Proceedings of the Federated Conference on
Computer Science and Information Systems pp. 1655–1660
DOI: 10.15439/2015F175
ACSIS, Vol. 5

Management of requirements for the projects of the diagnostic systems

Marcin Amarowicz
Silesian University of Technology
Institute of Fundamentals of Machinery Design
Konarskiego 18A, 44-100 Gliwice, Poland
Email: marcin.amarowicz@polsl.pl

***Abstract*—The paper deals with the problem of designing diagnostic systems for technical objects such as power plant, machining etc. The new approach for this problem that is based on the methodology that are used in the design of machines and some aspects of requirement engineering that derived from the software area is considered in the article. In general case the requirements may be used to formalized notation of the project need, that described the designed diagnostic systems. The evaluation of gathered set of requirements may be done by using the specialized expert systems, that may be developed as part of proposed approach. The whole process related to gathering, writing and evaluation of requirements for the purpose of designing diagnostic system is presented in the article.**

I. Introduction

During the operation of technical objects, exists the danger of occurrence various kinds of events, usually summary called as faults, that may have the negative consequences to the considered technical object and its immediate vicinity. These faults may be caused by different factors including the constructional errors committed during the design process, production errors associated with inaccuracy of technological processes, operational errors related to non-compliance with the prescribed terms of operation of the object and obsolescence errors that are the results of natural changes of object's state e.g. decreasing of strength etc., [15]. Probability of occurrence of particular faults and their consequences are interpreted as technical risk associated with the operated object. From the mathematical point of view, the technical risk may be written as:

$$R_i = P_i \cdot c_i, \tag{1}$$

where P_i is the probability of occurrence of i-th fault and c_i is the possible costs/consequences connected with the occurrence of this fault. In order to ensure the proper operation of a technical object it is necessary to minimize the technical risk. This can be achieved by diagnose the current technical state of the considered object. This process can be perform by using the diagnostic system that is designed specially for this object.

In technical diagnostics area it is assumed, that the technical state of an object is a function of faults [10]. Therefore, in order to correctly determine the state of the object it is necessary to detect particular faults. Process of their detection is performed based on available information about the existing relationships between the value of selected signals, recorded on considered technical object, and the possible faults. The occurrence of specific values of signal, values of several signals or e.g. values of selected features of these signals (e.g. medium, standard deviation etc.) is called a symptom of this fault. In the simplest case, the information about the exceeded of permissible value of some signal (e.g. exceeding the permissible rms value of vibration signal in the bearing node) could be the symptom of the fault [13].

In the structure of typical diagnostic systems, the two parts, the measurement and the software one can be distinguished [3]. The main purpose of the measurement part is to record the value of selected signals and save them, according to the assumed scheme, in the database e.g. in OPC servers. The software part of diagnostic system is responsible for the appropriate detection of faults. It consists of analysis of recorded signals, including the designation of the necessary features of these signals, and the inference about the technical state of the object. In many cases, this process is carried out by using advanced computational algorithms including the artificial intelligence methods. The results of performed analysis are presented (depending on the class of the diagnostic system) through various techniques e.g. sound and light alarms, synoptic screens, sms and email notifications etc.

The purpose of this article is to present the new approach to the designing of the diagnostic systems. This approach will be based on general methodology that are used in the design of machines and the introduction to it a some modifications. They are necessary because the specificity of the field which is the technical diagnostics must be taken into account [1], [2].

II. Diagnostic systems design method

In general case the process of design machines is a multi-stage. It begins from the definition of the need. At the general level of detail it expresses the expectations that should be met by the developed technical object. It is important to note, that the need cannot impose any restrictions and itself cannot define any potential solutions. In the next stage, with using various techniques such as brainstorming, teamwork, morphological table etc., the set of possible solutions is generated. After appropriate analysis and evaluation, the optimal solution is selected from this set. This one best meets the evaluation criteria and housed in imposed or adopted project limitations [7].

