Hierarchical Graph-Logical Models of Multiprocessor Systems Based on Grouping of Their Components

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Summary
Work is focused on creation of GL-models of hierarchical fault-tolerant multiple processor systems which serve for calculation of parameters of reliability by carrying out statistical experiments with models. In a hierarchical system, subsystems can contain not only subsystems of lower levels, but also processors themselves. Often these processors cannot replace failed subsystems. Besides, the possibility of any mutual replacement both among subsystems, and among processors not always takes place. It is proposed to divide both processors and subsystems into groups (in which mutual replacement is possible), for each of which to build a separate model in order to create a general GL-model of the system. After that, on each hierarchy level, models integrate by means of auxiliary models of a view K(0, L) where L - number of groups and, respectively, models.

Key words:
GL-models, hierarchical fault-tolerant multiple processor systems, calculation of parameters of reliability

1. Introduction

In the fault-tolerant multiprocessor systems (FMPS) developing process, sooner or later, the problem of determining their reliability parameters arises. This characteristic allows to check compliance of the developed system to the set criteria, and in case of need to take measures for its completion [1].
Different authors have proposed a number of methods [2] that solve this problem, which can be separated into two groups: the analytical, allowing to calculate precisely required parameters on formulas and statistical, based on carrying out experiments with behavior models of systems in a failure flow [3]. The methods of the first group, in spite of their attractiveness, turn out to be practically unsuitable for complex heterogeneous systems. At the same time, statistical methods allow estimating the reliability parameters of any system, however, they give this assessment with some error and require carrying out numerous statistical experiments with behavior models of systems in a failure flow which amount influences assessment accuracy.
Graph-logical or GL-models [4] were offered for modeling of behavior of compulsory health insurance in a failure flow and can be constructed for the systems of any complexity. The model represents the non directional graph whose edges correspond to the Boolean functions, called edge functions. If the edge function takes a null value, the corresponding edge is excluded from the graph. The graph connectivity corresponds to operability of a system: the connected graph if the system is efficient and disconnect graph if it is faulty. As the argument of edge functions the so-called state vector of a system is used: the vector consisting of values of Boolean variables each of which reflects a status of one of system processors: 1 - it is serviceable, 0 - it is faulty.
In [5] was offered the method of constructing models for basic systems, i.e. such which are efficient in only case when not less, than m from n of their processors - are serviceable [2]. Such models are also called basic by analogy with systems. In practice, the system can differ from basic (so-called non-basic systems and models). Models of such systems can be constructed of basic by their modification [6].
Sometimes the large systems solving complex problems are divided into a number of subsystems, each of which executes the subtask. These subsystems can sometimes consist in turn of subsystems of lower level, etc. Such systems are called hierarchical. The method of creation of GL-models of such systems was offered in [7]. According to the offered method the model is under construction for each of subsystems after which the received models are combined using the top-level model. Thus, to a hierarchical system there corresponds the hierarchical model.

2. Problem Statement

In [7] the systems containing processors only in subsystems of the bottom level of hierarchy were considered. At the same time, (sub)system may contain both subsystems of lower levels of hierarchy and directly the processors performing, in particular, functions of interface and/or post-data handling, which were received from subsystems of the bottom level. At the same time such system will be resistant on the one hand to failure of some subsystems, and with another - to failure of some processors.
It is possible to integrate vectors of state and subsystems, and processors in a single state vector and construct

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system GL-model using one of the known methods. However, considering heterogeneity of components of a system (it is obvious that the separated processor can hardly replace the whole subsystem), such model will probably turn out rather far from basic and therefore very complex, as well as process of its creation.
The real work is devoted to the solution to a problem of simpler method of creation of GL-models for systems of such type development.

