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Application of Computer Supported Multi–criteria Decision Models in Agriculture

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SUMMARY

Hierarchical multi criteria decision models (MCDM) are a general decision support methodology aimed at the classification or evaluation of options that occur in a decision-making processes. Decision models are typically developed through decomposition of complex decision problems into smaller and less complex sub-problems; the result of such decomposition is a hierarchical structure that consists of attributes and utility functions. Basic concepts of MCDM together with two multi criteria modeling methodologies (expert system DEX-i and analytical hierarchical process with application of Expert Choice decision support software) are presented and discussed. In order to show how the explained methods can be applied to agricultural decision problems, two applications of MCDM (DEX-i and AHP) for organic spelt processing planning problem are presented in detail.

KEY WORDS

multi criteria decision models (MCDM); expert system DEX-i; analytical hierarchical process (AHP); Expert Choice; spelt processing

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INTRODUCTION

In the last few decades, the agricultural decision makers have gotten accustomed to the use of computers and consequently to the implementation of different complex computer models for solution of various planning problems. This includes decision problems and agricultural project solutions, which have long been predominated by different types of simulation models (Rozman et al., 2002; Pavlovič, 1997) and cost benefit analysis (CBA) as presented by Pažek (2003). However, as reported by Tiwari et al. (1999), reality is complex, and the use of CBA alone may not be sufficient when the decision situation involves consideration of variables which cannot be easily quantified into monetary units and the decision-making process is likely to be influenced by multiple competing criteria. CBA is sometimes also criticized for the limitation that it does not generally take into account the interactions between different impacts. The main difficulty when applying a CBA method is that the evaluation of a project must relate to an unambiguous monetary uni-dimensional criterion, since a comprehensive cost-benefit approach requires all project option effects to be transformed into a single monetary dimension (Rogers et al., 1999). At this point in the decision-making process, the analyst should consider a multi-criteria (objective) decision analysis approach (hereinafter MCDA), which uses hierarchical multi attribute (criteria) decision models and different mathematically based methods for solution of decision problems.

Hierarchical multi-attribute (criteria) decision models (MCDM) are aimed at the classification and (or) evaluation of objects defined in attribute-value space. They are based on decomposition of a complex decision problem into smaller and less complex sub-problems. Sub-problems are represented by variables, which are organized into a hierarchy. Variables are connected by utility functions that serve for the aggregation of partial sub-problems into the overall evaluation or classification of objects (Bohanec et al., 2000). The application of MCDM for solution of agricultural decision problems is extensively discussed in scientific literature (Tiwary et al., 1999; Herrero et al., 1999; Mazetto and Bonera, 2003). The MCDM can use either quantitative or qualitative variables for evaluation of options. Probably the most common used multi criteria decision making approaches, the analytic hierarchy process - AHP (Saaty, 1980) and multi attribute utility theory (Belton and Stewart, 2002) evaluate alternatives in an empirical manner. On the contrary, expert system for multi attribute decision DEX (Bohanec et al., 1995; Bohanec et al. 2000) and his Windows successor DEX-i (Rozman et al., 2006; Pažek et al., 2006) use qualitative variables and utility function in the form of decision rules for evaluation of options.

In this article we present the approach to the development and application of hierarchical multi criteria decision models that are based on AHP and the DEX-i expert system. Section 2 defines basic concepts of hierarchical MCDM. Two selected applications of MCDM using AHP and DEX-i expert system are presented and discussed. A summary and proposals for further study conclude this paper.

