CASE STUDIES AND APPLICATIONS CONTRIBUTION

A FUZZY KNOWLEDGE BASE OF AN EXPERT SYSTEM FOR ANALYSIS OF MANUAL LIFTING TASKS

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Development of the fuzzy knowledge base of an expert system for analysis of manual lifting tasks (LI~AN) is described. The system, written in MacList and implemented on a DEC-10 mainframe computer, allows a non-expert in the field to utilize the relevant knowledge and apply it to analyze specific work situations. The knowledge base of LIFTAN consists of 85 rules related to risk analysis and 64 rules used to create explanations and messages to the user. The values of the variables used in the fuzzy knowledge base are represented using the linguistic approach. In order to illustrate the practical implementation of the developed knowledge base, an example is shown.

Keywords: Fuzzy knowledge base, Expert system, Risk of overexertion disability, Manual lifting.

1. Introduction

Extensive progress has been made in the past in analyzing and modeling maximum acceptable limits for manual lifting tasks [1, 6, 7, 20]. However, in order to amass a wealth of information in this area [13, 23], a practical method of putting the present knowledge to use is urgently needed.

There appear to be several problems in utilizing the knowledge about human capabilities to perform lifting tasks in industrial practice. First, the standards for safe lifting limits are incomplete, and the exact specifications for a given task cannot be easily established [26]. Second, lifting tasks involve complex and imprecise relationships between the task variables and the human operator’s characteristics [16–18]. Third, it takes years of training and experience to become an expert in the ergonomic evaluation and design of manual lifting tasks. Fourth, although human experts prove to be valuable, they are often expensive.

An alternative approach to the above problem may be offered with help from the field of knowledge engineering and computer technology. Since the knowledge of human experts can be represented via formal computer language structures like rules or frames [2, 11, 12], such an approach calls for the development of an intelligent computer system [3, 4, 8, 24, 27, 28].
This paper outlines the research efforts undertaken at the University of Louisville [15, 18, 19, 22] to develop a fuzzy knowledge base for the expert system (LIFTAN) aimed at evaluation of potential risk of overexertion injury due to manual lifting tasks. The ultimate goal of the LIFTAN system is to allow the non-experts to utilize the existing knowledge in the area of manual handling of loads, and to provide intelligent, computer-aided instruction for industrial engineering students.

2. The anatomy of expert systems

An expert system can be defined as "the embodiment within a computer of a knowledge-based component, from an expert skill, in such a form that the system can offer intelligent advice or make an intelligent decision about a processing function" [10]. Such properties as expertise, symbol manipulation, uncertainty, complexity, and reasoning and explanation appear to be common to almost all definitions [4, 12].

The power of an expert system lies in its knowledge [12], which may be represented, for example, in the form of production rules, or frames. The fact that expert systems allow for the interpretation of symbols, words and phrases makes them practical for application in qualitative or soft fields of knowledge. Certainty or belief factors [4], Bayesian logic, and likelihood ratios [10], are often used to the represent uncertainty. Other methods of assigning certainty values, like those based on fuzzy belief factors [10–12], are also used.

The reasoning or inference mechanism contains the control or meta knowledge that plans the strategy needed to reach a conclusion. An inference mechanism which collects facts directly or through questioning the user and then applies rules in succession until a conclusion is reached, is said to be of forward chaining or data-driven control type. By contrast, backward chaining or goal directed control starts with a hypothesis and proceeds to prove or disprove each hypothesis until a conclusion is found [4].

3. The structure of LIFTAN

The LIFTAN system consists of three major components (modules). These include: (a) a fuzzy knowledge base, (b) an inference mechanism, and (c) a human interface. The fuzzy knowledge base, written using the production rules, provides the expertise to the system. The inference module used in LIFTAN is the General Purpose Inference Engine Expert System (GPIEES), which has both forward and backward chaining capabilities [19]. GPIEES is written in MacLISP [25] and runs on a DEC-10 main frame computer.

