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Multilevel redundancy allocation using two dimensional arrays encoding and hybrid genetic algorithm ☆

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ABSTRACT

With the popularity of multilevel design in large scale systems, reliability redundancy allocation on multilevel systems is becoming attractive to researchers. Multilevel redundancy allocation problem (MLRAP) is not only NP-hard, but also qualifies as hierarchy optimization problem. Exact method could not tackle MLRAP very well, so heuristic and meta-heuristic methods are often used to solve it. To improve the effectiveness of current algorithms on MLRAP, this paper proposes a hybrid genetic algorithm (HGA) based on the two dimensional redundancy encoding mechanism. Instead of hierarchical genotype representation, a two dimensional array is used to represent the solutions to MLRAP. Each row of the array contains the redundancy information of a certain unit in the system and each element in one row stands for the redundancy value of one element of that unit. The number of rows of this array is fixed and equals to the number of distinct units in the system. Each row of the array is an unfixed-length vector whose length depends on the redundancy of all elements of its parent unit. On top of this two dimensional arrays, a local search operator employing simulated annealing strategy is used to generate new population for the next generation instead of the traditional genetic operators. Experimental results have shown that our two dimensional arrays based HGA outperforms the state-of-the-art approaches using two kinds of multilevel system structure.

1. Introduction

The demand for complex processing tends to make the scale of real world systems increasingly large. Multilevel design is often used for large-scale systems and reliability has also become a great concern for them. The reliability of multilevel systems could be calculated from lower-level modules or components and also could be improved through provision of redundant components (Kuo & Wan, 2007). The difference between redundancy configuration in multilevel systems and that in single-level systems is that redundancy could be allocated to sub-systems or components at any level. Similar to small systems, the reliability of a multilevel system could also be optimized by allocating appropriate redundancy to less reliable subsystems or components at different levels, subject to certain constraints (Kumar, Izui, & Masataka, 2008). To decrease the additional cost brought by redundant components, the tradeoff of redundancy on different level should be considered. Thus, multilevel redundancy allocation problem (MLRAP) is becoming increasingly attractive mainly for the following reasons. Firstly, multilevel redundant designs are prevalent in many practical systems, such as communication systems, computing systems, control systems, and critical power systems (Wang, Loman, & Vassiliou, 2004). The popularity of service-oriented technology and web service composition has also provided the possibility of multilevel software system design. Secondly, comparing with traditional redundancy allocation problem, which is nonlinear integer programming problem and NP-hard (Chern, 1992), multilevel redundancy allocation problem qualify as hierarchical optimization problems (Anandlingam & Friesz, 1992). The complexity of such problems is much larger than the traditional ones.

In spite of its importance in the real world, MLRAP has rarely been investigated, and few approaches have been proposed. To provide a general representation of MLARAP, a hierarchy solution encoding mechanism is proposed by Kumar et al. (2008) and the following researches (He, Wu, & Wen, 2012; Wang, Tang, & Yao, 2010) employ the same mechanism to implement their genetic algorithm (GA) or memetic algorithm (MA). The hierarchy

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Nomenclature

U_i	the ith unit
U_{im}	the mth child unit of U_i
U_{im}^j	the jth redundant unit of mth child unit of U_i
n_i	the number of child units of U_i
x_{im}	the number of redundant units of U_{im}
R_i	the reliability of U_i
R_{im}^j	the reliability of U_{im}^j
R_{sys}	the reliability of system
C_i	the cost of U_i
C_{im}^j	the cost of U_{im}^j
λ_{im}	the additional cost of U_{im} when configuring redundancy
C_{sys}	the cost of system
$\boldsymbol{x}$	a set of units redundancy x_{im}
$\boldsymbol{X}$	the array of $\boldsymbol{x}$ using two dimensional array encoding mechanism
$\lvert\boldsymbol{X}\rvert$	the number of rows of $\boldsymbol{X}$
n_X	the number of nonredundant units in a system
$\boldsymbol{X_i}$	the vector of redundancy of each element of U_i
$\lvert\boldsymbol{X_i}\rvert$	the number of columns of $\boldsymbol{X_i}$
X_{ij}	the number of redundant units of jth element of U_i
R_{sys_i}	the reliability of system after increasing the redundancy of U_i by 1
C_{sys_i}	the cost of system after increasing the redundancy of U_i by 1
ΔR_{sys_i}	$R_{sys_i} - R_{sys}$
ΔC_{sys_i}	$C_{sys_i} - C_{sys}$
$\boldsymbol{y}$	a vector of units' parent unit
y_i	the parent unit of U_i