MULTI CRITERIA DECISION MODELING METHODOLOGY

The first step in MCDM development is structuring of the decision hierarchy. In general, a hierarchical decision model is composed of attributes Xi and utility functions F_i (Figure 1). Decision attributes (sometimes also referred to as performance variables, parameters, objectives, or criteria) are variables that represent decision sub-problems. They are organized hierarchically so that the attributes that occur on higher levels of the hierarchy depend on lower-level attributes. In theory, a hierarchy is represented by a directed acyclic graph, but in practice it is usually simplified to a tree. According to their position in the hierarchy, we distinguish between basic attributes (leaves or terminal nodes) and aggregate attributes (internal nodes, including the roots of the hierarchy) (Bohanec et al., 2000). Figure 1 shows a multi criteria model developed for selection of spelt (*Triticum spelta*) processing project on organic farms that consists of six basic attributes X_1–X_6, and four aggregate attributes, X_7-X_9 and Y. For each aggregate attribute there is a corresponding utility function F that determines the dependency of that attribute with respect to its immediate descendants in the hierarchy. Options are represented by value a_i of basic attributes. The evaluation of options is performed by an aggregation that is carried out from bottom to the top of hierarchy according to its structure and defined utility functions. The overall evaluation (also called utility) of an option is finally represented by the value of one or more root attributes (Y in Figure 1).

Decision models are primarily developed for *option evaluation*: each option (described by values of basic attributes) is evaluated according to the model. This yields an overall evaluation for each option. Based on this, the options are compared and ranked and the best one can be eventually identified and chosen by the decision-maker. After the hierarchy has been selected the next step that the analyst must take, is to choose a multi criteria modeling methodology. In the following case study we highlight the application of expert system for multi attribute decision making DEX and AHP based decision support system Expert Choice (EC), which are particularly interesting and useful for the applications in agriculture and farm management.

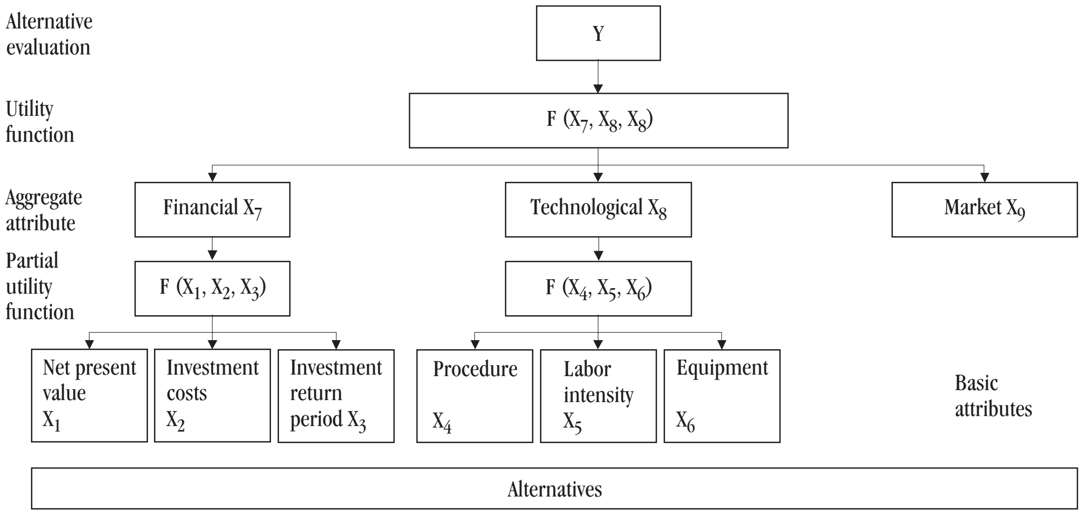

Figure 1.
The attribute tree for the spelt processing problem and decision model structure (Bohanec et al., 2000; Rozman et al., 2005)