The LIFTAN system has the ability to incorporate the degree of certainty, $c_i$, the user may have in his evaluation concerning a specific value of the relevant variable [14]. If the user estimates that the given value is, for example, low, he may also input the degree of belief, or certainty factor, of such an estimate.
Estimates close to 0 would indicate a small degree of certainty in the reliability of the given data while estimates closer to 1 would indicate a greater certainty value.

In addition, various segments of the rule base are assigned different weights. Such weighting factors, $w_i$, show the relative importance that particular segments of the rule(s) play in reaching a conclusion. Values ranging from one to five, with one being the least and five being the most influential, are used for this purpose.

These weighting factors, $w_i$, combined with the certainty values, $c_i$, are used by the system to calculate an output confidence value, $C$, for the reached conclusion. Specifically, this confidence value is calculated as follows:

$$C = \frac{\sum_i (c_i \cdot w_i)}{\sum_i w_i}$$

where the summation is over the set $\{i\}$ of all rule segments that were relied upon in reaching the conclusion.

4. Development of the fuzzy knowledge base for LIFTAN

The output in the present version of the LIFTAN system takes the form of an estimate of 'potential risk of low back disability or injury due to overexertion' which restricts the worker's ability to perform the lifting job.

The fuzzy knowledge module of LIFTAN is rule-based, and consists of a total of 149 production rules. Eighty-five rules relate to risk analysis, while sixty-four rules are used to produce explanations of the reasoning process as well as messages regarding the potential for job redesign, which are communicated to the user through an explanation mode. The problem of risk analysis is divided into two parts, i.e., (1) analysis of the TASK-RELATED RISK (34 rules) and (2) analysis of the OPERATOR-RELATED RISK (51 rules).

The TASK-RELATED RISK mode assesses the potential risk of low back disability to a 'young healthy male' utilizing only the task variables. An 'ideal worker' is characterized as being strong, fit and of general good health. These characteristics provide the worker a low risk profile.

The OPERATOR-RELATED RISK refers to the specific worker. The use of task variables in combination with worker characteristics allow for the systematic analysis of the worker-lifting system. In addition, the above procedure can aid in better matching the job demands to the worker's abilities.

4.1. Selection of input parameters

The most influential factors for the task and work variables used as possible inputs to the system are as follows: (1) load size [kg], (2) frequency of lift [lifts/min], (3) horizontal distance from the body [cm], and (4) heights of lift. Since load size is a central issue in lifting tasks, the rule base was designed with load size as the primary influence on the potential risk.

The worker characteristics selected for use in the knowledge base include: (1) muscular strength, (2) fitness, (3) age. Since research has shown that strength is
directly linked to the amount of weight a person can lift safely, worker's strength is given highest priority. Similarly, as frequency of lift increases, the aerobic capacity of a person becomes more critical. Therefore, fitness, as an indirect measure of aerobic capacity, is also included. Lastly, since strength and aerobic capacity are both functions of age, the age of a worker, is also considered.

5. Linguistic characterization of task and worker variables

In order to account for the natural imprecision inherent to the task and operator variables (15–18), linguistic representations of these variables are used (30–32). The linguistic values (primary terms) of such variables are interpreted as labels for fuzzy restrictions on the values of the specific bases. The specific definitions of the linguistic values represented by fuzzy sets are used in LIFTAN as descriptors for the selected task and operator variables (see Figure 1). It should be noted that the introduction of linguistic values does not prevent the use of precise descriptions in case these are known.

