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Successive approximate model based multi-objective optimization for an industrial straight grate iron ore induration process using evolutionary algorithm

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ABSTRACT

Multi-objective optimization of any complex industrial process using first principle computationally expensive models often demands a substantially higher computation time for evolutionary algorithms making it less amenable for real time implementation. A combination of the above-mentioned first principle model and approximate models based on artificial neural network (ANN) successively learnt in due course of optimization using the data obtained from first principle models can be intelligently used for function evaluation and thereby reduce the aforementioned computational burden to a large extent. In this work, a multi-objective optimization task (simultaneous maximization of throughput and Tumble index) of an industrial iron ore induration process has been studied to improve the operation of the process using the above-mentioned metamodeling approach. Different pressure and temperature values at different points of the furnace bed, grate speed and bed height have been used as decision variables whereas the bounds on cold compression strength, abrasion index, maximum pellet temperature and burn-through point temperature have been treated as constraints. A popular evolutionary multi-objective algorithm, NSGA II, amalgamated with the first principle model of the induration process and its successively improving approximation model based on ANN, has been adopted to carry out the task. The optimization results show that as compared to the PO solutions obtained using only the first principle model, (i) similar or better quality PO solutions can be achieved by this metamodeling procedure with a close to 50% savings in function evaluation and thereby computation time and (ii) by keeping the total number of function evaluations same, better quality PO solutions can be obtained.

1. Introduction

Multi-objective evolutionary algorithms, specially based on genetic algorithms, when amalgamated with computationally expensive first principle process models, demand a lot of computational time, which makes the application less amenable to real time implementations. The fact that the evolutionary algorithms are robust optimizers with proven search capabilities and their inherent capabilities of dealing with mixed kind of variables (real, binary or integer) making them very popular and useful for many practical optimization applications encourages the decision maker to work with selective use of these expensive models so that the applications can be utilized on a real time basis (Nain and Deb, 2002). The main cause of the computational burden is the repetitive function evaluations for different candidate solutions in evolutionary algorithms. Since evolutionary algorithms work with a population of candidate solutions, this kind of function evaluations cannot really be avoided because a substantial reduction of population number used for different generations may not really help the two main purposes of these multi-objective evolutionary algorithms in terms of identifying the high quality fairly spread PO solutions (Deb, 2001). One of the ways towards achieving this is the use of metamodels or approximation models of the actual first principle models successively trained during the course of optimization and their intelligent usage to achieve the goals (Nain and Deb, 2002).

The idea of usage of approximate models in conjunction with the first principle model originated from the effort of carrying out optimization of computationally expensive models such as programs that use computational fluid dynamics or finite element methods where each of function evaluation may need a day's time. Primary questions raised against the use of approximate models were whether the quality of PO solutions and their spread