Taking into account that the need to develop a diagnostic system is the main project's need, it may be seen that the direct use of this approach to the design of diagnostic systems, encounters to the some problems at the stage of development possible solutions of this system. This is due to the necessity to take into account the wide knowledge about technical object, the ways of its diagnosis (methods of measurement, signal analysis etc.), accepted limitations etc., [5]. For this reason, it is not possible to define the set of potential solutions of the diagnostic system directly from the defined need. This problem can be solved by using an additional project's stage, during which the formalized description of the need is prepared. Due to the fact that the diagnostic system contains the software part that is responsible for analyzing of the signals and inference about object state, it seems reasonable to use certain design techniques that are directly derived from the software engineering area. The sets of requirements that describe the expected functionality of the designed systems are one of them.

In the process of designing the diagnostic systems requirements can be used to formalize the notation of the project's need. Within the defined need, some characteristic functionalities that are necessary from the diagnostic system point of view may be extracted. These functionalities can be accurately characterized by applying the requirements with the hierarchical structure. Stored in such way the need, would be better expressed/described expectations about the potential diagnostic system solutions, because it will take into consideration the specificity of the field which is the technical diagnostics and the characteristics of the technical object for which there is a need to develop a diagnostic system. Based on such formalized need it is possible to develop/generate a set of possible solutions of the diagnostic system. In the next stage of the design process, these solutions will be evaluated on the basis of the set of established criteria, wherein these criteria may be defined/derived from a set of defined requirements.

Individual requirements may be defined based on the available diagnostic and operation knowledge, knowledge about the considered technical object etc. An important advantage of the use of requirements in the design process is the ability to define the individual requirements by independent persons, so-called domain experts. This is particularly important in the area of technical diagnostics, due to the fact that the modern technical objects are very often complicated and the design the diagnostic system by the small group of people may be very difficult.

III. Requirement engineering

In literature, there are available many different definitions of the term requirement e.g. in [12], [16] or [17]. For the purpose of presented studies, the following statement may be assumed: *Requirement is a formalized description of function/atributte, that designed object should realize/meet*. Just as in the literature exist many definition of the term requirement, the different divisions and classifications of requirements exist also. However, two groups of requirements i.e. functional and

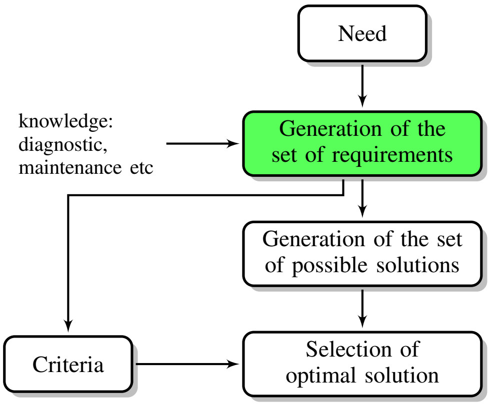

Fig. 1. Scheme of the proposed diagnostic systems design process

nonfunctional requirements are usually distinguished. Functional requirements describe the basic functions of the system, i.e. the way in which the system operates, colloquially what the system should to do. This, how the particular functions of the system should be implemented is described by the nonfunctional requirements. Very often there are also called as a quality requirements due to the fact that they describe the operation of the system (implementation of particular functional requirements) from the quality point of view. Repeatedly, an overall evaluation of the developed system and the recognition that the system has been developed according to the assumptions depend from them [12], [16].

IV. Notation of the set of requirements

The use of requirements for the purpose of formalized description of the need, requires the introduction some additional assumptions, that are not seen in the software engineering area. These assumptions are connected with the necessity of adoption of a specific manner of notation of defined requirements. This notation is caused by the specific properties of the area that is the technical diagnostics. Namely, the detection of individual faults is considered as the major functionality of the diagnostic system. In order to achieve this task, certain diagnostic rules (symptoms of faults) should be applied. Each diagnostic rule may be realized with using some measurement methods e.g. measurement and analysis of temperature, vibration measurement etc., which include various types of sensors, measurement cards etc. All of these elements must be saved as a component of the established definition of the requirement.

