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TESTING AND VALIDATION OF AN EXPERT SYSTEM FOR ADVISING ON SPARES FOR MAINTENANCE PURPOSES

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Abstract: The aim of the paper is to present the results of testing and validation of a fuzzy expert system, SPARTA II, for advising on spare parts for maintenance of electrical and electromechanical systems. The expert system was examined within a wide-ranging series of tests, which include both precise and vague (fuzzy) data. A conclusion is derived that SPARTA II generates good lists of spare parts stock levels for missions specified by a fixed duration and for infinite time horizon tasks.

Keywords: Spare parts, expert system, fuzzy rule, testing, validation.

1. INTRODUCTION

SPARTA II (standing for Spare Parts Adviser) is an expert system for advising on spare parts for corrective maintenance purposes. It is based on both heuristic rules and algorithms which produce recommendations for spares in two specific cases: (a) for a mission specified by a fixed time of duration T, (b) for an infinite time horizon. Using an item approach SPARTA II suggests the assortment and quantities of both repairable and consumable spares for electronic and electromechanical systems. The domain of expertise is restricted to the parts for which the exponential distribution of the times between failures can be assumed. To advise the list of spare parts that will provide a high improvement in system reliability and availability, SPARTA II considers: individual part failure rates, operating hours, essentiality of part for proper system operation, unit costs, weights and volumes, availability of consumables on the market and efficiency of repair for repairables. Data that describe system parts and

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relations between them are uncertain, imprecise and vaguely defined. Their representation and reasoning upon them are based on fuzzy sets and probability theory.

SPARTA II is designed as a user-friendly, menu driven software package. It operates on a standard personal computer under MS-DOS and was written in the Arity/Prolog language completely. By applying software engineering principles, it was prototyped quickly (SPARTA I) and then built upon the prototype [3].

When SPARTA II was implemented an interesting practical question of validating its performance and verifying the correctness of its inferencing arose. The validation is holding the theoretical attention too, because the system is faced with imprecisions and uncertainties in the domain of expertise. Therefore, one cannot simply apply the testing and validation standards which are in use for a non-fuzzy environment.

The aim of this paper is to present the results of testing and validation of SPARTA II. The paper is organized in the following way. Section 2 describes the functions of SPARTA II, its logical composition and implementation. This is done at a comprehensive level and the details are left to references [4]. In Section 3 some general aspects of validation procedure are discussed, and illustrative examples with test results are presented in Section 4 .

2. LOGICAL COMPOSITION AND IMPLEMENTATION

SPARTA II is logically composed of 3 parts.

(a) **Part 1.** In this part of expert system a sort of deep reliability and queuing knowledge is built. The demand for spares of type j, ($j = 1, \ldots, J$) resulting from random failures of parts in the systems in operation is calculated.

The demand depends on:

M the number of systems which have to be maintained,

e the operation intensity rate of systems,

n_j the numbers of identical parts of type j in each system,

λ_j catalog or estimated failure rate of part j.

The kernel of the SPARTA II knowledge base includes (a) the Poisson functions which express the probabilities that demand will be less than a given number and (b) the queuing formulae expressing the probabilities that arrivals have to wait for service.

(b) **Part 2.** In the second logical part of SPARTA II a collection of heuristic rules is implemented:

- in the case of a mission, using fuzzy IF-THEN rules the selection of the probability to satisfy demand for part j at time T is made,
- in the case of an infinite time horizon task, fuzzy IF-THEN rules select the probability that a random request for spare part j will be served from the shelf.

Generally, the nearer the value of the above mentioned probabilities to unity the larger the stock of spares. The choice of probabilities depends on:

- the system complexity,
- the required system readiness / availability,
- the essentiality of part for proper system operation,
- the price of part,
- the weight of part (for a mission)
- the volume of part (for a mission),
- the availability of spares on the market during maintenance (for consumables in infinite time horizon task),
- the efficiency of repair (for repairables in infinite time horizon task).