The first linguistic variable, the load size, has four alternative values: (1) light, (2) medium, (3) heavy, and (4) very heavy, to describe the weight lifted. In order to find the specific compatibility functions of the proposed linguistic values, several sources were consulted [13, 23, 26], and the following compatibility or membership functions for the load size were proposed:

\[
\text{light} = \left\{ \frac{1}{1}, 0.8, 0.5, 0.2, 0.1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0 \right\},
\]

\[
\text{medium} = \left\{ 0, 0.1, 0.5, 0.8, 1, 0.75, 0.5, 0.1, 0, 0 \right\},
\]

\[
\text{heavy} = \left\{ 0, 0, 0.2, 0.5, 0.75, 1, 0.75, 0.5, 0.3, 0 \right\},
\]

\[
\text{very heavy} = \left\{ 0, 0, 0, 0, 0.1, 0.5, 0.8, 0.9, 1.0, 1.0 \right\},
\]

where for each element of the paired numbers, for example \(\{\frac{1}{3}\} \) (Eq. (2)) the denominator denotes a value of the base variable (30 kg), while the numerator represents the compatibility (0) of 30 kg with the specific linguistic value, in this example light.

The frequency of lift has three possible linguistic values, i.e.: (1) low, (2) medium, and (3) high. The height of lift consists of six general research categories. These include: (1) floor-to-knuckle, (2) floor-to-shoulder, (3) floor-to-reach, (4) knuckle-to-shoulder, (5) knuckle-to-reach, and (6) shoulder-to-reach, and sufficiently cover the range of lifting heights.

The horizontal distance from the body is classified as either close or far. Close refers primarily to those objects that are either small or within easy reach and can be kept close to the body. The value far refers to large objects or ones which are further removed from the body. The compatibility functions for the above values are shown in Figure 1.
Fig. 1. Linguistic values for the task and operator variables.
The operator variable strength was divided into three categories: (1) average, (2) strong, and (3) very strong. The average category corresponds to the strength values represented by the 50th percentile of male population. The strong category corresponds to the 75th percentile, and very strong implies the 95th percentile. For the purposes of this knowledge base, it was assumed that workers who were under the 50th percentile strength category would not be considered for possible employment in jobs requiring manual lifting.

The operator-fitness variable related to the aerobic capacity [ml O\textsubscript{2}/kg min] can be one of two values: (1) average, and (2) excellent. Inasmuch as routine assessments of aerobic capacity are not prevalent in industry today, any more than two categories might lose their significance. Therefore, only two compatibility functions are used by LIFTAN to assess fitness status (see Figure 2). The values selected for the variable operator-age are: (1) young, and (2) middle-aged. Since research findings show that workers between 30 and 50 years of age have a higher incidence of low back problems [7], this phenomena is accounted for in the proposed compatibility functions.

6. Development of the production rules for the fuzzy knowledge base

6.1. Task rules – Extremely high risk

The first 32 rules are task-related risk rules. In some rules, all four task variables are required in order to deduce a conclusion as given below:

(Rule 5): If (load size is very heavy
and frequency of lift is medium
and horizontal distance away from the body is close
and height is low)
Then (task risk is high).

At other times, only two or three variables are sufficient to reach a conclusion. For example:

(Rule 3): If (load size is very heavy
and frequency of lift is high)
Then (task risk is extremely high).

Depending on the number of extreme variables and their relationship to one another, judgments are made in order to rank the rules in decreasing order of risk. Ten possible task risk levels are proposed: (1) extremely high, (2) very high, (3) high, (4) less than high, (5) medium, (6) less than medium, (7) more than small, (8) small, (9) less than small, and (10) negligible.

Initially, the task is rated with respect to the weight, e.g., heavy weight would induce a high risk; medium weight, medium risk, etc. Next, the risk is adjusted by the factors of frequency, horizontal distance and vertical height. The most
hazardous category of risk, *extremely high*, would result when the load is *very heavy* and the frequency is *high*.

Some rules lead to a *very high risk* conclusion. For example:

(Rule 9): If (load size is *heavy* 
and frequency of lift is *high*
and horizontal distance is *far*)
Then (task risk is very high).

Five separate rules lead to the conclusion of *high risk*. Three of these rules are the "closer" variation of *very high* risk rules. The two other situations which lead to *high risk* are:

(Rule 10): If (load size is *heavy* 
and frequency of lift is *high*
and horizontal distance is *close* 
and vertical height is *low*)
or

(Rule 12): If (load size is *heavy* 
and frequency of lift is *medium* 
and horizontal distance is *far* 
and vertical height is *low*)
Then (task risk is *high*).