Taking into account the mentioned remarks, each functional requirements req_i may be recorded as

$$req_i = < c_r, attr_r, pf_r, drule >, \tag{2}$$

where:
c_r – content of requirement, $attr_r$ – attributes of requirement, pf_r – preference factor, $drule$ – diagnostic rule.
The content of the requirement is the description of the functionality of the diagnostic system. It is related with the necessity of detection on specific fault e.g. *The necessity to*

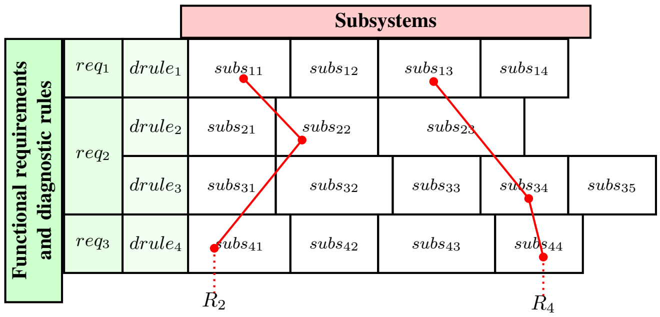

Fig. 2. Morphological table with the set of possible solutions of diagnostic system project

detect breakage of the gear tooth. For each requirement it is possible to assignment some set of attributes,

$$attr_r = \{attr_{r1}, attr_{r2}, ...\}, \tag{3}$$

which are used to detail the description of this requirement and are the basis for evaluating the usability of the functionality which are described by this requirement. *Level of reduction the probability of fault occurrence described by the requirement*, or *level of reduction of costs associated with the occurrence of this fault* may the examples of these attributes. For each functional requirement, is possible to assign some value from the range $< 0; 1 >$, called the degree of preference. It expresses the need to take into account this requirement in the final solution of the diagnostic system. Preference factor may be considered as a subjective assessment of the suitability of the given requirement to the achieve by the diagnostic system the established goal, which is the minimization of technical risk. For each functional requirement is possible to define the set of possible diagnostic rules:

$$drule = \{drule_1, drule_2, ...\}, \tag{4}$$

which are used to detect the specific fault. Each diagnostic rule is expressed as:

$$drule_i =< c_{dr}, attr_{dr}, pf_{dr}, subs, ko > . \tag{5}$$

Scheme of marks is similar like in the case of requirements. So c_{dr} is a verbal description of the rule, e.g. *exceeded the root mean square value of vibration signal*, $attr_{dr}$ is a set of possible attributes, that may be used to accurately describe each of the rule e.g. *level of the false alarms*, and pf_{dr} is a degree of preference assigned to each rule. Each of the diagnostic rules may be fulfilled by using different measurement systems, for the purpose of this study, called subsystems. Each subsystem $subs_i$ may be expressed as:

$$subs_i =< elem, attr_s, pf_s >, \tag{6}$$

where:
$elem$ – subsystem elements, $atrr_s$ – attributes of subsystems, pf_s – preference factor.
Each element of subsystem may be considered as:

$$elem_i =< elem_{type}, elem_{value}, attr >, \tag{7}$$

where $elem_{type}$ is a type of element, e.g. relative vibration sensor, measurement card (DAQ card) etc. and $elem_{value}$ is a possible items of the specific element type, that is, e.g. specific sensors from catalogues of certain producent. These elements may be described by numerous attributes $attr$ e.g. measurement range, sensitivity, cost etc. For the purpose of limiting the applicability of the selected elements included in the subsystems, it is possible to define a set of limiting criteria ko that are assigned to each diagnostic rules $drule_i$. Diagnostic rules and subsystems assigned to them may be regarded as non-functional requirements defined for selected functional requirements, that describe the necessity to detection of individual faults.

Requirements (i.e. hierarchically saved elements req_i, $drule_i$ and $subs_i$), that are gathered by using the proposed method, describe in the formalized manner the project's need. Based on this formalized need, it is possible to generate the set of possible solutions of the diagnostic system. To perform this operation it is necessary to use the catalog of possible elements that are the part of subsystems $subs_i$, and take into account the limiting criteria. In this way, for the defined combination of functional requirement - diagnostic rule, is generated a set of possible subsystems. These three elements i.e. functional requirement, diagnostic rule and subsystem are the component of the project of the diagnostic system. Morphological table [18] (see example in Fig. 2) may be used for easier presentation the set of possible solutions of this diagnostic system.

In order to use the proposed method of formalization of project's need, it is necessary to answer on two fundamental questions. First of all, how to acquire the necessary set of requirements. And the second, how to evaluate the generated set of possible solutions so as to choose the optimal solution. The answer to these two questions is contained in two successive chapters.

