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Optimum utilisation of low-capacity combine harvesters in high-yielding wheat farms using multi-criteria decision making

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About 23% of wheat farms in Iran have yields of more than 5 t ha^{-1}, but the technology and the capacity of over 85% of the existing combine harvesters are low and they are not suitable for handling such high yields mainly because of their high harvest losses due to high feed rates. Therefore, it is necessary to match machines with the farms by optimising their feed rate either by changing the effective width or the ground speed. However, simply reducing the effective width, which is the most common method, may also lead to a higher seed breakage (SB). A proper technical framework was developed for harvesting such fields with current combine harvesters, based on multi-criteria decision making (MCDM) technique. Several aspects mainly, SB, total harvest losses, fuel consumption, and combine field capacity were considered as harvesting attributes. Nine different combinations of ground speed and effective width were defined as harvesting candidate alternatives. The MCDM technique indicated that simply reducing the effective width is not the most suitable solution for this problem. For example, the optimum solution for a field with the average yield of 7.4 t ha^{-1} was to use a speed 3.5 km h^{-1} and the full platform width.

1. Introduction

In Iran the harvesting of cereal crops is currently a difficult operation, since it is mostly performed by inefficient combine harvesters with low capacity; a situation which is commonly associated with high harvest losses. The lack of modern combine harvesters is mainly due to their relatively high price and the financial restrictions felt by farmers. Nationwide harvest losses in Iran have been estimated to be 7.78% from which 68% came from platform losses (Behroozi Lar *et al.*, 1994).

Several studies have revealed a direct correlation between combine feed rate and the harvest losses (e.g., Anil *et al.*, 1998; Sudajan *et al.*, 2002; Navid *et al.*, 2004; Spokas & Steponavicius, 2006). In Iran about 23% of wheat farms have more than 5 t ha^{-1} yield, while over 85% of the existing

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Nomenclature

SB	Seed breakage
TL	Total harvest losses
FC	Fuel consumption
CFC	Combine field capacity
ECW	Effective cutting width
S_1	ground speed of 1.5 km h^{-1}
S_2	ground speed of 2.5 km h^{-1}
S_3	ground speed of 3.5 km h^{-1}
W_1	100% of platform width
W_2	80% of platform width
W_3	60% of platform width
RL	Rear losses (thresher + separator)
HL	Header losses
A_i	ith alternative
X_j	jth attribute
r_{ij}	the value of jth attribute for ith alternative
m	the number of alternatives
n	the number of attributes
P_{ij}	the uncertainty of a discrete probability distribution function
d_j	degree of deviation from data belonging to "ith" attribute
$w_2 = w_j$	matrix of weight of attributes
HAWM	Hierarchical additive weighting method
C_j	jth multiplication factor of the decision matrix

combine harvesters in the country were constructed with a maximum nominal capacity of 3234 kg h^{-1} of grain. In other words, a yield of more than 4.5 t ha^{-1} is beyond the capacity of these harvesters (Anon, 2004). Therefore many machines cannot work in such fields without significant harvest losses.

One solution to this problem is the partial usage of the platform (reduced effective width). However, this may lead to higher platform losses and grain breakage. It is also believed that partial usage of platform might also lead to an uneven feeding of the thresher and hence a poor separation (Behroozi Lar *et al.*, 1994; Mansoori and Minaei, 2003). On the other hand, due to design restrictions of existing harvesters, the minimum ground speed is limited to about 1.5 km h^{-1}, hence in some situations reducing ground speed is not suitable and the operators are forced to reduce platform width.

At present, there are no immediate substitutes for these harvesters. Therefore, it is necessary to improve their performance through optimising their feed rate. Combine harvester feed rates may be optimised, by choosing the proper effective cutting width (ECW), the suitable ground speed or appropriate combinations of both. Thus, the main object of this optimisation is to limit the harvest losses to reasonable level as well as to reduce seed damage, fuel consumption (FC) and operation time.

Due to the complex interrelationship of the relevant factors, this optimisation requires precise management strategies and the use of decision-making techniques. When solving decision-making problems with more than one effective factor, multi-criteria decision making (MCDM) can be a promising technique. The theoretical aspects of this technique can be found elsewhere (El-Gayar and Leung, 2000) but MCDM models are widely used in many areas such as business, economics and manufacturing (El-Gayar and Leung, 2000). It has also been employed in areas related to agriculture such as irrigation (e.g., Bazzani, 2005; Gómez-Limón and Martinez, 2006; Riesgo and Gómez-Limón, 2006) and sustainable rural development (e.g., Greening and Bernow, 2004; Meyer-Aurich, 2005; Zavadskas and Antucheviciene, 2007).