3. Method of Creation of Model

As it was already noted, separate processors and subsystems usually perform absolutely different functions (at least on scale), i.e. it is often impossible to replace the failed subsystem with serviceable processors and vice versa. The idea of a method consists in splitting model of a system into two submodels. The first submodel will calculate system status proceeding from statuses of its processors, and the second - proceeding from statuses of its subsystems as it is offered in [7]. In order for the system was operable, it is necessary that both a sufficient number of its processors and a sufficient number of its subsystems were serviceable, which corresponds to a situation where both submodels show an operational condition. Thus, the results received by means of the above-stated submodels can be combined with conjunction or model K(0, 2).
Let's note also that in some systems subsystem can execute various roles, i.e. not each subsystem will be able to replace another failed. In that case for creation of model of a subsystem it is worth separating into several groups in which such replacement is possible. The same can be told also about separate processors which can have so different architecture and execute so different roles that will not be able to replace each other in case of failure. In that case it is worth separating processors on similar groups. Further for each of the groups (formed both by subsystems, and processors) the corresponding model describing her behavior in a failure flow is under construction then they integrate by means of model K(0, L) where L - the number of groups.
Thus, it is easy to notice that each level of the system hierarchy can generate not one, but two levels of the model hierarchy, and the number of submodels can exceed the number of subsystems. Let's note that the similar situation is not unique and arises, for example, for systems with the sliding reserve [8]. Also it should be noted that in some, even not hierarchical systems, division of processors into groups can take place. In such cases to not hierarchical system there will correspond the hierarchical model.
Let's note also that, as well as for the case described in [7] each of subsystems, in turn, can also include several hierarchy levels (moreover, for each of the subsystems their quantity may be different). In each case model of subsystems can be constructed the same way.
In addition, at some levels of the hierarchy, the need for the above grouping may not be necessary. In particular, it can take place at the most bottom levels of hierarchy where there are no subsystems of lower level (however as it was already described above, sometimes there is still a possibility of the grouping processors). Also, some of the subsystems may not contain separate processors but may consist only of subsystems of a lower level. At all these cases actually there is only one group, and creation of model is possible according to [7] though, also the possibility of its creation according to the method offered here is not excluded, using intermediate model $K(0, 1)$. The last, obviously, is less effective, however, in certain cases can simplify process of automation of generation of models.
Let's notice that according to [5] it is possible to construct model $K(m, n)$ where $1 \leq m<n$. For creation of model $K(0, L)$ it is enough to construct model $K(1, L+1)$ for which as an input vector to use the input vector of initial model complemented with one zero ($<x_1, x_2, \ldots, x_L, 0>$). Let's note that the result of the creation of such a model according to [5] one of its edge functions will always matter that equal to zero, and the corresponding edge to it can be excluded. In general the graph of model from cyclic will turn into linear and will contain the L edges, and the remained edge functions will have appearance $f_i = x_i$ where x_i are components of an input vector of initial model (fig. 1).

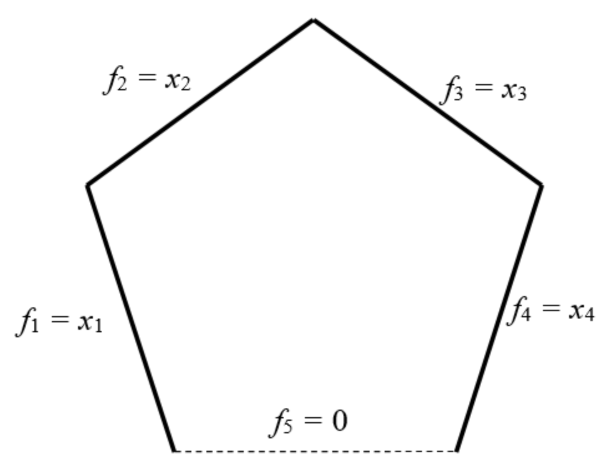

Fig. 1 An example of model $K(0,4)$ for an input vector $<x_1, x_2, x_3, x_4>$ (the excluded edge is noted by a dotted line)

4. Example

Let's review an example (fig. 2). The system has two hierarchy levels. Subsystems of the bottom level contain

11, 9, 12, 7 and 15 processors, and, respectively, are resistant to failure 4, 3, 5, 2 and 4 of them. Besides, the subsystem of the top level also contains 10 processors and is resistant to failure 3 of them (we will note that the system is intentionally selected rather similar from considered in [7] that will allow to compare the received models).

Let's remind that all subsystems were selected as basic only for simplification of the examples. In case of non-basic subsystems for creation of adequate models it would be possible to use one of methods of their modification [6].

