A decision support system for fuzzy multi-attribute selection of material handling equipments

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Abstract

Effective use of labor, providing system flexibility, increasing productivity, decreasing lead times and costs are some of the most important factors influencing selection of material handling equipment. In this study, a decision support system (FUMAHES: fuzzy multi-attribute material handling equipment selection) considering these factors for material handling equipment selection is developed. FUMAHES consists of a database, a rule-based system and multi-attribute decision making modules. This database includes detailed data about equipment types and their properties. The rule-based system module provides rules, which are utilized by inference engine for determining the most proper material handling equipment type. Ultimately, a final decision is made for the most proper equipment among the alternatives of the same type using the information axiom of axiomatic design principles. Evaluation of alternatives is made for the cases of both complete and incomplete information. This paper also introduces a fuzzy information axiom approach and uses it in the selection of material handling equipment in a real case.

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1. Introduction

Material handling equipment selection is an important activity in the design of an effective manufacturing system design. Selecting appropriate material handling equipment can decrease manufacturing lead times, increase efficiency of material flow, improve facility utilization and increase productivity. Material handling can account for 30–75% of the total cost, and efficient material handling can be primarily responsible for reducing a plant’s operating cost by 15–30% (Sule, 1994). Therefore, determination of proper material handling system is very important for reduced costs and increased profits. As a wide variety of equipment is available today, each having distinct characteristics and cost that distinguish from others, determination of the proper equipment for a designed manufacturing system is a very complicated decision.

In the literature, there are various studies focused on the solution of this complicated problem. Intelligent computer systems have been developed such as expert systems and decision support systems for the selection of material handling equipments. One of the most successful applications of experts systems is SEMH: selection of equipment for material handling. SEMH searches its knowledge base to recommend the degree of mechanization, and the type of material handling equipment to be used, based on some characteristics, i.e. type, weight, size, etc. (Fonseca, Uppal, & Greene, 2004). Malmborg, Agee, and Choudhary (1987) have developed a prototype expert system considering 17 equipment attributes and 47 devices for industrial truck type selection. Fisher, Farber, and Kay (1998) have introduced MATHES: material handling equipment selection expert systems for the selection of a material handling equipment from 16 possible choices. MATHES including 172 rules considers path, material flow volume, unit sizes and distance between departments as parameters. Swaminathan, Matson, and Mellichamp (1992) have developed EXCITE: expert consultant for in-plant transportation equipment addressing 35 equipment types, 28 material, move and method attributes.

Chu, Egbelu, and Wu (1995) have provided a computer-aided material handling equipment selection system

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including an economic analysis in the decision-making process. Park (1996) has developed ICMESE: intelligent consultant system for material handling equipment selection, including 50 equipment types and 29 attributes, i.e. move attributes, material characteristics, operational requirements and area constraints. Kim and Eom (1997) have introduced MAHSES: material handling selection expert system. It consists of two modules and first one deal with the selection of material handling alternatives for electronic assembly. Chan, Ip, and Lau (2001) have developed an intelligent material handling equipment selection system called MHESA: material handling equipment selection advisor. In this study, an expert system has been integrated with analytic hierarchy process (AHP). Fonseca Uppal and Greene (2004) have been developed a prototype computer-based system to select suitable conveyor solutions from a list of 76 conveyor types. The system ranks the conveyor types on the basis of their suitability scores, computed through the weighted evaluation method and the expected value criterion.

Existing expert systems for the selection of material handling equipment have several limitations. Most of these systems do not consider all of the technical, strategic and economic criteria simultaneously in the selection of most appropriate equipment. These systems also cannot evaluate the alternatives for the cases of both complete and incomplete information. Approaches that include more than one measure of performance in the evaluation process are termed multi-attribute or multi-criteria decision methods. The advantage of these methods is that they can account for both financial and non-financial impacts. Among these methods, the most popular ones are scoring models (Nelson, 1986), AHP (Kahraman, Cebeci, & Ruan, 2004), analytic network process (ANP) (Buyukozkan, Ertay, Kahraman, & Ruan, 2004) utility models (Sloggy, 1984), TOPSIS (Deng, Yeh, & Willis, 2000) and outranking methods (De Boer, Van Der Wegen, & Jan Telgen, 1998). Axiomatic design principles including the information axiom also presents an opportunity for multi-attribute evaluation (Suh, 2001). A new model based on this axiom is generated to support decision-makers in material handling equipment selection process. In order to avoid the pitfalls of preceding methods, AD based method enables decision-makers to evaluate both qualitative and quantitative criteria together.