V. Requirements acquisition

The process of gathering the requirements for the purpose of design diagnostic system is not an easy task. As in the software engineering area [12], [16], it depends on many factors, including the availability of knowledge about the possible faults of object, methods of their diagnosis etc., [5]. The process of obtaining the relevant requirements, should therefore be adaptive aided by using different kinds of knowledge banks, catalogues of elements, etc. In general case, for each technical object it is possible to develop a so-called catalog of hazardous events, which includes the possible faults of its individual components. For individual fault, it is possible to estimate the risk (probability/frequency of occurrence of the event, the potential costs of the consequences of this event) associated with their occurrence. Based on this set of faults, it is possible to define the set of diagnostic rules, that include typical symptoms of individual faults. For the purpose of describing the subsystems that are used to provide various diagnostic rules, it is possible to create a catalog of elements in the form of pairs: element type - a list of elements.

Using data banks prepared in this way, is possible to perform the process of requirements acquisition, that assumes the defining of following elements that are included in the definition of requirements, in hierarchical order, i.e. functional requirement, diagnostic rule and subsystem, whereby during this stage, it is possible to use the pre-defined knowledge banks. It is assumed that, depending on the needs and the technical possibilities (see Sec. VII) for individual objects may be assigned different attributes. These attributes are the basis for assessment of the suitability of individual requirements, and also allow to generate a set of possible solutions of the diagnostic system. Additionally, it is assumed that during the stage of defining the diagnostic rules, it is possible to define the limits (limiting criteria) that must be met by the subsystems used to implement the specific diagnostic rule. However, the limiting criteria must refer to the attributes assigned to individual elements.

An important advantage of using this approach is the possibility of a separate preparation knowledge banks and acquiring the set of requirements. Both of these stages can be performed not only independently, but also by different persons, such as domain experts. The entire process of obtaining requirements can be further simplified by making the decomposition of the technical object and define the requirements for such separate components.

VI. Requirements evaluation

In the software engineering area the process of evaluation of obtained requirements takes many forms. However, it usually amounts to the negotiation between the customer that order the project and its potential developer. Each of them articulate own needs and expectations. After a series of conversations, they together agree a final set of established requirements [8]. This approach, due to the several factors cannot directly be used in the case of designing the diagnostic systems. The first of them is the lack of explicit customer for the requirements negotiation process. A person who contracts or expresses the need to perform diagnostic system in many cases not have complete knowledge about the considered technical object. Therefore, this person will not be able to correctly assess the whole set of requirements. Additionally, in many cases the knowledge about technical object, particularly the knowledge about the manner of its diagnosis may not be fully accessible and good quality. So, it is necessary to apply a some software system, that will be support the process of evaluation of requirements based on the collected data. This system may be treated as a virtual customer, that represents the technical object and articulates the necessary requirements.

The overall objective of the stage of the requirements evaluation, is to determine the answer for two fundamental questions, namely:

- what should be the functionalities of the diagnostic system, i.e. which faults should be detected by the diagnostic system and which diagnostic rules should be applied for this purpose,
- what should be the structure of the diagnostic system, i.e. which subsystems that carrying out specific diagnostic rules should be applied and which items from available element types should be used.

For the purpose of carrying out the mentioned above activities, it seems reasonable to develop an expert system. It allows not only to carry out the process of inference about the usefulness of individual requirements, taking into account the existing data/information, but also the assessment of individual solutions of the diagnostic system in order to select an optimal solution.

The basic components of a typical expert system is a knowledge base, database, inference algorithm and the user interface, through which is provided the access to the individual components of system [14]. The use of expert system for the described purposes, requires the develop of the knowledge base in the appropriate form. This is due to the necessity to take into account the numerous set of attributes, based on which will be performed the process of evaluating of individual requirements. For the purpose of developing the knowledge base the graphic models e.g statement networks [4] or belief network [9], [11] can be used. In considered case the belief networks are used.

Belief network is a directed graph G in which the set of nodes N and set of directed edges V may be distinguished. Nodes of this network are used to represent the available information on observed facts and made observations. Causal relationships between the selected facts are represented by defined edges between the relevant nodes. The size of the impact of individual nodes to each other is determined in the conditional probabilities tables that are defined for each of nodes.