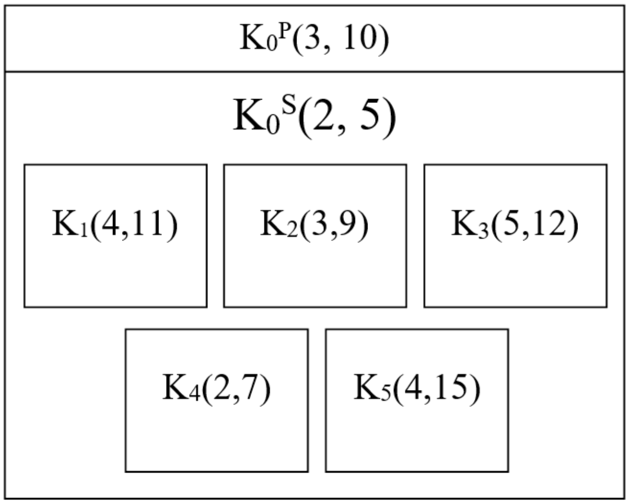

Fig. 2 Structure of a system

In accordance with the proposed method, three models will correspond to the top-level subsystem: the model describing behavior of a subsystem in a failure flow of subsystems of the bottom level (M_0^S), the model describing behavior of a subsystem in a failure flow of processors (M_0^P) and also the model integrating two previous models (M_0). Models of systems of the bottom level do not contain subsystems and can be constructed according to [7] (fig. 3).

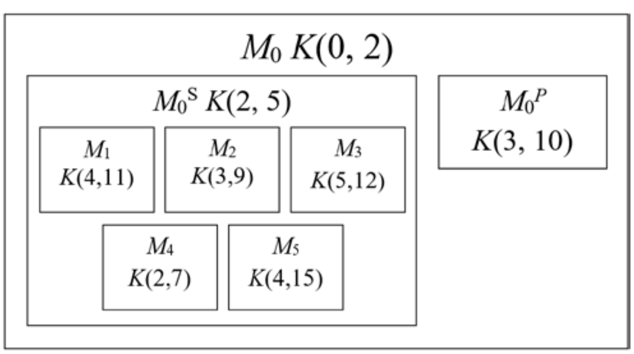

Fig. 3 Structure of model

Let's construct model of the considered system. In the beginning we will construct models of subsystems K_1-K_5 according to [5]. First subsystem will correspond to a model $K(4, 11)$. Edge functions of model of this system constructed according to [5] are given below:

$$f_1^1 = x_1 \vee x_2 \vee x_3 \vee x_4x_5x_6$$

$$f_2^1 = (x_1 \vee x_2)(x_1x_2 \vee x_3) \vee (x_4 \vee x_5)(x_4x_5 \vee x_6)$$

$$f_3^1 = x_1x_2x_3 \vee x_4 \vee x_5 \vee x_6$$

$$f_4^1 = (x_1 \vee x_2 \vee x_3)((x_1 \vee x_2)(x_1x_2 \vee x_3) \vee x_4x_5x_6) \wedge$$
$$\wedge (x_1x_2x_3 \vee (x_4 \vee x_5)(x_4x_5 \vee x_6))(x_4 \vee x_5 \vee x_6) \vee x_7x_8x_9x_{10}x_{11}$$

$$f_5^1 = (x_1 \vee x_2)(x_1x_2 \vee x_3)(x_1x_2x_3 \vee x_4x_5x_6)(x_4 \vee x_5)(x_4x_5 \vee x_6) \vee$$
$$\vee (x_7 \vee x_8)(x_7x_8 \vee x_9)(x_7x_8x_9 \vee x_{10}x_{11})(x_{10} \vee x_{11})$$

$$f_6^1 = x_1x_2x_3x_4x_5x_6 \vee (x_7 \vee x_8 \vee x_9)((x_7 \vee x_8)(x_7x_8 \vee x_9) \vee x_{10}x_{11}) \wedge$$
$$\wedge (x_7x_8x_9 \vee x_{10} \vee x_{11})$$

$$f_7^1 = x_7 \vee x_8 \vee x_9 \vee x_{10}x_{11}$$

$$f_8^1 = (x_7 \vee x_8)(x_7x_8 \vee x_9) \vee x_{10} \vee x_{11}$$

The graph of the model has is presented in fig. 4.