Expert system DEX-i

DEX is an expert system shell for qualitative multi-attribute decision modeling and support. During the last decade it has been applied over fifty times in complex real-world decision problems, including agriculture (Bohanec and Rajkovič, 1999; Rozman et al., 2005). The expert system DEX (MS DOS) and his Windows successor DEX-i (DEX for Instruction) combine the "traditional" multi-attribute decision making with some elements of Expert Systems and Machine Learning. The distinguishing characteristic of DEX-i is its capability to deal with *qualitative* models. Instead of numerical variables, which typically constitute traditional *quantitative* models, DEX-i uses qualitative variables; their values are usually represented by words rather than numbers, for example "low", "appropriate", "unacceptable", etc. Furthermore, to represent and evaluate utility functions DEX uses *if-then decision rules*. In contrast, this is traditionally carried out in a numerical way, using weights or similar indicators of attributes' importance (Bohanec and Rajkovič, 1999). The procedure of DEX (DEX-i) modeling for organic spelt processing is carried out in following steps:

1. Definition of alternatives, problem decomposition and hierarchy

The organic farm in North Eastern Slovenia considering spelt processing for direct marketing defined four possible agribusiness alternatives (A1…A4), each related to investment into specific processing equipment:

A1: Spelt husking and selling spelt grain in small packages

The husks must be removed in order to market spelt grain. This can be done either by service hiring or by the purchase of the own husking machine – this alternative is considered here.

A2: spelt bread production

A3: spelt cookies

A4: spelt flour

The problem was decomposed into following hierarchy (see Figure 1):

- Financial (net present value of each alternative, initial investment costs, and invested return period). The financial indicator for each alternative were calculated using a food processing simulation model EKOSIM 1.0 for investment planning on organic farms (for details see Pažek (2003) and Pažek et al. (2004)).
- Technological. The technological objective consists of labor intensity, equipment requirements and complexity of production procedure.
- Market. The market attribute describes consumer preference for each spelt product. For relevant estimation of this attribute a marketing study should be conducted, if observed expert judgments and experience were used for the estimation.

2. Definition of possible qualitative attribute values for each attribute

Each attribute is assigned with a set of possible qualitative values (scales or intensities). Numerical attributes (such as financial etc.) are categorized using classification intervals. For instance, the basic attribute net present value can be categorized using following algorithm:

"if NPV > A and NPV < B then NPV is assigned with qualitative value C "

Where:
A - lower boundary of a classification interval
B - upper boundary of a classification interval
C - qualitative value for {A…B}interval

3. Definition of decision rules (utility function)

The utility function is defined through the entire hierarchy for each aggregate attribute. The utility functions in DEX are described with a set of decision rules (Figure 2). The decision rule describes value of an aggregate attribute for each combination of input attributes and expresses the relative importance of individual attributes. For a less detailed representation of utility functions the *weights* can be used. Given a decision rule (such as in Figure 2), we use some suitable method to estimate the average importance of each input attribute for determining the value of dependent variable. We then obtain weights by expressing this importance as percentages relative to each other attributes. Two methods are used to assess weights with DEX: one is based on regression and the other on measuring attribute informativity as in machine learning methods (Bohanec et al., 2000).

Using the *regression*, a decision rule is interpreted as a set of points in a multi-dimensional space and approximated with a hyperplane in that space. Let $x_{1...}x_n$ represent the input attributes (financial, etc.) and y, the dependent variable, which is required to be ordered. For the purpose of this method, all qualitative values of attributes are represented by their ordinal numbers. Accordingly, we can interpret a decision rule as a collection of points and approximate them by a hyperplane. That means that we find the coefficients a_0, $a_{1...}a_n$ so that the approximation is optimal in the least-squares sense. The regression equation is as follows:

$$Y = a_0 + a_1x_1 + \ldots + a_nx_n \qquad (1)$$

Where:
$a_{1...}a_n$ - regression coefficients
$x_{1...}x_n$ - ordinal values of attributes

From now onwards, a_0 is usually omitted from the representation and $a_{1...}a_n$ are transformed into weights by representing them as relative percentages as shown in equation 2:

$$w_i = \frac{100a_i}{\sum_{j=1}^{n} a_j}; \quad i = 1, 2, \ldots, n \qquad (2)$$

Where:
w_i - weight (relative importance of attribute i)

As an alternative method for the estimation of weights the *informativity* can be used (Bohanec et al., 2000), a method used in machine learning algorithms to identify the most relevant attributes (Quinlan, 1993). This measure is based on the information theoretic measure of entropy, $-p_i \log_2 p_i$, where p_i is the probability of the ith event.