There is much research on farm decision-making using empirical studies, with more than one attribute in their utility functions (e.g., Kliebenstein *et al.*, 1980; Patrick and Blake, 1980; Cary and Holmes, 1982). Most of this research reports the complexity of decision making where there are several attributes. More recent work has established that farm decision-making processes are driven by several criteria that are usually conflicting (Berbel and Rodrıguez, 1998; Costa and Rehman, 1999; Willock *et al.*, 1999; Solano *et al.*, 2001). These complications are mostly related to social, cultural and natural situations, as well as the expected economic criteria (Gómez-Limón and Martinez, 2006).

Here we attempt to utilise MCDM in the area of agricultural mechanisation and, in particular, the utilisation of farm machinery in the field. We specifically formulate strategies for optimising the performance of low-technology combine harvesters when working in high-yielding fields.

Both branches of MCDM (multiple attribute decision making, MADM and multiple objective decision making, MODM) have been used to assist decision making. Since MADM is concerned with the ranking of alternative decision (Hua *et al.*, 2008) it is used in this study for ranking the different harvesting alternatives.

2. Materials and methods

This study comprised of two major sections; experimental setup and theoretical development.

2.1. *Experimental setup*

Four major factors including seed breakage (SB), total harvest losses (TL), FC, and combine field capacity (CFC) were considered as technical attributes and thereby measured. To investigate the effects of ground speed, ECW, and uneven feeding of thresher on the mentioned attributes, three speed levels ($S_1 = 1.5$, $S_2 = 2.5$, $S_3 = 3.5$ km h^{-1}) and three levels of ECW ($W_1 = 100\%$, $W_2 = 80\%$, $W_3 = 60\%$ of platform nominal width) were selected. The experiments were performed in a field with 7.42 t ha^{-1} yield *via* a strip block design with three replications, in Khorasan province, Iran in 2007. The wheat cultivar used was *Shiraz* which has high scattering resistance. Due to lack of combine harvester in the area under study, harvesting is usually postponed therefore the average moisture content of straw and seeds was 7.5%.

2.1.1. *Rear losses (Thresher + separator) measurements (RL)*

A steel measuring frame of 4.25 m length (equal to the cutter bar width) and 0.61 m width was fabricated to collect the grain losses data. The frame was randomly placed at different locations of the field before and after harvesting. Loose grains and cut/uncut heads were collected to determine: (i) the yield; (ii) pre-harvest losses; (iii) total losses (TL); (iv) header losses (HL); and (v) rear losses (RL).

CFC was calculated from total effective time taken by the combine to harvest a given area. SB was determined from average of three different samples of identical weight taken from grain tank. FC was also calculated from harvesting time and the reported rate of FC (Anon, 2005).

2.2. *Theoretical development*

The MADM model was formulated by the matrix which is shown in Table 1. In this table A_i and X_j are the ith alternative and jth attribute, respectively. r_{ij} is the value of jth attribute for ith alternative.

In this study the number of alternatives (m) and attributes (n) were 9 and 4, respectively. The measured attributes X_1 through X_4 represent CFC, TL, SB, and FC, respectively. The selected alternatives A_1 through A_9 are (the first number is ECW as % of platform nominal width and the second is ground speed in km h^{-1}): $W_1S_1 = 100$, 1.5; $W_1S_2 = 100$, 2.5; $W_1S_3 = 100$, 3.5; $W_2S_1 = 80$, 1.5; $W_2S_2 = 80$, 2.5; $W_2S_3 = 80$, 3.5; $W_3S_1 = 60$, 1.5; $W_3S_2 = 60$, 2.5; $W_3S_3 = 60$, 3.5, respectively.