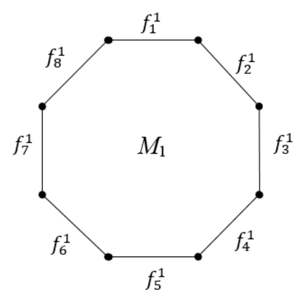

Fig. 4 Model M_1 $K(4, 11)$

The second subsystem will correspond to a model $K(3, 9)$ with edge functions:

$$f_1^2 = x_{12} \vee x_{13} \vee x_{14}$$

$$f_2^2 = (x_{12} \vee x_{13})(x_{12}x_{13} \vee x_{14}) \vee x_{15}x_{16}$$

$$f_3^2 = x_{12}x_{13}x_{14} \vee x_{15} \vee x_{16}$$

$$f_4^2 = (x_{12} \vee x_{13})(x_{12}x_{13} \vee x_{14})(x_{12}x_{13}x_{14} \vee x_{15}x_{16})(x_{15} \vee x_{16}) \vee$$
$$\vee x_{17}x_{18}x_{19}x_{20}$$

$$f_5^2 = x_{12}x_{13}x_{14}x_{15}x_{16} \vee (x_{17} \vee x_{18})(x_{19} \vee x_{20})$$

$$f_6^2 = x_{17} \vee x_{18} \vee x_{19}x_{20}$$

The graph of the model has is presented in fig. 5.

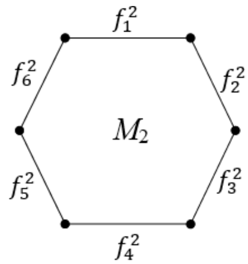

Fig. 5 Model M_2 $K(3, 9)$

The third subsystem will correspond to model $K(5, 12)$ with edge functions:

$$f_1^3 = x_{21} \vee x_{22} \vee x_{23} \vee (x_{24} \vee x_{25})(x_{24}x_{25} \vee x_{26})$$

$$f_2^3 = (x_{21} \vee x_{22})(x_{21}x_{22} \vee x_{23}) \vee x_{24} \vee x_{25} \vee x_{26}$$

$$f_3^3 = (x_{21} \vee x_{22} \vee x_{23} \vee x_{24}x_{25}x_{26}) \wedge$$
$$\wedge((x_{21} \vee x_{22})(x_{21}x_{22} \vee x_{23}) \vee (x_{24} \vee x_{25})(x_{24}x_{25} \vee x_{26})) \wedge$$
$$\wedge(x_{21}x_{22}x_{23} \vee x_{24} \vee x_{25} \vee x_{26}) \vee x_{27}x_{28}x_{29}x_{30}x_{31}x_{32}$$

$$f_4^3 = (x_{21} \vee x_{22} \vee x_{23})((x_{21} \vee x_{22})(x_{21}x_{22} \vee x_{23}) \vee x_{24}x_{25}x_{26}) \wedge$$
$$\wedge(x_{21}x_{22}x_{23} \vee (x_{24} \vee x_{25})(x_{24}x_{25} \vee x_{26}))(x_{24} \vee x_{25} \vee x_{26}) \vee$$
$$\vee(x_{27} \vee x_{28})(x_{27}x_{28} \vee x_{29})(x_{27}x_{28}x_{29} \vee x_{30}x_{31}x_{32}) \wedge$$
$$\wedge(x_{30} \vee x_{31})(x_{30}x_{31} \vee x_{32})$$

$$f_5^3 = (x_{21} \vee x_{22})(x_{21}x_{22} \vee x_{23}) \wedge$$
$$\wedge(x_{21}x_{22}x_{23} \vee x_{24}x_{25}x_{26})(x_{24} \vee x_{25})(x_{24}x_{25} \vee x_{26}) \vee$$
$$\vee(x_{27} \vee x_{28} \vee x_{29})((x_{27} \vee x_{28})(x_{27}x_{28} \vee x_{29}) \vee x_{30}x_{31}x_{32}) \wedge$$
$$\wedge(x_{27}x_{28}x_{29} \vee (x_{30} \vee x_{31})(x_{30}x_{31} \vee x_{32}))(x_{30} \vee x_{31} \vee x_{32})$$

$$f_6^3 = x_{21}x_{22}x_{23}x_{24}x_{25}x_{26} \vee (x_{27} \vee x_{28} \vee x_{29} \vee x_{30}x_{31}x_{32}) \wedge$$
$$\wedge((x_{27} \vee x_{28})(x_{27}x_{28} \vee x_{29}) \vee (x_{30} \vee x_{31})(x_{30}x_{31} \vee x_{32})) \wedge$$
$$\wedge(x_{27}x_{28}x_{29} \vee x_{30} \vee x_{31} \vee x_{32})$$

$$f_7^3 = x_{27} \vee x_{28} \vee x_{29} \vee (x_{30} \vee x_{31})(x_{30}x_{31} \vee x_{32})$$

$$f_8^3 = (x_{27} \vee x_{28})(x_{27}x_{28} \vee x_{29}) \vee x_{30} \vee x_{31} \vee x_{32}$$

The graph of the model has is presented in fig.6.