redundancy encoding mechanism could present the redundancy of multilevel system in a good manner, however, there are two shortcomings with this kind of mechanism and corresponding algorithms: (1) The result of hierarchy encoding is an un-fixed length array and it is difficult to implement genetic algorithm, which often works on fixed length of vector. (2) To implement algorithms on un-fixed length array, the crossover or mutation operation is often taken by level. For example, the memetic algorithm proposed by Wang et al. (2010) first selects a level in the system and then selected units from the certain level to do the following operation. This kind of operation heavily depends on the level division of a system and lost the generality of considering the units in a unified manner.

To tackle the above two problems, this paper first proposes a two dimensional genotype encoding strategy and converts the solution into a two dimensional arrays. For each system, there are fixed number of rows in this array and the number of rows equals to the number of units without redundancy in the system. A row of the array is a one dimensional array (a vector) with unfixed number of nodes representing the redundancy of all elements of that unit belonging to different parent units. The number of the columns in one row depends on the overall redundancy of its parent units, so the length of each vector is unfixed. Using this kind of encoding mechanism, each unit in the system could be treated in a unified manner. And since the number of rows is fixed, it is easier to conduct genetic algorithm operators. According to researches of Krasnogor and Smith (2005), MAs (Moscato, 1989) have been reported to search more efficiently than conventional GAs due to the local search procedure. So, this paper then conducts a further improvement on the genetic algorithm and proposes a two dimensional array based hybrid genetic algorithm (TDA-HGA) to solve MLRAP. An iterative local search method based on two dimensional solution arrays and simulation annealing algorithm is employed in TDA-HGA. Detailed experiments are conduct to compare our algorithm with MA provided by Wang et al. (2010) and improved memetic algorithm (IMA) by He et al. (2012) using the same system structures.

The whole paper is organized as follows: Section 2 provides related work on the redundancy allocation problem and MLRAP. Section 3 summarized the description of MLRAP and the corresponding problem formulation. Two dimensional array genotype encoding mechanism for solution of MLRAP is presented in Section 4 and the corresponding hybrid genetic algorithm is given in Section 5. Section 6 listed experiments and comparison results on the TDA-HGA and MA followed the conclusion of the whole paper in Section 7.

2. Related work

Traditional reliability redundancy allocation has been researched for decades. Optimal redundancy allocation attempts to achieve balance between reliability improvement and cost increase. According to the designers of systems, optimal redundancy allocation problem could be formulated into maximizing reliability under certain cost constraint or minimizing overall cost to achieve the reliability demand (Kuo & Wan, 2007).These problems have been well researched and various approaches have been provided to solve the problem including meta-heuristic methods (Lee, Yun, & Gen, 2002), exact methods (Lin & Kuo, 2002) and so on. Based on the formulation of a restricted problem and column generation decomposition, Zia and Coit (2010) proposed an optimization method, which got possible better solutions through a set of subproblems. In the majority cases presented by the authors, the overall quality of the solution matched or outperformed most of the existing heuristic methods with less computation time. To simultaneously optimize the system reliability, cost, weight and volume, researchers pay more and more attention to multi-objective system redundancy allocation recently. For multi-objective optimization of system redundancy allocation, Zio and Bazzo (2011) used the recently introduced Level Diagrams technique for graphically representing and reducing the resulting Pareto Front and Set. Assuming that there were functionally equivalent components with different performance in the network, Ramirez-Marquez and Rocco (2010) presented a three-step evolutionary algorithm for solving multi-objective optimization models in multi-state systems. Due to their robustness and feasibility, many meta-heuristic algorithms including memetic algorithm (Wang et al., 2010), hybrid genetic algorithm (Lee et al., 2002) and ant colony optimization (Liang & Smith, 2004) have been widely and successfully applied. For redundancy allocation in more general system other than the traditional binary series–parallel system, Li, Zuo, and Moghaddass (2011) reported their work of optimal reliability design in multi-state weighted series–parallel systems, in which there were multiple kinds of choices for the components. Genetic algorithm was used to solve the proposed physical programming based optimization model. To solve the constrained optimization problem of a system with interval valued reliability of each