The decision rules for the organic spelt processing problem (Figure 2) are presented in complex form, where '*' means any value and >= means equal or better.

4. Option evaluation

Finally, the attribute values for each alternative are put into the DEX-i input table and evaluation is performed.

The AHP (EC) model

The AHP is a decision-aided method which de-composes a complex multi-factor problem into a hierarchy, where each level is composed of specific elements. The general validity of the AHP, and the confidence placed in its ability to resolve multi-objective decision situations, is based on the many hundreds (now thousands) of diverse applications in which the AHP results were accepted and used by the cognizant decision makers for solutions of various decision making problems such as environmental decision making (Tiwari et al., 1999), resource allocation (Forman and Selly, 2002) or project management (AL-Harbi, 2001). The Analytical Hierarchal Process (AHP) is best illustrated by Saaty (1980). The AHP is a decision support tool, which can be used for solving complex decision problems. It uses a multi-level hierarchical structure of objectives, sub-objectives, and alternatives (Triantaphyllou and Mann, 1994). The variants are decomposed into specific parameters (criterion, attribute) and evaluated separately for each single parameter. Pros and cons as well as other influencing factors can be included as well. The final variant evaluation is provided with combine proceeding. Ratio comparisons are performed on a fixed ratio scale. The goal is defined as a statement of the overall objectives. For the precise accountant, who only wishes to deal with finite numbers, AHP allows decision-makers to derive ratio scale priorities as opposed to randomly assigning them. The AHP is a decision-aided method which enables the decision makers to incorporate both the subjective and objective matters into the decision making process. This is done by describing complexity as a hierarchy and ration through comparison of alternatives relative to the objective (called pair-wise comparison). However, at each level of the hierarchy, the relative importance of each component attribute is assessed by comparing them in pairs. The rankings obtained throught the pair-wise comparisons between the alternatives are converted to normalised rankings using the *eigenvalue* method. The pair-wise comparison reflects the estimates made by the decision maker of the relative importance of each alternative in terms of a given decision criterion. A typical problem examined by the AHP consists of a set of alternatives and a set of decision objectives (criteria, attributes). In applications of the AHP to real decision-making problems, the entries in the above reciprocal matrix are taken from the finite set: {1/9, 1/8,…1, 2,…8, 9}

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Decision rules (table)

	Financial indicators	Technological indicators	Market criteria	Spelt processing
	44%	21%	34%	
1	poor	*	*	unacceptable
2	*	*	poor	unacceptable
3	good	*	moderate:good	acceptable
4	>=good	unacceptable	moderate:good	acceptable
5	>=good	*	moderate	acceptable
6	>=good	unacceptable	excellent	good
7	>=good	acceptable	excellent	excellent
8	excellent	acceptable	>=good	excellent

	NSV	Investment costs	Investment return period	Financial indicators
	58%	21%	21%	
1	low	<=moderate	*	poor
2	low	*	<=average	poor
3	<=moderate	very high	*	poor
4	<=moderate	<=high	<=average	poor
5	<=moderate	<=moderate	<=long	poor
6	<=moderate	*	very long	poor
7	<=high	very high	very long	poor
8	very high	>=moderate	short	excellent
9	very high	low	>=average	excellent