All these factors are defined as fuzzy variables. For each of them the term sets of qualifiers are developed. For example, the term sets for essentiality of part are: *high*, *medium*, *low*. The typical heuristic rules are:

E1. IF Essentiality is *high* THEN *increase probability*

E2. IF Essentiality is *medium* THEN *leave probability alone*

E3. IF Essentiality is *low* THEN *decrease probability*

When the probability to satisfy demand is estimated, the corresponding stock level for consumables is computed using the Poisson functions. Similarly, the determination of the stock level for consumables and repairables in infinite time horizon task is performed using the queuing formula for an n-server system.

(c) **Part 3.** In the third part of SPARTA II when the stock for each item has been recommended, a system approach is used to obtain the system consequences of the complete list of spares suggested. SPARTA II is able to advise the items in the list for which it is the most reasonable to increase (decrease) the stocks of spares, depending on the budget available. This is accomplished by ranking the items algorithmically, according to the increment (decrement) of performance achieved per pound of constrained resource.

The implementation of SPARTA II in Arity/Prolog language gave many advantages. First, it reduced the semantic gap between Prolog code and the logical specification of spare parts problems. Furthermore, Prolog demonstrated expressiveness in creating rule-based systems, offered rapid knowledge tuning: additions to existing knowledge, amendments to fragments of the knowledge or deletion of redundant knowledge.

In order to allow reasoning under uncertainty a specific inference mechanism was created. It embodies different calculi to operate with fuzzy variables and manipulate fuzzy sets. It can be viewed as extensions of standard unification algorithm of pure Prolog which includes a form of semantic unification.

The users of SPARTA II are provided with a windows interface. Three types of windows are used:

- *display window* – an output only window,
- *menu* – a pop vertical menu,
- *prompt* – one line input window.

This makes SPARTA II an effective user-friendly software product.

3. VALIDATION

Validation and evaluation of an expert system are terms used in the literature with a variety of meanings. The aim of an evaluation is to assess an expert system's overall value. It should consider questions such as: adequacy of the knowledge representation scheme applied, accuracy, consistency and completeness of embedded knowledge, quality of the advice or conclusion provided by the system, correctness of reasoning, ease of interaction with the system, its efficiency and usability.

Since reliable and pertinent advice is an essential component of every expert consultation system, it is usually the area of the greatest interest in an evaluation. However, expert systems tend to be built for those domains in which the decisions of human experts are highly judgmental and nonstandardized. The appropriateness of systems' advice in such domains is difficult to define and that makes the evaluation a complex process.

Simply saying, SPARTA II will be considered worthy of the name expert system if its performance is similar to that of a human expert, who is capable of using advanced analysis and optimization methods in reliability engineering. However, SPARTA II uses fuzzy techniques to model the uncertainty in its application environment. An interesting question arises whether a fuzzy type expert system may be validated in the same manner as a nonfuzzy system. In the course of answering this question on SPARTA II case, the standpoint is that the validation of a fuzzy expert system is not at all an exact process. The approach was to test SPARTA II on a set of carefully selected representatives of the actual problems and data with which SPARTA II will deal and determine from the tests whether it meets expectations of human experts.

SPARTA II was built in a modular manner which simplified the validation process. The knowledge base and the paths through the reasoning mechanism were validated independently for mission and infinite time horizon tasks, for consumables and for repairables, for items where repair starts periodically and for those where repair starts instantly after a failure.

An important feature of SPARTA II to generate explanations of its own reasoning process was used in validation, too. That is to say that providing answers to user questions of the types "why the system needs a piece of information" and "how the system generates recommendations" is a sort of validation per se. The first type of questions can be posed during the consultation session with SPARTA II and the system responds with an explanation annotated to the rule being currently considered. The second type of questions can be posed after the consultation about a particular item and SPARTA II shows a chain of rules that were used for the generation of the recommendation.