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in the PO front obtained by approximate models are comparable to the solutions obtained by optimization using first principle models alone. Several researchers have reported their research studies in the field of metamodeling using evolutionary algorithms. An exhaustive survey on metamodeling techniques used in evolutionary computation has been conducted by Jin (2005). There could be approximations broadly at three levels: problem approximation, function approximation and evolutionary approximation. Problem approximation brings in a new problem statement that is easier to solve (Bradshaw et al., 1976). Function approximation formulates an alternate implicit or explicit function of the original function, which is faster to solve. On the other hand, in evolutionary approximation, the fitness value of the offspring individuals can be estimated from the fitness value of their parents (fitness inheritance, Smith et al. (1995)). Another approach could be that only the individual that represents its cluster will be evaluated using the fitness function (individuals are clustered into several groups) and the fitness of other individuals in the same cluster will be estimated from the representative individual based on a distance measure (fitness imitation, Kim and Cho (2001)). Sastry et al. (2001) made an attempt to use inheritance along with population sizing models and reported a saving of 20% function evaluation whereas fixing the population size, a 70% savings in function evaluation has been reported. Chen et al. (2002) extended this to multi-objective optimization and reported 40% savings without fitness sharing and 25% savings with fitness sharing. Interestingly, approximate models have been embedded in almost every element of evolutionary algorithms, including migration (Eby et al., 1998), initialization, crossover (Rasheed and Hirsh, 2000), mutation (Abboud and Schoenauer, 2002; Anderson and Hsu, 1999), and fitness evaluations. In the migration concept, the entire population is divided into several sub-populations (island concept) each one of which can be introduced for different resolutions of approximation. At a certain frequency, the individuals in the sub-populations that use higher accuracy approximations are migrated into those using approximations of lower accuracy though each one of them is evolved on their own (Eby et al., 1998). Rasheed and Hirsh (2000) used reduced models to build informed mutation and crossover operators for a complex engineering design problem that speeds up the process of ranking and selection and thereby evolutionary algorithm procedure. Different approximate models for function approximation use techniques from response surface (Farina, 2002), multivariate adaptive regression splines (Clarke et al., 2005), kriging (El-Beltagy et al., 1999; Ratle, 1998), artificial neural networks (Nain and Deb, 2002), radial basis function (Powell, 1987; Nakayama et al., 2002; Meghabghab, 2001) and support vector regression (Vapnik, 1998; Evgeniou et al., 2000; Clarke et al., 2005) methodologies. Though these methods can reduce exact function evaluation to a large extent, accuracy of the function evaluation using approximate model is of prime importance, which otherwise can mislead the search process completely. This has been addressed in evolutionary literature as model management or evolution control. This can be of different types: in presence of high fidelity model, function evaluation can be completely replaced by approximate models (no evolution control, Biles (1994)); exact function evaluation can be used judiciously for few generations (called controlled generations) out of the total number of generations or for few individuals in a population (called controlled individuals) and rest using approximate models either in fixed manner (fixed evolution control, Bull (1999), Ratle (1998)) or in truly in adaptive manner (adaptive evolution control, Dennis and Torczon (1997)). A framework given by Jin et al. (2002) guarantees the correct convergence while reducing the computational cost showing the use of controlled evolution in evolutionary strategy. On the other hand, the idea of controlled individuals using clustering and neural network has been studied by Jin and Sendhoff (2004). Here individuals around the center of the cluster were evaluated using expensive function evaluation whereas rests of the individuals were estimated using neural network trained using the expensive function evaluations. There have been quite a few studies (Carpenter and Barthelemy, 1994; Shyy et al., 1999; Simpson et al., 1998) that compare between various approximation based optimization techniques as mentioned above but no clear conclusions have been drawn on the advantages and disadvantages of the different approximation models. Most recently, approximate fitness evaluations have also been employed in evolutionary multi-objective optimization. Farina (2001, 2002) used radial basis neural network for approximating objective function in multi-objective optimization. Nain and Deb (2002) adopted controlled generation approach while combining feed-forward neural network and multi-objective evolutionary algorithms in a fixed evolution control mode for various multi-objective optimization problems and reported a savings up to 50% of function evaluations. Oduguwa and Roy (2002) conducted a multi-objective optimization study of rolling rod product design using a combination of design of experiments and response surface models replacing expensive finite element models. Fang et al. (2005) conducted the multi-objective optimization in vehicle crash studies using approximate modeling approaches such as response surface and radial basis function in place of original finite element based expensive calculations and reported that the former works better for mild non-linearities and the latter is good for approximating severe non-linearities at the cost of relatively more computational time. Messac and Mullur (2008) used the concept of pseudo-response surface and extended radial basis function to come up with an approach for building pseudo-response surface models that are accurate only in the vicinity of the Pareto region while carrying out multi-objective optimization for structural examples. Li et al. (2010) conducted a comparative study of various metamodeling techniques such as artificial neural network, radial basis function, support vector regression, kriging and multivariate adaptive regression splines, and concluded support vector regression to be the best found for their examples while carrying out job shop design optimization using single objective genetic algorithms. Gholap and Khan (2007) applied the concept of response surface for saving the computational cost behind the detailed thermodynamic model calculations for carrying out the alternative Pareto design analysis considering the trade-off between energy consumption and material cost. Similar applications of metamodeling associated with multi-objective optimization studies can be found in the literature for drawbead design (Sun et al., 2010), structural dynamics (Guedri et al., 2009), dynamics of the non-linear structures (Bouazizi et al., 2009) and crashworthiness design (Hou et al., 2008).

Iron ore induration is an essential step in the iron ore mineral processing and is considered to be critical for the downstream ironmaking steps. In this work, a multi-objective optimization task (simultaneous maximization of throughput and Tumble index, TI) of an industrial iron ore induration process has been studied to improve the operation of the process using a metamodeling approach. It is worth mentioning here that these steady state model based optimization applications generally appear in real time optimization (RTO) layer, one layer above the advanced process control (APC) layer, where APC algorithms try to keep the process around the target set by these RTO applications. These optimization applications, therefore, have to supply the target values for the APC layer with a particular frequency (poling frequency) and optimization at RTO layer has to be completed before that stipulated time. This requirement, in turn, controls the quality of Pareto optimal (PO) solutions to be supplied to the APC layer because better quality PO solutions could have been supplied to the APC layer had the optimization been completed much faster allowing more generations to be completed. Moreover, a faster completion of the optimization run has the potential to improve the poling frequency