	Labor intensity	Procedure	Equipment requirements	Technological indicators
	43%	29%	28%	
1	very high	<=demanding	*	unacceptable
2	very high	<=moderate	<=2	unacceptable
3	very high	*	<=3	unacceptable
4	<=high	very demanding	*	unacceptable
5	<=high	<=demanding	<=2	unacceptable
6	<=high	<=moderate	<=3	unacceptable
7	<=high	*	<=4	unacceptable
8	<=moderate	very demanding	<=3	unacceptable
9	<=moderate	<=demanding	<=4	unacceptable
10	<=moderate	<=moderate	5	unacceptable
11	*	very demanding	<=4	unacceptable
12	*	<=demanding	5	unacceptable
13	*	>=moderate	1	acceptable
14	*	simple	>=2	acceptable
15	>=high	>=demanding	1	acceptable
16	>=high	>=moderate	>=2	acceptable
17	>=high	simple	>=3	acceptable
18	>=moderate	*	>=2	acceptable
19	>=moderate	>=demanding	>=3	acceptable
20	>=moderate	>=moderate	>=4	acceptable
21	>=moderate	simple	*	acceptable
22	low	*	>=3	acceptable
23	low	>=demanding	>=4	acceptable
24	low	>=moderate	*	acceptable

Figure 2. Decision rules with weights for organic spelt processing problem (DEX-i print out)

(as suggested by Saaty (1980)). In practice, the above discrete set is usually used. Saaty (1980) and Saaty and Kearns (1991) developed the following steps for applying the AHP:

1. Define the problem and determine its goal. The goal in the presented case is selection of spelt processing business alternatives on organic farms.
2. Structure the hierarchy from the top (the objectives from a decision-maker's viewpoint) through the intermediate levels (objectives on which subsequent levels depend) to the lowest level, which usually contains a list of alternatives (Figure 1).
3. Construct a set of pair-wise comparison matrices (size n x n) for each of the lower levels with one matrix for each element in the level immediately above by using the relative scale measurement. The pair-wise comparisons are done in terms of which element dominates the other.
4. There are judgments required to develop the set of matrices in step 3. Reciprocals are automatically assigned in each pair-wise comparison.
5. Hierarchical synthesis is now used to weight the *eigenvectors* by the weights of the objectives and the sum is taken over all weighted *eigenvector* entries corresponding to those in the next lower level of the hierarchy.
6. Having made all the pair-wise comparisons, consistency is determined by using the *eigenvalue*, $ë_{max}$, to calculate the consistency index, CI as follows: CI = ($ë_{max}$ - n) / (n - 1), where n is the matrix size. Judgment consistency can be checked by taking the consistency ratio (CR) of CI with the appropriate value. The CR is acceptable, if it does not exceed 0.10. If it is more, the judgment matrix is inconsistent. To obtain a consistent matrix, judgments should be reviewed and improved.
7. Steps 3–6 are performed for all levels in the hierarchy.

Fortunately, there is no need to implement the steps manually. Professional commercial software, Expert Choice, developed by Expert Choice, Inc., is available on the market which simplifes the implementation of the AHP's steps and automates many of its computations. For the spelt processing problem we used the same hierarchy as in the DEX-i decision model (Figure 1). The relative importance of each criterion (attribute) and alternative priorities (alternative weights) were with eigenvector normalization of pair-wise comparison matrices. The Expert Choice software also enables the entering of attribute through the so called Data Grid. The use of the Data Grid (Figure 3 and 4) combines the power of the hierarchy and the pair-wise comparison process with the ability to evaluate hundreds or even thousands of alternatives. Pair-wise comparisons are still used to evaluate the elements in the hierarchy itself, but not for evaluating the alternatives. Alternatives' priorities are established relatively to each covering objective by using ratio scaled rating intensities (scales). This procedure can be particularly useful with large number of alternatives to be evaluated; there is no need to compare alternatives in the pairwise manner; the values are put directly into the Data Grid and priorities are calculated based on pair wise comparison of intensities. In the case observed, the same ratings scales (intensities) were used as in the DEX-i decision model.