In the first phase of validation the nonfuzzy operation of SPARTA II was examined. Some special cases, called the crisp corner examples, were covered [2]. A test example is said to be at the crisp corner if the crisp data are entered into the system instead of fuzzy data. Crisp corner examples played a specific role in the validation process because the results obtained using SPARTA II at a crisp corner examples could be directly compared with the corresponding solution obtainable via nonfuzzy optimization algorithm.

Of course, it was intractable to determine and test all crisp corner examples. A representative set of crisp corners which laid on boundaries of data entry were identified. Once the boundaries were tested, some cases within them were examined, giving insight into fuzzy operation of SPARTA II.

SPARTA II was also tested on erroneous input, to ensure that the code was robust. It was found that SPARTA II shut down in a graceful manner. It does not just quit upon an anomaly occurrence, but indicates where the anomaly has occurred.

4. TEST EXAMPLES

In this section four test examples for mission type of stock problems are presented and discussed. The first one is a crisp corner example. It is followed by 3 fuzzy examples to demonstrate fuzzy operation of SPARTA II.

4.1. EXAMPLE 1: CRISP CORNER

Consider a series system of 5 parts where only the failure rates of parts are different and all other relevant data about parts, given in Table 1, are identical.

SPARTA II suggested the list of spare parts which is given in Table 2.

The recommendation of stocks in Table 2 is similar to the stocks proposed as the solution of the corresponding optimization problem which is stated as "maximize system reliability under budget constraint (less than 110)", or "minimize total price under system reliability constraint (greater than .7)". Furthermore, after asking SPARTA II to reduce the list of spare parts in Table 2 to meet the budget available (less or equal 110), a new list is perfectly near to the optimal one, Table 3.

4.2. EXAMPLE 2: FUZZY UNIT PRICES

Consider a series of 5 parts with the same failure rates equal to 100 failures per million of hours. The unit prices of parts including their fuzzy expressions are different, see Table 4, and all other relevant input data are the same as in Example 1.

SPARTA II suggested the list of spare parts which is given in Table 5.

Table 1.

Input data				
Type of stock problem				mission
Number of identical systems				1
Percentage of time the systems are in operation				100
Mission readiness requirements				reliable
System complexity				less complex
Time period for which spare parts have to be determined (in months)				12
Is the part weight significant				No
Is the part volume significant				No
Number of types of spare parts				5
Part name	Failures (per 10^6 hours)	Part price	Part essentiality	Number of identical parts in the system
aaa	1	1	*maximum*	1
bbb	10	1	*maximum*	1
ccc	100	1	*maximum*	1
ddd	1000	1	*maximum*	1
eee	10000	1	*maximum*	1

Table 2.

List of spare parts recommended for Mission 1.				
Part name	Number of spare parts	Spare parts price	Rel. with spare parts	Rel. without spare parts
aaa	0	0	.99140	.99140
bbb	0	0	.91723	.91723
ccc	2	2	.94294	.42147
ddd	12	12	.90038	.00018
eee	98	98	.90157	.00000
Total price of spare parts				112
System reliability at the end of mission with spare parts				.69604
System reliability at the end of mission without spare parts				.00000

Table 3.

SPARTA II modified list of spare parts for Mission 1				
aaa = 0	*bbb* = 0	*ccc* = 2	*ddd* = 12	*eee* = 96
Total price of spare parts				110
System reliability at the end of mission with spare parts				.66458
Optimal list				
aaa = 0	*bbb* = 1	*ccc* = 3	*ddd* = 13	*eee* = 93
Total price of spare parts				110
System reliability at the end of mission with spare parts				.71778

Table 4.

Unit prices		
Part name	Unit price	Fuzzy expression of unit price
aaa	1	*costless*
bbb	3	*cheap*
ccc	10	*expensive*
ddd	30	*very expensive*
eee	100	*very, very expensive*

Table 5.