2.2.1. *Weight assessment of indices*

The value that decision maker (DM) assigns to a given attribute with respect to a parent attribute is called weight. This value lies within the range of parent attribute scale. In order to determine the comparative importance of each attribute, the entropy technique was used (Asgharpour, 2004). The uncertainty of a discrete probability distribution function (P_{ij}) such as the matrix shown in Table 1 is calculated as:

$$P_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}}; \forall i, j \qquad (1)$$

The uncertainty or degree of deviation "d_j" from data belonging to "ith" attribute can be determined as:

$$d_j = 1 + \frac{1}{\mathrm{Ln}(m)} \sum_{i=1}^{m} [P_{ij} \cdot \mathrm{Ln}(P_{ij})] \qquad (2)$$

Having calculated the above parameters, the weight of four attributes can be calculated as (Asgharpour, 2004):

$$w_2 = w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}; \forall j \qquad (3)$$

Table 1 – Decision-making matrix

Alternative	Attribute			
	X_1	X_2	…	X_n
A_1	r_{11}	r_{12}	…	r_{1n}
A_2	r_{21}	r_{22}	…	r_{2n}
⋮	⋮	⋮	⋮	⋮
A_m	r_{m1}	r_{m2}	…	r_{mn}

Finally, the well known hierarchical additive weighting method (HAWM) (Asgharpour, 2004), was used for the ranking of alternatives. Based on this technique, the level of factors which are crucial in decision making was determined (Fig. 1).

The first level is the goal with unit preference. The second level of hierarchical decision making contains four attributes which are affected by goal and their preference matrix (w_2). The third level contains alternatives that are influenced by attributes in the second level. The preference matrix in the third level is, in fact, the initial decision matrix (Table 3, obtained from experimental measurements) i.e., its all elements were normalised through multiplying by "C_j", where (Asgharpour, 2004):

$$C_j = \frac{\frac{1}{r_{ij}}}{\sum_{i=1}^{m} \frac{1}{r_{ij}}}; J = 1, 2, 3 \qquad (4)$$

and

$$C_j = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}}; J = 4 \qquad (5)$$

The general preference vector corresponds to the ranking of the alternatives. In other words it shows the importance of the elements in the third level (i.e., method of harvesting).

3. Results and discussion

3.1. *Harvest losses*

The effect of ground speed and ECW on RL, HL, TL, and SB were significant ($P < 0.05$) (Table 2). The results indicated that the yield of the field was 7.42 t ha^{-1}. Since pre-harvest losses are identical for all alternatives, they have no effect on

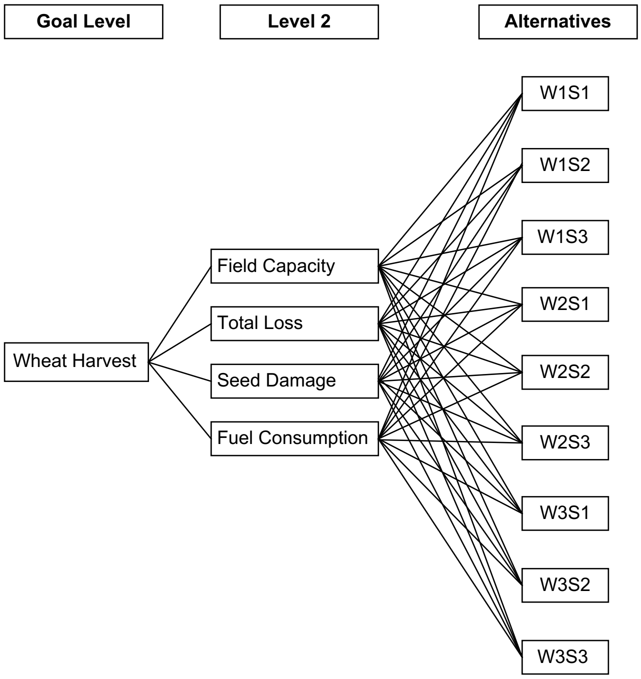

Fig. 1 – The level of factors engaged in wheat harvesting operation. These levels were determined using HAWM method.

Table 2 – Statistical analysis of factors

Source of deviation		Mean square			
	df	SB	TL	RL	HL
Block	2	$0.212^{n.s}$	$0.042^{n.s}$	$0.0004^{n.s}$	$0.042^{n.s}$
Effective width	2	2.54^{*}	0.543^{**}	0.914^{**}	0.643^{**}
Error A	4	$0.38^{n.s}$	$0.038^{n.s}$	$0.0006^{n.s}$	$0.315^{n.s}$
Ground speed	2	3.79^{*}	0.453^{**}	1.27^{**}	0.237^{*}
Error B	4	$0.15^{n.s}$	$0.026^{n.s}$	$0.00049^{n.s}$	$0.0218^{n.s}$
Ground speed × width	4	$0.08^{n.s}$	0.5^{**}	0.185^{**}	0.221^{**}
Coefficient of Variation (CV)	–	20.42	14.57	7.97	20.67

* and ** means significantly different at probability $p = 0.05$ and $p = 0.01$, respectively.

decision-making process and therefore they were used only to determinate header and RL.