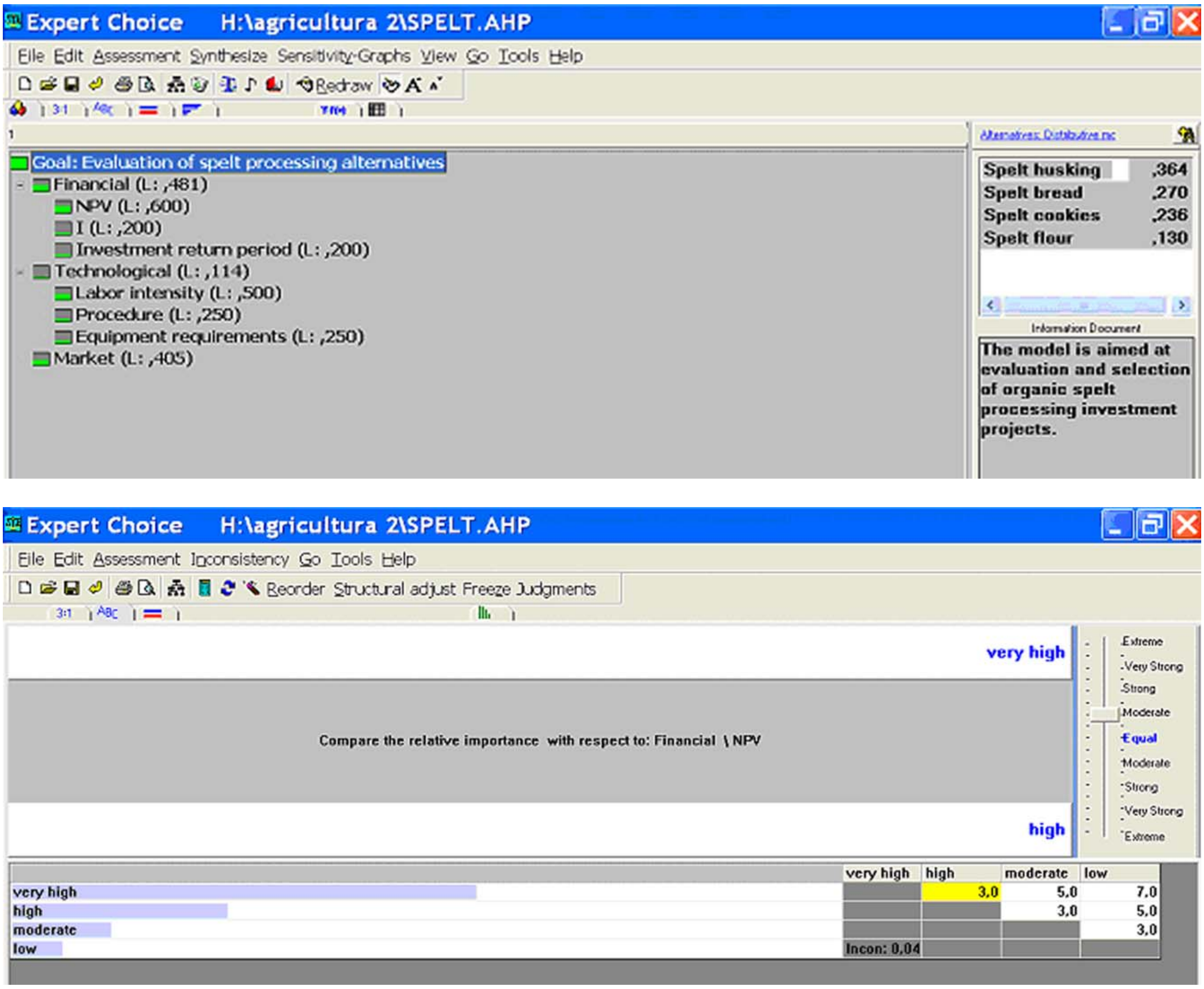

Figure 3. AHP hierarchy with derived weights and pair-wise comparison of intensities in Expert Choice software for financial attribute 'Net present value'