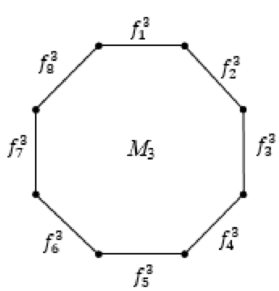

Fig. 6 Model M_3 $K(5, 12)$

The fourth subsystem will correspond to the model $K(2, 7)$ with edge functions:

$$f_1^4 = x_{33} \vee x_{34}$$

$$f_2^4 = x_{33}x_{34} \vee x_{35}x_{36}$$

$$f_3^4 = x_{35} \vee x_{36}$$

$$f_4^4 = x_{33}x_{34}x_{35}x_{36} \vee x_{37}x_{38}x_{39}$$

$$f_5^4 = x_{37} \vee x_{38}$$

$$f_6^4 = x_{37}x_{38} \vee x_{39}$$

The graph of the model has is presented in fig.7.

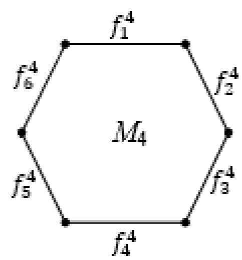

Fig.7. Model M_4 $K(2, 7)$

The fifth subsystem will correspond to model $K(4, 15)$ with edge functions:

$$f_1^5 = x_{40} \vee x_{41} \vee x_{42} \vee x_{43}$$

$$f_2^5 = (x_{40} \vee x_{41} \vee x_{42}x_{43})(x_{40}x_{41} \vee x_{42} \vee x_{43}) \vee x_{44}x_{45}x_{46}x_{47}$$

$$f_3^5 = (x_{40} \vee x_{41})(x_{40}x_{41} \vee x_{42}x_{43})(x_{42} \vee x_{43}) \vee$$
$$\vee(x_{44} \vee x_{45})(x_{44}x_{45} \vee x_{46}x_{47})(x_{46} \vee x_{47})$$

$$f_4^5 = x_{40}x_{41}x_{42}x_{43} \vee (x_{44} \vee x_{45} \vee x_{46}x_{47})(x_{44}x_{45} \vee x_{46} \vee x_{47})$$

$$f_5^5 = x_{44} \vee x_{45} \vee x_{46} \vee x_{47}$$

$$f_6^5 = (x_{40} \vee x_{41} \vee x_{42}x_{43})(x_{40}x_{41} \vee x_{42} \vee x_{43}) \wedge$$
$$\wedge((x_{40} \vee x_{41})(x_{40}x_{41} \vee x_{42}x_{43})(x_{42} \vee x_{43}) \vee x_{44}x_{45}x_{46}x_{47}) \wedge$$
$$\wedge(x_{40}x_{41}x_{42}x_{43} \vee (x_{44} \vee x_{45})(x_{44}x_{45} \vee x_{46}x_{47})(x_{46} \vee x_{47})) \wedge$$
$$\wedge(x_{44} \vee x_{45} \vee x_{46}x_{47})(x_{44}x_{45} \vee x_{46} \vee x_{47}) \vee x_{48}x_{49}x_{50}x_{51}x_{52}x_{53}x_{54}$$

$$f_7^5 = (x_{40} \vee x_{41})(x_{40}x_{41} \vee x_{42}x_{43})(x_{42} \vee x_{43}) \wedge$$
$$\wedge(x_{40}x_{41}x_{42}x_{43} \vee x_{44}x_{45}x_{46}x_{47}) \wedge$$
$$\wedge(x_{44} \vee x_{45})(x_{44}x_{45} \vee x_{46}x_{47})(x_{46} \vee x_{47}) \vee$$
$$\vee(x_{48} \vee x_{49})(x_{48}x_{49} \vee x_{50}x_{51})(x_{50} \vee x_{51}) \wedge$$
$$\wedge(x_{48}x_{49}x_{50}x_{51} \vee x_{52}x_{53}x_{54})(x_{52} \vee x_{53})(x_{52}x_{53} \vee x_{54})$$