Many AD applications in designing products, systems, organizations and software have appeared in the literature in the last 10 years. Suh (1990) has pioneered the AD theory and principles. Kim, Suh, and Kim (1991) have implemented AD principles on software design. AD principles have also been used in design of quality systems (Suh, 1995) and general system design (Suh, 1997). Suh, Cochran, and Paulo (1998) have provided a manufacturing system design using AD principles. AD principles have also been applied in designing flexible manufacturing systems (Babic, 1999). Chen, Chen, and Lin (2001) have proposed a knowledge-based decision support system using independence axiom of AD in order to improve cell performance. Kulak, Durmusoglu, and Tufekci (2005) have provided a road map for designers to transform their traditional production system from process layout to cellular layout, based on AD principles. Kulak and Kahraman (2005a) have applied multi-attribute AD and AHP approaches for the selection of proper transportation company under determined criteria (such as cost, time, damage/loss, flexibility and documentation ability). Kulak and Kahraman (2005b) have also provided the comparison of advanced manufacturing systems using second axiom. These studies have convincingly shown the applicability and benefits of AD in solving industrial problems.

In this paper, a decision support system (FUMAHES) for the selection of material handling equipment meeting the designer requirements is introduced and the application process is shown using a real application. In Section 2, the system structure of FUMAHES is presented in detail. In Section 3, AD principles including crisp and fuzzy information axiom is illustrated for multi-attribute decision module. An application processes to material handling equipment selection is shown in Section 4. Finally, the results of the system are summarized and the area for future research is suggested.

2. System structure of FUMAHES

Expert systems are programs in which domain knowledge about a problem is embodied in a set of modular chunks, known as rules, frames, objects, or scripts, that are stored in a repository called a knowledge base. FUMAHES, which is developed in order to simplify the selection process of the most appropriate material handling system, consists of the following modules (see Fig. 1).

2.1. Introduction modules

The FUMAHES consists of material handling equipment information module (IM), axiomatic design and principles IM, and expert systems IM. User is provided with detailed information in the above given user-guide modules about the system.

2.2. Database for material handling equipments

In the literature, material handling equipments are classified into main groups of industrial trucks, conveyors, automated guided vehicles, cranes, industrial robots and storage/retrieval systems (Sule, 1994). This module includes examples of 40 move equipment types and six storage equipment types with their performance criteria (Table 1).
2.3. Database for manufacturing system requirements

This module includes the relevant data of material-handling equipment attributes from the literature. The data mentioned in Table 2 should be entered into the system accurately and in a reliable way for selection of the equipment for the production system.

2.4. Knowledge base

FUMAHES includes 142 rules in the knowledge base, assuming a 100% confidence factor. These rules are acquired from manufacturing systems experts and the literature about material handling equipments. Arity PROLOG language is used so that FUMAHES system will not be badly influenced by the variations in the methods or the changes in the knowledge base. The inference mechanism can also be updated easily. Some examples of knowledge base rules, which are in accordance with IF–THEN structure, are presented below.

Rule 27:

IF Function type_move and
   Move area and path_fixed and

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Material handling equipment types</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Industrial trucks</td>
</tr>
<tr>
<td>2</td>
<td>Conveyors</td>
</tr>
<tr>
<td>3</td>
<td>Automated guided vehicles (AGV)</td>
</tr>
<tr>
<td>4</td>
<td>Cranes</td>
</tr>
<tr>
<td>5</td>
<td>Storage/retrieval systems</td>
</tr>
<tr>
<td>6</td>
<td>Robots</td>
</tr>
</tbody>
</table>

   Handcart, tier platform truck, hand lift truck, power-driven handtruck, power-driven platform truck, forklift truck, narrow-aisle trucks, material lift, tractor-trailer train, drum truck, drum lifter
   Belt conveyor, roller conveyor, chute conveyor, slat conveyor, screw conveyor, chain conveyor, plain chain conveyor, trolley conveyor, wheel conveyor, tow conveyor, bucket conveyor, cart-on-track conveyor, pneumatic tube conveyor, overhead monorail conveyor
   Manual load/unload AGV, low-lift AGV, high-lift AGV, rugged AGV, roller deck AGV, stationary deck AGV, lift deck AGV
   Stacker crane, tower crane, gantry crane, jib crane
   Unit load AS/RS, man-on-board AS/RS, shelf storage system, pallet rack system, block stocking on floor, block stocking in rack
   Pneumatic robot, electric robot, hydraulic robot, mechanized manipulator
Floor space available
THEN Most proper move type_conveying.