*Less than high* risk is the conclusion of four rules. The load is *heavy* for all four rules, while the frequency, horizontal distance and vertical height vary. With tasks of *medium* and lesser risk, there is no one crucial or extreme factor which makes the task risky. The risk categories were chosen here to show not only the absolute but also the relative assessments of risk. Two (out of six) rules which lead to the conclusion of *medium* risk are:

(Rule 21): If (load size is *medium* 
and frequency of lift is *high* 
and horizontal distance is *close* 
and vertical height is *low*)
or

(Rule 23): If (load size is *medium* 
and frequency of lift is *medium* 
and horizontal distance is *far* 
and vertical height is *low*)
Then (task risk is *medium*).

In the final categories of risk, *more than small* through *negligible*, the tasks probably do not have to be redesigned for practical as well as economical reasons.
This expert system is designed to aid in the analysis of manual material handling tasks. The program can deduce TASK-RISK and OPERATOR-RISK. The TASK-RISK analyzes only the characteristics of the task including LOAD SIZE, FREQUENCY OF LIFT, HORIZONTAL DISTANCE FROM THE BODY and the HEIGHT OF LIFT and outputs the risk for an imaginary young healthy male. In order to evaluate a particular operator's ability to perform this task, several operator characteristics, including STRENGTH, FITNESS and AGE will be required. The result will be the EXPECTED RISK OF LOW BACK DISABILITY OR INJURY DUE TO OVEREXERTION FOR A PARTICULAR WORKER.

Throughout this program, certainty factors and linguistic values are implemented. When asked for a certainty factor, indicate 1 when you are certain of your input information or indicate some decimal value less than 1 to express your lack of certainty. Linguistic values, such as MEDIUM or HEAVY, are used rather than actual numerical values of the relevant factors. Consult instructions for equivalence values.

REMINDER: Be sure to use a dash - when indicated. Press spacebar, not RETURN, to continue.

WHAT LOWER CONFIDENCE LIMIT DO YOU WANT? 0
WHAT PARAMETER VALUE DO YOU WANT TO DEDUCE? Operator-risk
DO YOU WISH TO INPUT ANY FACTS? (YES OR NO): no
FOR LOAD SIZE PLEASE CHOOSE FROM THE FOLLOWING SET:
   (LIGHT MEDIUM HEAVY VERY-HEAVY)
DEFAULT VALUE IS HEAVY
LOAD SIZE? heavy
INPUT CERTAINTY OF HEAVY? 0.9

FOR HEIGHT OF LIFT PLEASE CHOOSE FROM THE FOLLOWING SET:
   (FLOOR-TO-KNUCKLE FLOOR-TO-SHOULDER FLOOR-TO-REACH KNUCKLE-TO-SHOULDER KNUCKLE-TO-REACH SHOULDER-TO-REACH)
DEFAULT VALUE IS FLOOR-TO-KNUCKLE
HEIGHT OF LIFT? shoulder-to-reach
INPUT CERTAINTY OF SHOULDER-TO-REACH? 0.9

FOR FREQUENCY OF LIFT PLEASE CHOOSE FROM THE FOLLOWING SET:
   (LOW MEDIUM HIGH)
DEFAULT VALUE IS MEDIUM
FREQUENCY OF LIFT? high
INPUT CERTAINTY OF HIGH? 1

FOR HORIZONTAL DISTANCE FROM THE BODY PLEASE CHOOSE FROM THE FOLLOWING SET:
   (CLOSE FAR)
DEFAULT VALUE IS CLOSE
HORIZONTAL DISTANCE FROM THE BODY? far
INPUT CERTAINTY OF FAR? 0.8

