the equation of finish time P_i for every activity as shown in Fig. 6.

$$P_i=b_i+(d_i-b_i)a_i. \tag{6}$$

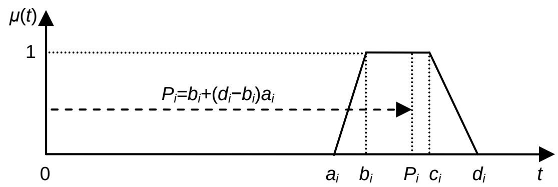


Fig. 6 Project time estimation using the degree of fuzziness

Table 3 FQFD/FAHP results of the project as shown in Fig. 4

	A	B	C	D	E	F	G	H	I	J	K	Importance of CA
PTL	M	H	VH	M	H	L	VL	VL	VH	H	VL	(0.21, 0.37, 0.74)
PABT	L	M	VH	L	H	VL	VL	VL	H	H	VL	(0.14, 0.33, 0.58)
PB	M	M	H	M	H	VL	L	VL	VH	VH	L	(0.07, 0.15, 0.33)
MP	M	H	VH	H	M	H	L	VL	H	VH	L	(0.05, 0.09, 0.21)
TD	H	M	H	H	L	VH	M	VL	H	VL	VL	(0.02, 0.04, 0.08)
FR	VH	L	H	M	M	H	M	L	H	H	L	(0.01, 0.02, 0.05)
W_i	0.64	0.84	1.10	0.66	0.94	0.40	0.26	0.17	1.06	0.99	0.24	
a_i	0.37	0.49	0.64	0.39	0.55	0.23	0.15	0.10	0.62	0.58	0.14	

For the case of more than one precedent activity, such as P_s and P_t as precedents of P_k, the critical path can be determined from the longest finish time as

$$P_k = \max(P_k^s, P_k^t), \tag{7}$$

where $P_k^s = \sum_{i=1}^{s} P_i$ and $P_k^t = \sum_{i=1}^{t} P_i$. The total project time will be equal to the summation of P_k on the critical path.

Table 4 lists the project time comparisons of the proposed method with the usual fuzzy PERT. The estimated total project time 164 d is based on the proposed method in this study. The estimated project time of 164 d will be more reliable for managers, and the sequential plot of activity finish time will be more practical for project management. The uncertainty in activity duration is too difficult to quantify. It is mostly determined according to the subjective experience of project managers. By integrating FAHP and FQFD, the degree of fuzziness can be defined and further applied to the starting time estimation for every activity. The fuzzy Gantt chart as shown in Fig. 7 can provide a practical tool for the management of fuzzy project scheduling. Application of the proposed fuzzy activity duration time estimation algorithm is shown both effective and efficient.

Table 4 Scheduling results of different fuzzy estimations

Method of estimation	Project time (d)
Latest finish (Σd_i)	185
Late possible (Σc_i)	171
Early possible (Σb_i)	143
Proposed algorithm	164

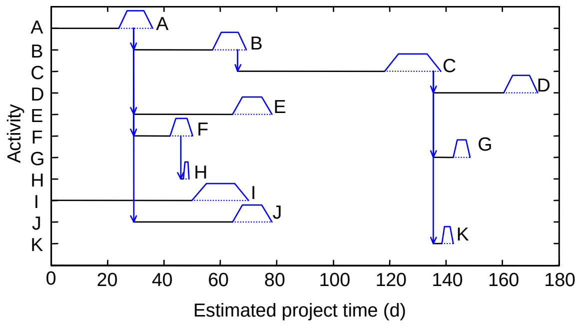


Fig. 7 Sequential finish time plot for the project as shown in Fig. 4

4 Conclusions

1. With the application of FQFD and FAHP methods, the degree of fuzziness for every project activity is calculated under the considerations of the importance of CAs and project characteristics, including PTL, PABT, PB, MP, TD, and FR.

2. The fuzzy finish time model is proposed based on the degree of fuzziness to provide a reasonable and clear estimation of activity finish time in fuzzy scheduling. Instead of providing the finish time of the whole project, the proposed method can provide a clear and reasonable finish time for every activity in a project, and that will be more reliable and practical in project management applications.

3. In addition to the finish time estimation, the fuzzy Gantt chart is also developed. Compared to the usual fuzzy scheduling methods, this plot provides an easy-to-manage tool for project managers.

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