Rule 68:

IF Move type_conveying and
  Individual type_packaged and
  Move direction_horizontal and
  Operation control_uncontrollable and
  Bottom surface_not flat
THEN Most proper conveyor type_Wheel conveyor.

Rule 69:

IF Move type_conveying and
  Individual type_packaged and
  Move direction_horizontal and
  Operation control_controllable and
  Bottom surface_not flat and
  Material weight_X < 100 kg
THEN Most proper conveyor type_Belt conveyor.

2.5. Inference engine

The inference mechanism works in interaction with both
knowldege base and database, searches all material-
handling equipments and determines the most appropriate
one. Simultaneously, the candidate equipment type that will
be evaluated at the multi-criteria decision making module is
determined.

3. Principles of axiomatic design

The most important concept in axiomatic design is the
existence of the design axioms. The first design axiom is
known as the independence axiom and the second axiom is
known as the information axiom. They are stated as follows
(Suh, 1990):

Axiom 1 The independence axiom: Maintain the indepen-
dence of functional requirements
Axiom 2 The information axiom: Minimize the informa-
tion content

The independence axiom states that the independence of
functional requirements (FRs) must always be maintained,
where FRs are defined as the minimum set of independent
requirements that characterizes the design goals (Suh,
2001). In the real world, engineers tend to tackle a complex
problem by decomposing it into sub-problems and attempt-
ting to maintain independent solutions for these smaller
problems. This calls for an effective method that provides
guidelines for the decomposition of complex problems and
independent mappings between problems and solutions.

3.1. Crisp information axiom

The information axiom states that among those designs
that satisfy the independence axiom, the design that has the
smallest information content is the best design (Suh,
2001). Information is defined in terms of the information content,
$I_i$, that is related in its simplest form to the probability of
satisfying the given FRs. $I_i$ determines that the design with
the highest probability of success is the best design. Information content $I_i$ for a given FRi is defined as follows

$$I_i = \log_2 \left( \frac{1}{p_i} \right)$$

where $p_i$ is the probability of achieving the functional
requirement FRi and log is either the logarithm in base 2
(with the unit of bits). This definition of information follows
the definition of Shannon, although there are operational
differences. Because there are $n$ FRs, the total information
content is the sum of all these probabilities. If $I$ approaches
infinity, the system will never work. When all probabilities
are one, the information content is zero, and conversely, the information required is infinite when one or more probabilities are equal to zero (Suh, 1995).

In any design situation, the probability of success is given by what designer wishes to achieve in terms of tolerance (i.e. design range) and what the system is capable of delivering (i.e. system range). As shown in Fig. 2, the overlap between the designer-specified ‘design range’ and the system capability range ‘system range’ is the region where the acceptable solution exists. Therefore, in the case of uniform probability distribution function \( p_i \) may be written as

\[
p_i = \left( \frac{\text{Common range}}{\text{System range}} \right)
\]

(2)

Therefore, the information content is equal to

\[
I_i = \log_2 \left( \frac{\text{System range}}{\text{Common range}} \right)
\]

(3)

The probability of achieving \( FR_i \) in the design range may be expressed, if \( FR_i \) is a continuous random variable, as

\[
p_i = \int_{d_{rl}}^{d_{ru}} p_s(FR_i) dFR_i
\]

(4)

where \( p_s(FR_i) \) is the system PDF for \( FR_i \). Eq. (4) gives the probability of success by integrating the system PDF over the entire design range (i.e. the lower bound of design range, \( d_{rl} \), to the upper bound of the design range, \( d_{ru} \)). In Fig. 3, the area of the common range \( (A_{cr}) \) is equal to the probability of success \( p_i \) (Suh, 2001).