Fig. 2. Case study – advice and explanation provided by LIFTAN.
FOR OPERATOR STRENGTH PLEASE CHOOSE FROM THE FOLLOWING SET:
(VERY-STRONG STRONG AVERAGE)
DEFAULT VALUE IS STRONG
OPERATOR STRENGTH? strong
INPUT CERTAINTY OF STRONG? 0.9

FOR OPERATOR FITNESS PLEASE CHOOSE FROM THE FOLLOWING SET:
(EXCELLENT AVERAGE)
DEFAULT VALUE IS AVERAGE
OPERATOR FITNESS? excellent
INPUT CERTAINTY OF EXCELLENT? 1

FOR OPERATOR AGE PLEASE CHOOSE FROM THE FOLLOWING SET:
(YOUNG MIDDLE-AGED)
DEFAULT VALUE IS YOUNG
OPERATOR AGE? young
INPUT CERTAINTY OF YOUNG? 1

THERE IS A 0.95 CONFIDENCE THAT OPERATOR RISK IS MODERATE.

DO YOU WISH TO CONTINUE THIS PROCESS? no

EXPLANATION REQUIRED (YES OR NO): yes
Since, LOAD SIZE IS HEAVY
and since, FREQUENCY OF LIFT IS HIGH
and since, HORIZONTAL DISTANCE FROM THE BODY IS FAR
Then, according to Rule 9,

THERE IS A 0.9 CONFIDENCE THAT TASK RISK IS VERY HIGH.
In this situation, the worker is stressed both muscually and cardio-
vascularly. In order to reduce the stresses on the musculoskeletal
system, one should either:
1. reduce the weight of the load
or 2. reduce the horizontal distance, possibly by a redesign of the
workplace or the size of the container.
In order to reduce the cardiovascular stress, either:
1. the frequency of the lift should be reduced
or 2. appropriate rest pauses should be provided so that the worker
may regain his strength and recover from the effects of fatigue.

Press a C and the SPACEBAR to continue

Since, TASK RISK IS VERY HIGH
and since, OPERATOR STRENGTH IS STRONG
and since, OPERATOR FITNESS IS EXCELLENT
and since, OPERATOR AGE IS YOUNG

Then, according to Rule 43,

THERE IS A 0.95 CONFIDENCE THAT OPERATOR RISK IS MODERATE.
Although the demands of this task are very high, the physical capacities
of the worker provide for the best possible match between the task and
the operator and the risk of low back disability or injury is optimized.

Fig. 2 (continued).
6.2. Operator rules

Three of four similar task-related rules are combined into groups to aid in assessing the operator-related risk. The various combinations of operator characteristics were examined for their effects on the overall risk. If, for example, a task risk is medium and the operator capacities are adequate, the operator risk would remain medium or moderate. If the critical operator capacities are better than those required for the job, the operator risk would decrease, possibly to less than moderate. If the critical operator capacities are under the demands of the job, the operator risk would increase to more than moderate or less than high.

7. User instructions and example of analysis

The implementation of the developed expert system for manual lifting tasks using four basic steps is shown in Figure 2.

An example situation from analysis to output is also shown in Figure 2. In this job, a 22 year old man is required to lift a 28 kg irregularly shaped bulky object from one overhead conveyor to another. He must repeat this task every 6 seconds. In a pre-employment strength test, it was determined that his arm muscles could exert 45 kg of force. Although the worker's aerobic capacity was not quantitatively measured, his fitness was estimated to be excellent by a company physician. An analysis of both the task-risk and the operator-risk is desired.

The output (see Figure 2) indicates that the operator-risk is moderate with a 0.95 confidence value. The task-risk, however, is very-high with a 0.90 confidence value. The message points out why the task risk is very high and what can be done to improve the situation.

8. Discussion

As illustrated in the sample case, quantitative estimates of the important variables may not be readily available. This is especially true of the operator parameters of strength and fitness. If this is the case, the user should not totally disregard the operator-risk. Rather, he/she could input estimates of these values for analysis. Whenever the estimates are used, the user should view the output results with at least the same uncertainty that was present in his initial inputs.

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