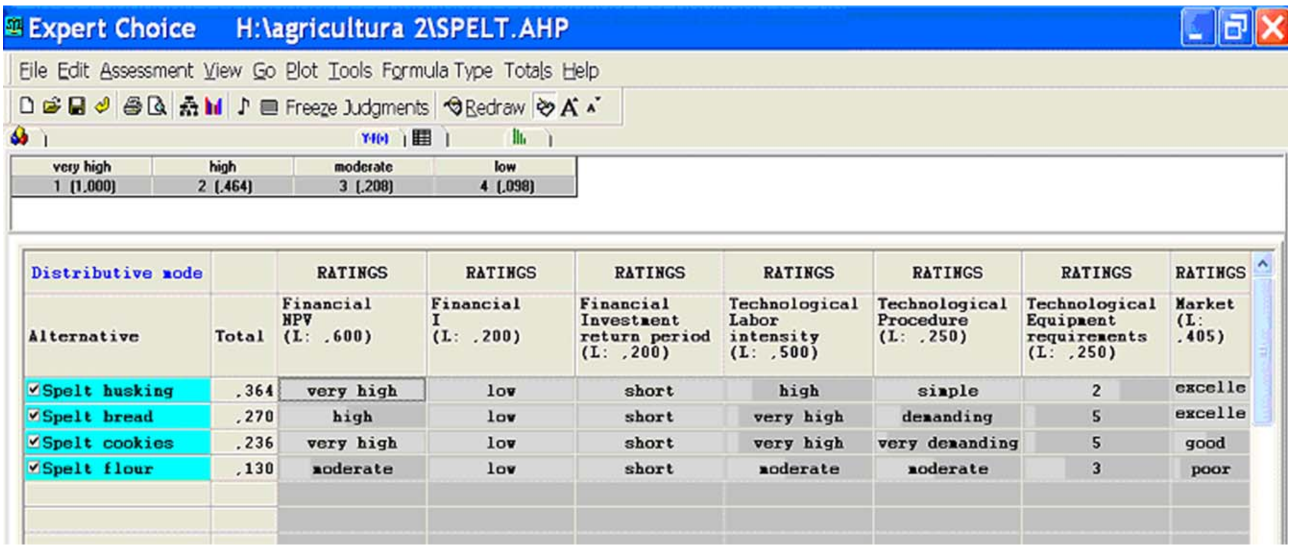

Figure 4. Data grid with derived total alternative priorities

EVALUATION RESULTS AND DISCUSSION

As mentioned earlier the financial and technological analysis (Table 1) was performed using organic food processing simulation model EKOSIM 1.0 (Pažek, 2003).

The simulation model can also provide enough information for derivation of remaining attributes such as labor intensity. The remaining attributes were estimated by the decision maker (farm operator) or using some other source. The simulation results were further evaluated with described MCDM methodologies (Figure 6).

The DEX-i and AHP evaluation (EC) show the same ranking of organic spelt processing alternatives. The most suitable alternative is spelt grain processing, which got the highest evaluation (EC = 0.364; DEX-i assessment = *excellent*), followed by on farm spelt bred production (EC = 0.270; DEX-i assessment = *good*), spelt cookies production (EC = 0.236; DEX-i assessment = *acceptable*), and finally spelt flour production which yields with the lowest evaluation (EC = 0.130; DEX-i assessment = *unacceptable*). The poor ranking of spelt flour can be contributed to *poor* input value of marketing attribute. Compared to an another applied MCDA decision approach (DEX-i), the AHP based Expert Choice model presents more detailed, but similar ranking of alternatives. The relative importance weights of aggregate attributes derived by AHP (as results of pair-wise comparisons) and DEX – i (derived on the basis of analyst estimated decision rules) are principally not different (see Figures 3 and 4). Furthermore, the AHP allows us to manage inconsistencies in pair-wise judgments, while inconsistencies in decision rules can sometimes be difficult to find, especially in the case of a very large number of decision rules (in the observed case there are 24 decision rules for the business project evaluation while there are 64 decision rules for aggregate financial attribute). On the other hand, the DEX-i with its qualitative modeling and the ability to handle inaccurate and/or incomplete data about options appears to be particularly convenient for decision problems that involve qualitative concepts and a great share of expert judgments. Likewise, the DEX-i assessment can be used for exclusion of "unacceptable" alternatives (as demonstrated in Figure 5). In contrast, the AHP evaluation results in a single number (total priority) and does not exclude any alternatives. The shortcoming of DEX-i is also its inability (in contrast to