3.1.1. *Header losses (HL)*

As shown in Fig. 2, using the whole width of the platform and increasing the ground speed increases HL. This is in agreement with Mansoori and Minaei (2003). However, with partial use (i.e., 60% and 80%) of platform, larger HL were observed, but they decreased sharply with increasing in ground speed. The extremely high HL with partial use of the platform was mainly due to rebound of the previously cut stems onto the ground. This was specifically observed in the unused section of the platform. For this reason, in the alternatives W_2S_1 and W_3S_1 (Fig. 1) HL were almost the same and at a maximum.

3.1.2. *Rear losses (RL)*

The interaction effect of ground speed and ECW on RL is shown in Fig. 3. It is seen that by increasing both ground speed and ECW, RL also increased sharply. Based on calculations, for every unit of ground speed (km h^{-1}) the feed rate increased by 12.36 kg min^{-1} per unit length (m) of cutter bar. Therefore, increasing both ground speed and ECW produces a very high feed rate. This produces more losses on cleaning unit (Srivastava *et al.*, 1990; Navid *et al.*, 2004). Fig. 4 shows the effect of grain feed rate on RL. Having accepted 1% as maximum allowable RL, it can be seen that the grain feed rate should not exceed from 150 kg min^{-1} which, based on field average yield and calculations, corresponds to 2.96 km h^{-1}.

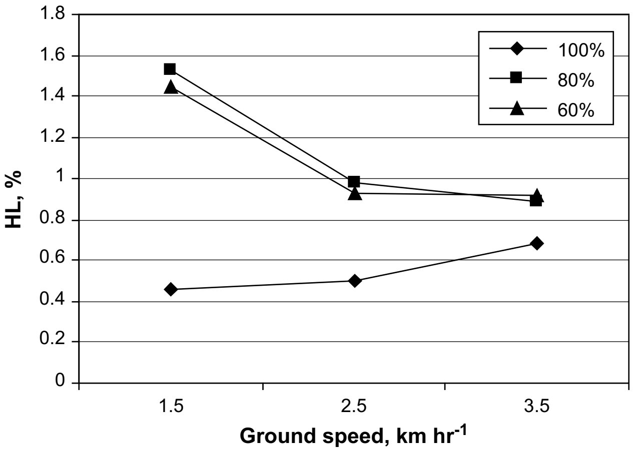

Fig. 2 – Interaction effect of ground speed and ECW on HL.

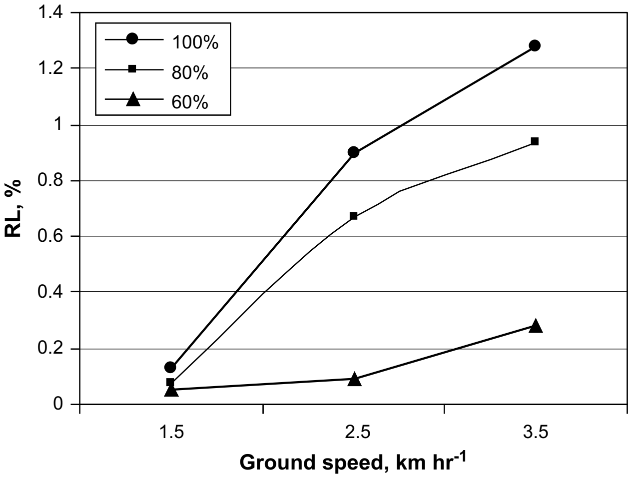

Fig. 3 – Interaction effect of ground speed and ECW on RL.