List of spare parts recommended for Mission 2.				
Part name	Number of spare parts	Spare parts price	Rel. with spare parts	Rel. without spare parts
aaa	4	4	.93176	.11533
bbb	4	12	.93176	.11533
ccc	4	40	.93176	.11533
ddd	3	90	.82716	.11533
eee	3	300	.82716	.11533
Total price of spare parts				446
System reliability at the end of mission with spare parts				.55345
System reliability at the end of mission without spare parts				.00002

Then the expert system was asked to generate the sequence of the items in the list for which it was reasonable to increase the stocks by one, for the budget available is larger than 446. The recommended 5–step sequence of items added is *aaa–aaa–bbb–bbb–aaa*, giving the total price 455 and the system reliability achieved is .63206. It quite fits expert opinions.

4.3. EXAMPLE 3: FUZZIFIED READINESS REQUIREMENT

Consider again Example 1. The mission readiness requirement was defined as reliable. In example 3, this requirement is fuzzified by requesting very–very reliable mission. In SPARTA II it is performed by intensification operation using power hedge on fuzzy set reliable, which produces a concentration of the fuzzy set [1]. A new recommendation of spare parts for very, very reliable mission is given in Table 6 and differs from the corresponding recommendation for reliable mission in Table 2.

Table 6.

List of spare parts recommended for fuzzified Mission 1.				
Part name	Number of spare parts	Spare parts price	Rel. with spare parts	Rel. without spare parts
aaa	0	0	.99140	.99140
bbb	1	1	.99648	.91723
ccc	3	3	.98825	.42147
ddd	14	14	.96906	.00018
eee	102	102	.95539	.00000
Total price of spare parts				120
System reliability at the end of mission with spare parts				.90388
System reliability at the end of mission without spare parts				.00000

Fuzzy operation of SPARTA II in this example is in a sense double–checked. First, the recommended list of spares and system reliability achieved, which is more than .9, are proved by human experts. Furthermore; absolutely the same list as in Table 6 is derived from Table 2 asking SPARTA II to extend the list of spares until the total price of spare parts 120 is reached, starting from 112.

4.4. EXAMPLE 4: FUZZY UNIT PRICES AND PART ESSENTIALITIES

Consider an example where all input remains the same as in Example 2 except for part essentialities. With each part there is associated a fuzzy variable representing part essentiality on a subjective scale ranging from non–essential, which means that the system operates properly without such a part, to very high essentiality, which means maximum importance of the part for system operation. Part essentialities are given in Table 7.

Table 7.

Part essentiality	
Part name	Part essentiality
aaa	*non_essential at all*
bbb	*small essentiality*
ccc	*medium essentiality*
ddd	*high essentiality*
eee	*very high essentiality*

Now, the list of spare parts recommended, given in Table 8, differs to a large extent from the corresponding recommendation in Table 4.

Table 8.

List of spare parts recommended for fuzzified Mission 2.				
Part name	Number of spare parts	Spare parts price	Rel. with spare parts	Rel. without spare parts
aaa	2	2	.99972	.42147
bbb	2	6	.94294	.42147
ccc	2	20	.94294	.42147
ddd	2	60	.94294	.42147
eee	2	200	.94294	.42147
Total price of spare parts				288
System reliability at the end of mission with spare parts				.74545
System reliability at the end of mission without spare parts				.01330

It is in perfect agreement with the attitude of experts in the field.

5. CONCLUSION

This paper presents some results obtained in validating and testing a fuzzy rule based expert system SPARTA II. The validation was based on extensive use of normative and statistical techniques. The approach is developed to test nonfuzzy operation of expert system at the beginning and then to extend the testing to fuzzy operation. A general conclusion was derived that SPARTA II generates good lists of spare parts stock levels. SPARTA II is useful to: (a) manufacturers who keep spares for the purpose of maintaining their products during warranty period, (b) organizations which have their own maintenance service and allocate budgets for the procurement of spares.

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