Table 1. Financial CBA analysis of the planned spelt processing projects on a sample farm (after 10 years, discount rate =14%)

Product	Quantity (kg/year)	Investment costs (€)	Net Present Value (€)	Investment return period (years)
Spelt grain	2400	2759	15784	1
Spelt bread	2700	5279	3797	5
Spelt cookies	2160	4315	109189	1
Spelt flour	2160	1416	9875	2

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Evaluation results

Attribute	Spelt grain	Bread	Cookies	Flour
Spelt processing	*excellent*	good	acceptable	**unacceptable**
Financial indicators	*excellent*	good	*excellent*	good
NSV	*very high*	high	*very high*	moderate
Investment costs	*low*	*low*	*low*	*low*
Investment return period	*short*	*short*	*short*	*short*
Technological indicators	*acceptable*	**unacceptable**	**unacceptable**	*acceptable*
Labor intensity	high	**very high**	**very high**	moderate
Procedure	*simple*	demanding	**very demanding**	moderate
Equipment requirements	*2*	**5**	**5**	3
Market criteria	*excellent*	*excellent*	good	**poor**

Figure 5. DEX- evaluation results (DEX-i print out)

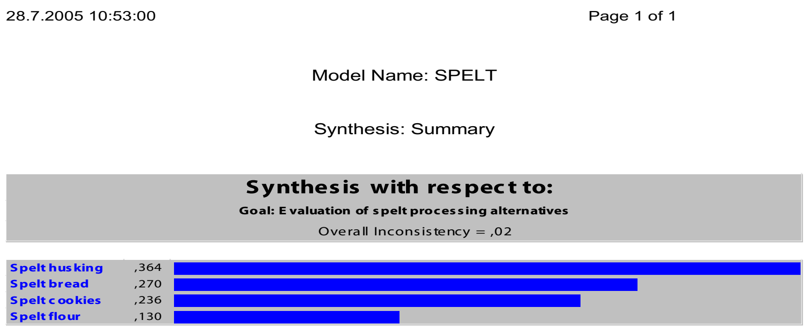

Figure 6. AHP evaluation of alternatives - Expert Choice printout

AHP) to separate between alternatives with the same qualitative evaluation. The use of both approaches can bring additional information into the decision-making framework (for instance the "unacceptable" alternatives can be excluded with the use of the DEX-i model, while the precise ranking of remaining alternatives is based strictly on the AHP Expert Choice model). It should also be noted here that both MCDA methods favored spelt grain processing, while for spelt cookies production the highest estimated NPV was revealed.

CONCLUSION

Hierarchical decision models are increasingly used within agriculture and farm management. For practical applications, it is particularly important that these models and supporting decision-making tools (such as DEX-i and AHP presented in this paper), allow the structuring of domain knowledge and are also capable of dealing with qualitative variables and utility functions. Furthermore, they represent a methodologically sound and (in combination with the use of computers) an efficient decision support tool in farm management applications. All these features provide a foundation for a systematic, transparent, and justified decision-making, which is especially important for complex multi objective decision problems with conflicting goals that often occur in agriculture and farm management. A real life application (selection of spelt processing alternative on the organic farm) demonstrates the applicability, advantages and shortcomings of both presented multi criteria modeling approaches. We believe, that the application of the proposed decision support system (combination of AHP and DEX-i model) would increase the accuracy of information needed for developing farm business plans and that in addition it would help preventing many inappropriate decisions being made on family farms.

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