3.1.3. *Total losses (TL)*

As shown in Fig. 5 using the whole width of the platform and increasing the ground speed caused a dramatic increase in TL, because the feed rate appeared to have exceeded the capacity of the combine. At an ECW of 80%, increasing the ground

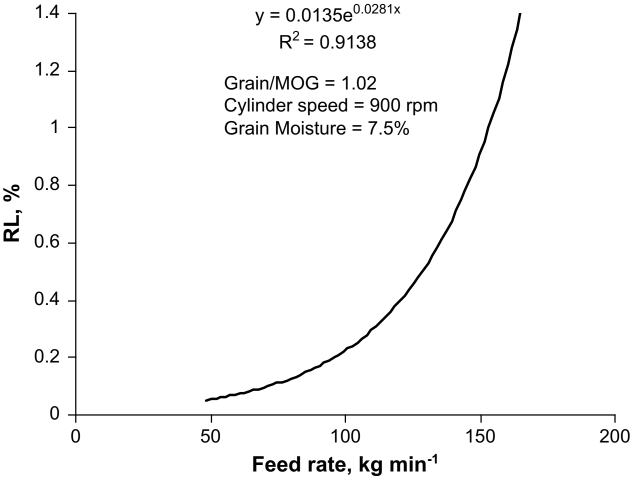

Fig. 4 – Effect of grain feed rate on RL (thresher + separator). * MOG refers to materials other than grain index.

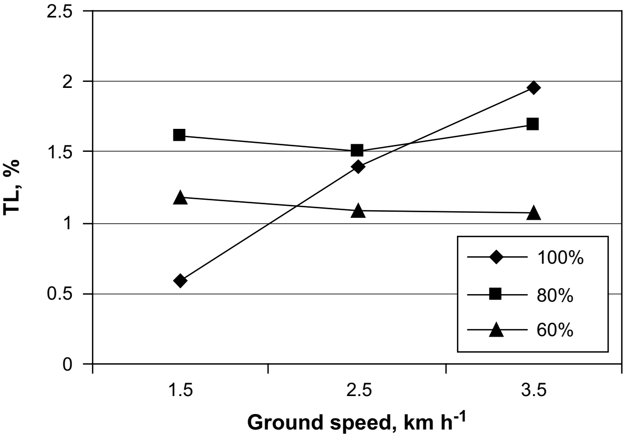

Fig. 5 – Interaction effect of ground speed and ECW on TL.

speed did not alter the TL, but it was still high. By increasing the ground speed, the effects of increasing RL on TL were somehow compensated for by decreases in HL. Therefore TL were unaffected by ground speed. Finally, if the ECW was decreased to 60%, increasing ground speed moderately decreased the TL. The lowest TL (0.59% of total yield, equal to 43.78 kg ha^{-1}) occured at the lowest selected ground speed with the full platform width (W_1S_1 alternative). The maximum TL occurred with alternative W_1S_3 with 1.09% of total yield or 145.4 kg ha^{-1}.

3.1.4. *Seed breakage (SB)*

SB slightly decreased when the feed rate increased either by increasing ground speed or increasing ECW. This can be seen in Table 3. However, the interaction between ground speed and ECW on SB was not significant. This is because SB is more susceptible to cylinder (thresher) speed, concave clearance and seed moisture content than feed rate (Kepner et al, 1978).

3.2. *Combine field capacity (CFC) and fuel consumption (FC)*

As was expected, increasing in ground speed and ECW resulted in a higher CFC as well as lower FC. For this reason, and as shown in Table 3, the W_1S_3 alternative gave the maximum CFC (0.84 ha h^{-1}) and the minimum FC (19.1 l ha^{-1}).

Table 3 – Matrix of decision making for harvesting of wheat by low-capacity combines

Alternative	Attribute			
	CFC (ha h^{-1})	TL (%)	SB (%)	FC (l ha^{-1})
W_1S_1	0.49	0.59	3.63	32.56
W_1S_2	0.73	1.40	3.16	22.00
W_1S_3	0.84	1.96	2.49	19.15
W_2S_1	0.40	1.61	4.18	40.33
W_2S_2	0.59	1.50	3.45	27.14
W_2S_3	0.68	1.70	2.77	23.58
W_3S_1	0.30	1.18	4.94	53.19
W_3S_2	0.45	1.09	3.88	35.60
W_3S_3	0.52	1.08	3.61	30.84

3.3. *Decision-making analysis*

Results of measurements and calculations of attributes including CFC, TL, SB and FC are shown in Table 3 as the initial matrix of decision making.