In the presented case, the structure of required belief networks is constant. Example of the structure of the required network that is necessary to represent the knowledge associated with the functional requirements is shown in Fig. 3. Nodes of four classes i.e. *requirements*, *attributes for requirements*, *criteria*, and *auxiliary nodes* exist in this structure. The attributes and criteria for attributes are the input nodes, while the functional requirements are the output nodes. As the values of the *attributes* nodes, qualitative data collected at the stage of defining requirements are introduced. *Criterion* node determines whether the attribute is important from the point of view of the project of a diagnostic system. Conditional probability tables are fixed for nodes within each group and may be elaborated based on available literature data or expert's knowledge. In the same way the network for diagnostic rules can be defined. As a result of the inference process, for the individual functional requirements and diagnostic rules the preference factor is assigned. The value of this factor indicates about whether the certain solution (requirement or diagnostic rule) is desirable in the designed diagnostic system.

The stage of assessment of subsystems is the next process that can be performed by using expert system. It is assumed, that based on the obtained database of elements and defined constraints imposed on the subsystems, is possible to generate very large set of potential subsystems. The process of their evaluation involves the use of optimization functions, that

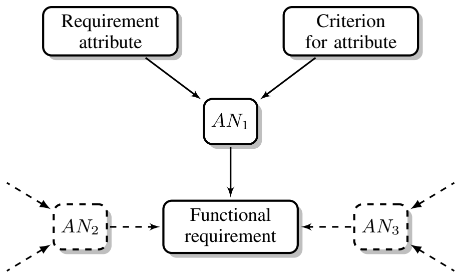

Fig. 3. Structure of belief network for considered task, AN_i – auxiliary node

looking for the best solution. The most commonly used functions minimize or maximize the value of one or more attributes assigned to the individual elements e.g. cost minimization. In this way the set of desirable functional requirements and rules and within their the optimal subsystems are determined. The optimal structure of the diagnostic system is generated by the choice of a certain subset of functional requirements (e.g. those for which the appointed degree of preference is greater than the certain predetermined value) and iterative merge of selected subsystems. The iterative merge assumes, that is possible to omit certain elements of subsystems, for example measurement cards, because they are already elements of another subsystems and can be used repeatedly. This approach allows in many cases to simplify the structure of the diagnostic system as well as to reduce its cost.

VII. Short example of proposed approach

For the purpose of presentation described in this article the method of aided the development of diagnostic systems process, one simple example will be presented. A simple technical object which is typical rotating machine equipped with the ball bearings is considered. For this object it is possible to define the needs that may be written as: *determine the current technical state of the object*. As it has already been mentioned, this need may be met by developing appropriate diagnostic system. For such defined problem, it is possible to begin the process of defining requirements. As a result of this process, the set of functional requirements may be defined. Examples of these requirements may be given as follows:

- req_1 – the need to detect the wear of the bearing raceway,
- req_2 – the need to detect crack of the outer raceway of the bearing.

These requirements may be described by the following attributes:

- the level of reduction of the probability of fault occurrence,
- the level of reduction of cost associated with occurrence of fault,
- downtime of the object after fault occurrence,
- the applicability of the requirement in other projects of the diagnostic systems.

Considering only the requirement req_1, it is possible to define for it a diagnostic rule written as, $drule_1$ – *exceeding the allowable root mean square value of vibration signal in the bearing*, and the limiting criterion for the subsystem on the content: *measuring range up to 10kHz*. Diagnostic rule $drule_1$ can be realized by the subsystem of the structure: absolute vibration sensor, connecting cables, measuring card and software for signal analysis. Fragment of a possible catalog of available sensors may include for example such elements as: CMSS 2100, CMSS 2100T, CMSS 2200, CMSS 780C, CMSS 2100 etc. all of these sensors are produced by the SKF company. Described process of requirements defining should be carried out in the same way for the remaining functional requirements. For the purpose of the presentation the inference process with using the belief networks the Netica environment was used. The defined statements network for the elementary data is shown in Fig. 4. The network structure is consistent with the assumptions shown in Fig. 3 and described in Sec. VI. After entering to the network the data related with: the probability of occurrence of considered fault, possible cost of the fault occurrence and information about the necessity to take into account some attributes, the value of preference factor for the considered requirement will be appointed (see Fig. 5). The next stage of the assessment involves the selection of the optimal form of the subsystem. For this purpose, based on the available sets of items and the defined limiting criterion, the set of possible solutions is generated. In this set the solution characterized by the minimum cost is now sought.