$$f_8^5 = x_{40}x_{41}x_{42}x_{43}x_{44}x_{45}x_{46}x_{47} \vee$$
$$\vee(x_{48}x_{49} \vee x_{50} \vee x_{51})(x_{48} \vee x_{49} \vee x_{50}x_{51})\wedge$$
$$\wedge((x_{48} \vee x_{49})(x_{48}x_{49} \vee x_{50}x_{51})(x_{50} \vee x_{51}) \vee x_{52}x_{53}x_{54})\wedge$$
$$\wedge(x_{48}x_{49}x_{50}x_{51} \vee (x_{52} \vee x_{53})(x_{52}x_{53} \vee x_{54}))(x_{52} \vee x_{53} \vee x_{54})$$

$$f_9^5 = x_{48} \vee x_{49} \vee x_{50} \vee x_{51}$$

$$f_{10}^5 = (x_{48} \vee x_{49} \vee x_{50}x_{51})(x_{48}x_{49} \vee x_{50} \vee x_{51}) \vee x_{52}x_{53}x_{54}$$

$$f_{11}^5 = (x_{48} \vee x_{49})(x_{48}x_{49} \vee x_{50}x_{51})(x_{50} \vee x_{51}) \vee (x_{52} \vee x_{53})(x_{52}x_{53} \vee x_{54})$$

$$f_{12}^5 = x_{48}x_{49}x_{50}x_{51} \vee x_{52} \vee x_{53} \vee x_{54}$$

The graph of the model has is presented in fig. 8.

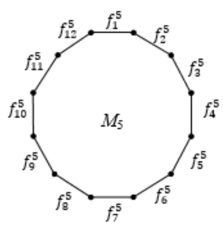

Fig. 8 Model M_5 $K(4, 15)$

According to the statuses of subsystems calculated by means of the above models we will create a state vector for model M_0^S: $<y_1, y_2, y_3, y_4, y_5>$, where y_j corresponds to a graph connectivity of the corresponding submodel: 1, if connected graph and 0 otherwise. Model K(2, 5) will have the following edge functions:

$$f_1^S = y_1 \vee y_2$$

$$f_2^S = y_1y_2 \vee y_3$$

$$f_3^S = y_1y_2y_3 \vee y_4y_5$$

$$f_4^S = y_4 \vee y_5$$

The graph of the model has is presented in fig.9.

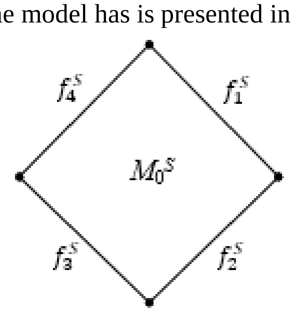

Fig. 9 Model M_0^S $K(4, 15)$

Now we will turn to the above-noted features of the proposed method, namely, the construction of the M_0^P model corresponding directly to the processors of the upper-level subsystem. This model $K(3, 10)$ for the input vector containing the variables displaying statuses of processors of a submodel of the top level $<x_{55}, x_{56}, x_{57}, x_{58}, x_{59}, x_{60}, x_{61}, x_{62}, x_{63}, x_{64}>$ will have the following edge functions:

$$f_1^P = x_{55} \vee x_{56} \vee x_{57}$$

$$f_2^P = (x_{55} \vee x_{56})(x_{55}x_{56} \vee x_{57}) \vee x_{58}x_{59}$$

$$f_3^P = x_{55}x_{56}x_{57} \vee x_{58} \vee x_{59}$$

$$f_4^P = (x_{55} \vee x_{56})(x_{55}x_{56} \vee x_{57})(x_{55}x_{56}x_{57} \vee x_{58}x_{59})(x_{58} \vee x_{59}) \vee$$
$$\vee x_{60}x_{61}x_{62}x_{63}x_{64}$$

$$f_5^P = x_{55}x_{56}x_{57}x_{58}x_{59} \vee$$
$$\vee (x_{60} \vee x_{61})(x_{60}x_{61} \vee x_{62})(x_{60}x_{61}x_{62} \vee x_{63}x_{64})(x_{63} \vee x_{64})$$

$$f_6^P = x_{60} \vee x_{61} \vee x_{62}$$

$$f_7^P = (x_{60} \vee x_{61})(x_{60}x_{61} \vee x_{62}) \vee x_{63}x_{64}$$

$$f_8^P = x_{60}x_{61}x_{62} \vee x_{63} \vee x_{64}$$

The graph of the model has is presented in fig.10.