3.3.1. *Weight assessment*

Using entropy method, the weight of CFC, TL, SB and FC were calculated as 0.277, 0.289, 0.123, and 0.311, respectively. Hence, the preference vector of second level is:

$$w_j = \{0.277, 0.289, 0.123, 0.311\} \tag{6}$$

This shows SB had the least role in decision making, but FC can strongly influence the decision-making process.

3.3.2. *Decision ranking and alternative scoring*

The results of data analysis and alternatives ranking, utilising Criterium DecisionPlus (version 3.0.4/S, InfoHarvest Inc., USA) software is shown in Fig. 6. This chart shows the overall score of individual alternatives within the decision model. The alternatives are ranked on the basis of their relative values of the decision scores. The allocated value of each alternative corresponds to the preference of that alternative, i.e., how well that alternative meets the decision goal. Conceptually, the decision score of an alternative is the sum of its rating against each lowest criterion, weighted by the relative importance of those attributes. Considering this chart, alternative W_1S_3 earned the maximum score. It means that the decision-making system selected this alternative as the best decision for this field condition (7.4 t ha^{-1} and 7.5% seed moisture content).

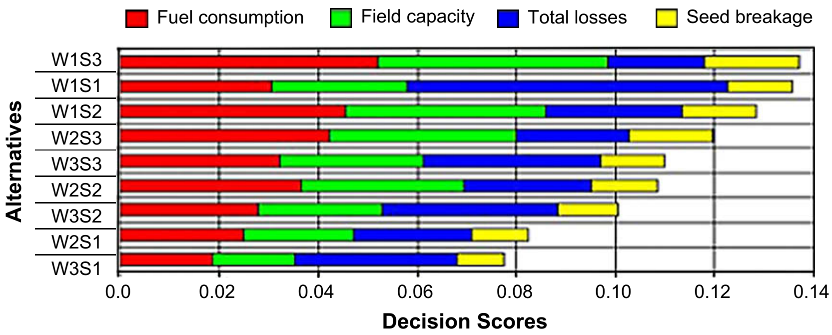

Fig. 6 – Ranking different alternatives of wheat harvesting for a farm with 7.4 t/ha yield and 7.5% seed moisture content.

It is interesting to note that the first three top scored alternatives are those using the entire cutter bar. Thus, despite of common farmer opinion, in a high-yield farm, from economic and technical points of view; the partial use of platform is not the most appropriate recommendation. The MADM showed that although RL decreases with partial use of platform, on the other hand, more FC and higher HL reduces the total scores obtained.

This ranking chart also shows the effectiveness of each criterion on the achieved score of an alternative. For example, W1S3 had the maximum TL score (it has the minimum length for TL among all alternatives) but it earned the high scores from CFC and FC, which could compensate its score deficit and hence achieved the maximum overall scores.

It should be emphasised that MCDM, especially in the area of farm machinery management, is a dynamic and seeking system with a flexible framework, which assists the DM to maximise his/her profit simultaneously from all interested attributes. The DM may use this framework as guidance to choose the best alternative from top scored alternatives, based on any change in conditions and the importance of attributes.

3.3.3. *Sensitivity analysis*

The *DecisionPlus* software can also be employed to explore the sensitivity of alternatives to the attributes. As examples, Figs. 7 and 8 show the sensitivity of the five most critical alternatives to TL and FC, respectively. The same graphs can also be created for other attributes including SB and CFC, to assess the sensitivity of alternatives to any interested attribute. The interpretation of such graphs is straightforward. For clarity Fig. 7 is explained with more details. The horizontal axis represents the weight of attribute under study. As mentioned before, this attribute (TL) earned the highest weight (0.289, which was rounded to 0.29), among other attributes. If a vertical line is drawn from this value to intersect the inclined lines which represent the indices of five critical alternatives and then a horizontal line from this intersection to intersect the vertical axis, gives the earned score of each alternative. If the position of this vertical line is changed from the current weight value of the attribute along the horizontal axis, it means the priority of this attribute is changed. Because the alternatives have different slopes, then the earned score of the alternative may be altered and hence the order of their preference will be changed. In this case, it can be observed that, if the weight of TL was more than 0.31, the rank of alternative W_1S_1 would swap with that of W_1S_3. If required, the same procedure can be performed on the sensitivity chart of other attributes to explore the sensitivity of other attributes to the alternatives.