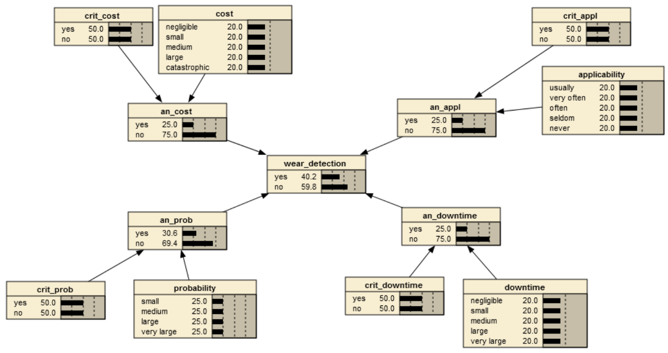

Fig. 4. Belief network with elementary data

Taking into account that for the considered technical object, it is possible to define large set of requirements, the described the way of proceeding should be carried out for each of them. At the end, it is necessary to carry out the optimization of the whole structure of diagnostic system, to exclude repeating items.

VIII. Environment for diagnostic systems design process

Presented in this article, the method of elaborating of the projects of the diagnostic systems, may be aided by using a dedicated software environment. Four main modules, i.e. requirements acquisition module, requirements evaluation module, presentation module as well as database may be dis-

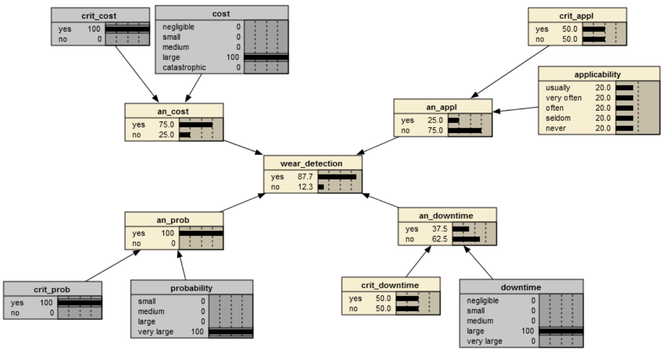

Fig. 5. Belief network after entering the obtained data

tinguished in the structure of this environment. Requirements acquisition module is responsible for collecting and storing requirements that describe developed diagnostic system. It cooperates with the banks of knowledge, in which are recorded information about known collections of faults, possible diagnostic rules, and known catalogues of elements in the form of pairs type of element - element. Based on the defined functional requirements and diagnostic rules the knowledge base for expert system is generated. The inference process will be carried out by using the package *REx* that is developed in R programming language [6]. The preference factot is assigned to each functional requirements and diagnostic rules as the result of inference process. The process of evaluating the individual subsystems and integration of the overall project of the diagnostic system will be performed in the evaluation module. For the purpose of presentation of the results the presentation module will be used, while the individual data, knowledge, etc. will be stored in the suitably developed database. Currently this environment is under construction.

IX. Conclusion

The process of designing the diagnostic systems is a very complex task. In many cases these systems are prepared for the critical machines e.g. turbines of power plant, etc. that appropriate diagnosis is essential. During the design process of these systems is necessary to take into account numerous factors including available knowledge, existing limitations etc. In order to properly management of the available data, it is necessary to support the process of defining the diagnostic systems. For these purposes the set of requirements may be used. The used requirements may formalize the notation of the main project need. The formalized notation of the need assumes that exist three elements i.e. functional requirements, diagnostic rules and subsystems. Each of these elements can be developed based on existing catalogues of faults, measurement systems or catalogues of elements of those systems. Based on the formalized project need it is possible to generate the set of possible solution of the diagnostic systems. Because the evaluation of these solution, there is the selecting of the optimal solution is a challenging task, the additional software environment so-called expert system may be used. As a result of the use of expert system the optimal solution of the designed diagnostic system is isolated. Each of the necessary stages of the proposed approach may be performed by using specialized environment which is currently being developed. Future work will be related to the testing of this environment and removing possible inconveniences and drawbacks of the proposed method.

Acknowledgment

Described herein are selected results of study, supported partly from the budget of Research Task No. 4 implemented under the strategic program of The National Centre for Research and Development in Poland entitled *Advanced technologies of generating energy*.

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