Therefore, the information content is equal to

\[
I = \log_2 \left( \frac{1}{A_{cr}} \right)
\]

(5)
3.2. Fuzzy information axiom

The crisp information axiom approach mentioned before can be used for the solution of decision-making problems under certainty. This approach cannot be used with incomplete information, since the expression of decision variables by crisp numbers would be ill defined. For this reason, multi-attribute fuzzy information axiom is developed by Kulak and Kahraman (2005a,b). At the same time, a problem including both crisp and fuzzy criteria can be solved by integrating crisp and fuzzy AD approaches. This feature is an important advantage which cannot be found in other multi-attribute approaches. The definition and formulation of the developed fuzzy approach are given in the following.

The data relevant to the criteria under incomplete information can be expressed as fuzzy data. The fuzzy data can be linguistic terms, fuzzy sets, or fuzzy numbers. If the fuzzy data are linguistic terms, they are first transformed into fuzzy numbers. Then these numbers (or fuzzy sets) are assigned crisp scores. The following numerical approximation systems are proposed to systematically convert linguistic terms to their corresponding fuzzy numbers. The system contains five conversion scales (Figs. 4 and 5).

In the fuzzy case, we have incomplete information about the system and design ranges. The system and design range for a certain criterion will be expressed by using ‘over a number’, ‘around a number’ or ‘between two numbers’. Triangular or trapezoidal fuzzy numbers can represent these kinds of expressions. We now have a membership function of triangular or trapezoidal fuzzy number (TFN), whereas we have a probability density function in the crisp case.

4. An application of FUMAHES

4.1. Determination of most proper equipment type

The observed current manual material handling system does not provide simple and continuous material flow in a textile manufacturing system. Therefore, excessive non-value adding times and work-in-process increase production lead times. In order to decrease these lead times, the materials must be handled from one department to another effectively.

Decision-makers start on an important project to integrate an efficient material handling equipment to the manufacturing system. The user inputs the data on required equipment attributes following the search path constructed in the knowledge base. This data consists of the attributes related to movement, material, operational and area constraints. Fig. 7 shows an illustrative user screen.

FUMAHES then matches its knowledge to the specific values of attributes input by the user and recommends a plain chain conveyor with the alternatives as most proper equipment type (see Fig. 8). Table 3 illustrates the important criteria of the six equipment categories built in FUMAHES.

4.2. Selection of most proper conveyor

In this section, the decision-maker determines the most proper equipment among the alternatives of the same type using the multi-attribute decision-making module.

4.2.1. Crisp information axiom approach

This approach is used when all values are crisp. Each criterion is defined as a functional requirement for
the decision-makers, who intend to choose the proper material handling system. The criteria proposed in the selection process are categorized into groups of costs and technical characteristics. The group of costs includes fixed and variable costs per hour. The group of technical characteristics consists of conveyor speed, item width, item weight and flexibility. Maximum conveyor length is excluded since the values of these criteria are the same for each candidate. The company’s design ranges for the above criteria, which expresses the functional requirements (FR) of designer are as follows:

\[ \begin{align*}
\text{FR}_{\text{FC}} & \quad \text{Fixed costs per hour (FC) must be in the range of 1.5–2} \\
\text{FR}_{\text{VC}} & \quad \text{Variable costs per hour (VC) must be in the range of 0.40–0.44} \\
\text{FR}_{\text{S}} & \quad \text{Speed of conveyor (S) must be in the range of 8–10} \\
\text{FR}_{\text{W}} & \quad \text{Item width (W) must be in the range of 10–20} \\
\text{FR}_{\text{IW}} & \quad \text{Item weight (IW) must be in the range of 0–10} \\
\text{FR}_{\text{F}} & \quad \text{Flexibility (F) must be in the range of 16–20}
\end{align*} \]

Alternative conveyors costs and their technical performance scores evaluated by the experts with respect to certain criteria are given in Table 4. The data given in Table 4 are arranged to include the minimum and maximum performance values supplied by the system.

The information content given in Table 5 is calculated for each conveyor using the design and system ranges given above and Eq. (3).