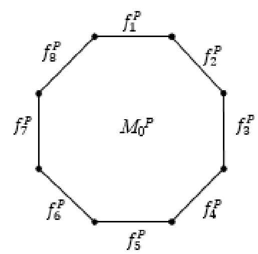

Fig. 10 Model M_0^P $K(3, 10)$

Let's create a vector $<w_0^S, w_0^P>$, where w_0^S and w_0^P correspond to the connectivity of graphs of submodels M_0^S and M_0^P respectively: 1, if connected graph and 0 otherwise. This vector will be used as a submodel of the top level of M_0. This model $K(0, 2)$ as it was already shown, will be based on the linear graph (the cyclic graph with a removed edge) and will have the following edge functions:

$$f_1^0 = w_0^S$$

$$f_2^0 = w_0^P$$

The graph of the model has is presented in fig. 11.

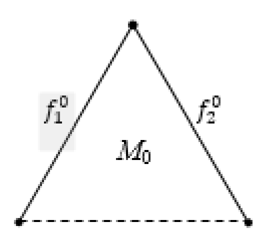

Fig. 11 Model M_0 $K(0, 2)$

In general the system model is presented on fig. 12. It has three hierarchy levels and consists of eight submodels.

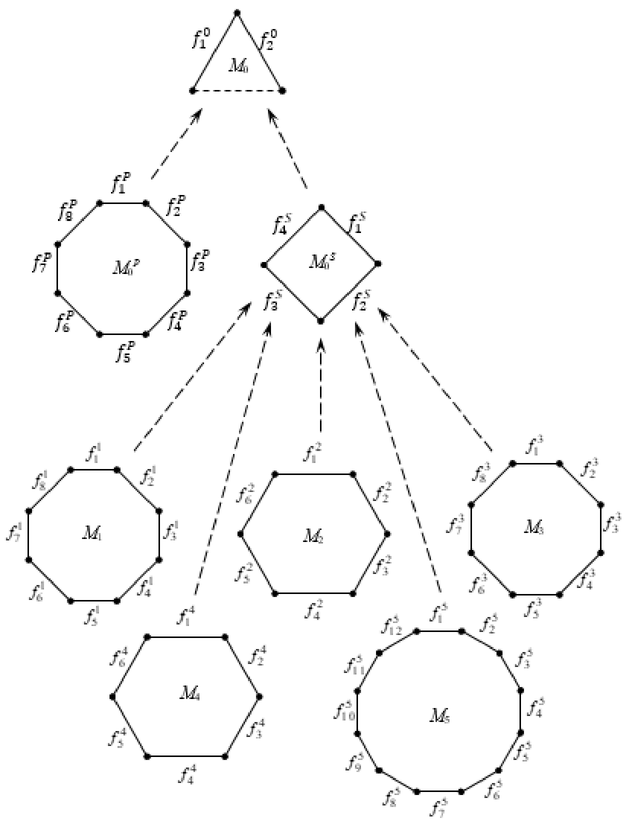

Fig. 12 Model of the system

5. Conclusions

Calculation of hierarchical systems reliability parameters is a difficult task. For creation of the general GL-model that reflects the behavior of the system as a whole is proposed to build separate submodels, for each subsystems, integrating them in a single model.

In a hierarchical system, subsystems can contain not only subsystems of lower levels, but also processors themselves. As a rule these processors cannot replace the failed subsystems. Besides, the possibility of arbitrary mutual replacement both among subsystems and among processors not always takes place. It is in that case offered to separate both processors and subsystems into groups (in which mutual replacement is possible) and build separate GL-model for each of this group. Further the received models integrate by means of models of higher levels, forming hierarchical model. It is assumed that as components of the state vectors of models of higher levels of the hierarchy may use the results obtained by using models at lower levels.

As models of top levels, at the same time, not only the models responding some subsystems but also the auxiliary models which are used only for combination of results of submodels of the bottom levels are used. Thus, quantity of hierarchy levels in model and a system, as well as quantity of objects on each of them can be different.

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