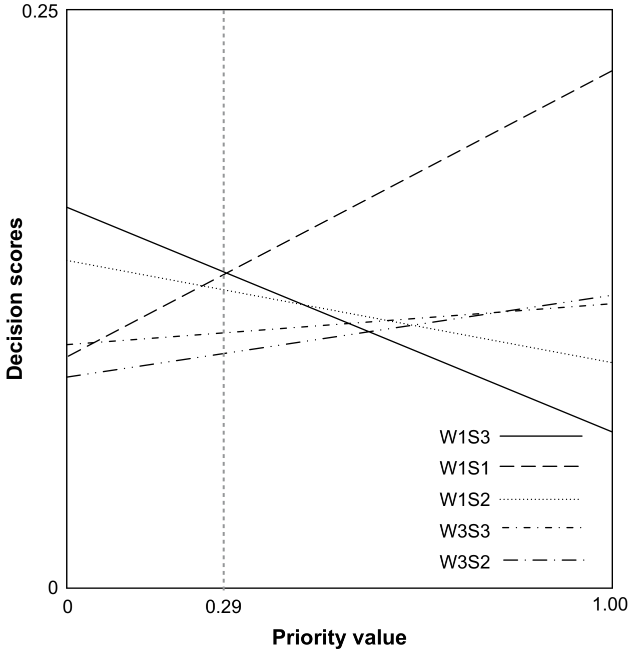

Fig. 7 – Sensitivity of alternatives to the TL attribute. The current priority (weight) is 0.29.

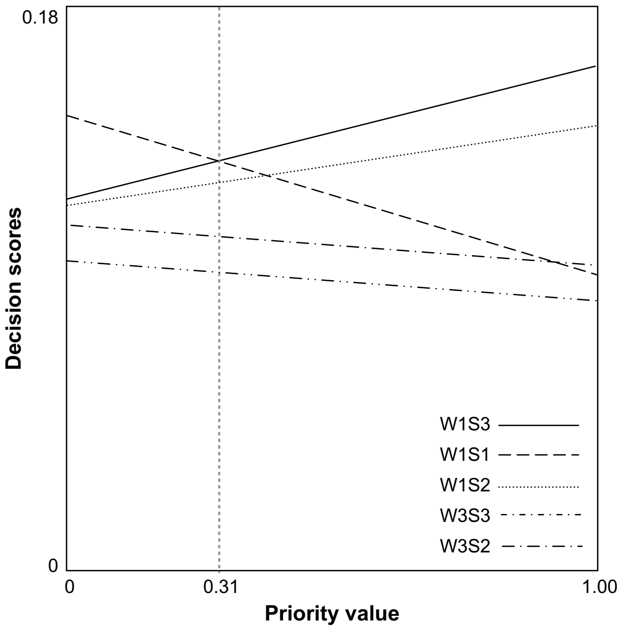

Fig. 8 – Sensitivity of alternatives to the FC attribute. The current priority (weight) is 0.31.

4. Conclusion

The MCDM technique was employed to select a better strategy for harvesting high-yield farm with low-capacity combine harvesters. The results of farm observations showed that in a low-capacity combine harvester, increasing in ground speed and/or effective width of platform leads to an increase in RL. With partial use of cutter bar, increasing ground speed resulted decreasing in HL. The HL will be the minimised if the whole width of cutter bar and minimum ground speed is selected as harvesting alternative. The maximum TL occurred with entirely width of the platform used and the maximum ground speed. SB increased with decreasing of feed rate however, the influence of feed rate on SB was not significant.

In spite of the highest TL of alternative W_1S_3, this alternative was preferred as an optimum strategy for harvesting a field with 7.4 t ha^{-1} yields. In this regard if the ground speed is maintained as low as 2.96 km h^{-1}, RL will not exceed 1% of the total yield.

According to the prediction of MCDM, if the harvesting condition is changed and the weights of CFC and FC rise to a higher value, a higher ground speed could be suggested. On the other hand if the weight of total loss (TL) reaches 0.31 and beyond, reducing the ground speed to 1.5 km h^{-1} would be the best decision. These predictions from MCDM demonstrate the flexibility of this method for solving agricultural management problems in general and machinery operations in particular. Since the problem investigated is widespread throughout Iran, a comprehensive suitability assessment for harvesting wheat, employing MCDM, could be performed to establish a nationwide mechanisation strategy.

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