The conveyor (C1) with the minimum information content is selected based on the results given in Table 5. Unfortunately, as the information contents of C1 and C2 conveyors are close to each other, the proper conveyor selection decision is difficult for the decision-maker.
4.2.2. Integrated information axiom approach

All of the criteria about the selection problem does not pure crisp or pure fuzzy in every time. In order to solve these kinds of problems, the integrated information axiom approach which is capable to solve both crisp and fuzzy values in same model during the evaluation process can be used (Kulak & Kahraman, 2005a,b). The properties of this approach, which is not offered by other multi-criteria evaluating methods, provide some advantages in decision-making. In the material handling selection problem presented in this study, fixed and variable costs cannot be defined easily using crisp values. The flexibility in the group of technical characteristics is also a linguistic variable. Therefore, integrated information axiom approach can be implemented to this problem. The company’s design ranges the above criteria are as follows:

- **FR\(_{FC}\)** Fixed costs per hour (€/h) must be low
- **FR\(_{VC}\)** Variable costs per hour (€/h) must be low
- **FR\(_S\)** Conveyor Speed (S) must be in the range of 8–10
- **FR\(_W\)** Item width (W) must be in the range of 10–20
- **FR\(_{IW}\)** Item weight (IW) must be in the range of 0–10
- **FR\(_F\)** Flexibility (F) must be excellent

The system according to experts produces the system range data and uses the linguistic expressions for costs and flexibility as in Table 6. Figs. 9–11 show the membership functions of the linguistic expressions about fixed costs, variable costs and flexibility, respectively. For example in Fig. 11, the decision-maker subjectively evaluates the alternatives with the linguistic term ‘poor’ if these two criteria are assigned a score of (0, 0, 6) over 20; ‘fair’ with a score of (4, 7, 10) over 20; ‘good’ with a score of (8, 11, 14) over 20; ‘very good’ with a score of (12, 15, 18) over 20; ‘excellent’ with a score of (16, 20, 20) over 20.

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### Table 4
System range data for conveyor costs and technical characteristics

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fixed costs per hour (€/h)</td>
</tr>
<tr>
<td>C1</td>
<td>1.5–2</td>
</tr>
<tr>
<td>C2</td>
<td>1.85–2.30</td>
</tr>
<tr>
<td>C3</td>
<td>1.75–2.25</td>
</tr>
<tr>
<td>C4</td>
<td>1.90–2.40</td>
</tr>
</tbody>
</table>

### Table 5
The results of Suh’s information content for conveyors

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Information content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( I_{FC} )</td>
</tr>
<tr>
<td>C1</td>
<td>0.000</td>
</tr>
<tr>
<td>C2</td>
<td>1.585</td>
</tr>
<tr>
<td>C3</td>
<td>1.000</td>
</tr>
<tr>
<td>C4</td>
<td>2.322</td>
</tr>
</tbody>
</table>

### Table 6
The system range data for conveyor costs and technical characteristics

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fixed costs per hour (€/h)</td>
</tr>
<tr>
<td>C1</td>
<td>Low</td>
</tr>
<tr>
<td>C2</td>
<td>Medium</td>
</tr>
<tr>
<td>C3</td>
<td>Medium</td>
</tr>
<tr>
<td>C4</td>
<td>High</td>
</tr>
</tbody>
</table>

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Fig. 9. TFNs for tangible factors (fixed costs).
The information content for conveyors can be computed using Eqs. (3) and (6), the system ranges in Table 6, and the design ranges. The results of information content can be seen in Table 7.

As the conveyor with minimum information content is the most suitable alternative with respect to the designer’s requirements, C2 is selected. As shown in Table 7, the difference between information contents of C2 and C1 conveyors is significant. C4 is eliminated since system and design ranges for fixed costs are not overlapped.

In these approaches, all of the criteria are considered has equal importance on total. The cases with unequal importance may be considered using Equation for information content developed by Kulak and Kahraman (2005a) in future researches.

5. Conclusion

A decision support system FUMAHES, which considers both technical and economic criteria in material handling equipment selection process, is presented in this paper. FUMAHES system is developed by integration of an expert system and multi-attribute decision-making modules. The rule-based system module provides rules, which are utilized by inference engine for determining the most proper material handling equipment type. Ultimately, a final decision is made for the most proper equipment among the alternatives of the same type using the information axiom of axiomatic design principles.

Crisp multi-attribute decision-making (MADM) methods solve problems in which all decision data are assumed to be known and must be represented by crisp numbers. The methods effectively aggregate performance scores. Fuzzy MADM methods have difficulty in judging the preferred alternatives because all aggregated scores are fuzzy data. A multi-attribute integrated information axiom approach including both crisp and fuzzy criteria is proposed in the multi-attribute decision-making module.
FUMAHES has the capability and potential to become a useful design tool for manufacturing system designers in industry. As a future research, a simulation tool can be integrated into represented consultant system to evaluate the performance of the equipment selection process.

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References


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