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Multi-Objective GA-Based Optimization to Maximize Sustainability for Product Design and Manufacturing.

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ABSTRACT

Responding quickly and economically to the diversification of customer needs has forced manufacturing companies adopting approaches to delivering low cost, high quality sustainable products based on finding a link between the design or the manufacturing processes and other key elements of sustainability; economic, environmental, and social. However, these approaches had limited success. The most likely reason for the lack of integration between the design and manufacturing stages of the product and complexity of addressing the above mentioned three key elements of sustainability due to existing of many variables in relation to design, manufacturing, locations, logistic operations and so on. Taking into account the required integration as well as the associated complexity of considering sustainability elements can lead to large space alternative solutions and it is more difficult to use only exact methods to the optimization of such problem. This paper presents a genetic algorithm (GA) approach aiming to optimize a high sustainability performance by designing a product and the corresponding manufacturing processes for that product. Process optimization is carried out in terms of the highest fitness function achieved where different objectives are to be optimized simultaneously. The proposed GA approach is applied to the industrial case example. The proposed approach can assist decision makers to help explain when justifying their decision on what are the best product design and its manufacturing processes to obtain high sustainability performance.

1. Introduction

In recent times the manufacturing industry was needed for sustainable growth and development to keep the challenges faced caused by global competition, increasing the demands of market, and limited availability of resource. Consequently, manufacturers have increased their emphasis on the three pillars of (sustainability, economic, social and environmental) also known as “the triple bottom line or the "3P" (planet, people, and profit) [1]. Most of the manufacturing organizations expend large quantities of resources at the same time generate wastes and pollution. However with recent increase in sustainability issues, organizations should consider taking suitable measures to enhance their sustainability aspects. It has thus become the need of the time for manufacturers to pursue manufacturing activities, which helps in minimizing environmental impacts while maintaining social and economic benefits [2]. Thus, the design and manufacturing of sustainable products need to follow a comprehensive approach that simultaneously considers the economic, environmental, and societal aspects of the TBL. For this reason, genetic algorithm (GA) is proposed to solve the problem of Sustainable manufacturing and design of product optimization, targeting the yield of optimal (or near-optimal) solution in large search areas quite faster than other optimization techniques due to their feature of parallel searching [6]. In the present time, GA that is needed for such demonstration doesn't exist in literature on the topic.

Liu et.al, (2017) proposed model for the problem of bi-objective optimization which reduce the total non-processing consumption of electricity, and total tardiness of weighted in job shop. One of the applied approaches for electricity saving is the (Turn off/Turn on) approach. Novel multi-objective genetic algorithm based on NSGA-II was developed. For the purpose of expanding the solution pool, two new steps were introduced and then the elite solutions selected. The research was focusing on the environment of classical job shop, which is used widely in the manufacturing industry and offers significant opportunities for saving energy [3].

Zhou et.al, (2008) this paper gave an integrated approach for optimize the multi-objectives of material selection. This was based on the material characteristics consideration, and sustainable strategies. Selecting suitable materials help designers to develop sustainable products for requirements satisfying; materials evaluation indicators are presented. The Life Cycle Assessment method (LCA method) was used to calculate the environmental impacts. An integration of artificial neural networks (ANN) with genetic algorithms (GAs) is proposed to optimize the multi-objectives of material selection [4]

Wu, et.al (2010) A multi-objective genetic algorithm has been proposed for optimizing the design of Water Distribution Systems. Environmental objective (minimization of GHG emissions) has been taken into account in addition to the traditional economic objective (minimization of total life cycle cost). The results showed that the presence of GHG emission minimization as one objective result in significant trade-offs in the form of a Pareto-optimal front between the economic and environmental objectives. [5]

However, these approaches had limited success. The most likely reason for the lack of integration between the design and manufacturing stages of the product and complexity of addressing the above mentioned three key elements of sustainability due to existing of many variables in relation to design, manufacturing, locations, logistic operations and so on.

In the next section GA is evaluated as the approach for optimization selected, also a description of the structure developed for this approach to handle the design example problem presented in this paper. Section 3, introduces the details of design example problem that this paper tries to solve. Then the results of the GA results search are presented in section 4. Finally, in section 5, the conclusion of this paper is presented.

2. Genetic Algorithm (GA)

Genetic Algorithm (GA) is considered one of the most popular approaches that can be used to solve problems, particularly for NP-hard and complex optimization problems [7]. It is also a computer based technique, which is adapted and developed for a changing and highly competitive environment. GA therefore has the sets of advantages over the other meta-heuristic techniques [8]. GA is a population based approach enabling simultaneous searches from a wide sampling of target space. In forthcoming next sections details about the structure of GA.

2.1 Fundamental Procedures of GA

Genetic algorithm (GA) has been recognized as a robust adaptive technique for optimizing the multi-objective problems (e.g. sustainable manufacturing and design of product problem in this paper) especially when these objectives are converted into a single objective [9]. GA is a meta-heuristic (a heuristic that uses another heuristic) stochastic technique aimed at finding a solution that is global and optimal for the problem of combinatorial optimization (Onwubolu 2001). It mimics the mechanism of genetics and natural selection (survival of the fittest) natural genetics that described by Charles Darwin [10] and was introduced GA in the 1960's and 1970's as a technique to develop an optimal solution from a population of initial feasible solutions available for solving an optimization problem. The routinely used form of GA was further extended and popularized by [11]. GA belongs to larger type of evolutionary algorithms (EA) as they include the two main principles of the natural evolution which are used in EA; evolutionary programming and evolution strategies. GA has been successfully applied successfully to solve a diverse range of optimization problems in engineering design and planning.

2.2 Design of the GA structure for the optimization of the sustainable product design and manufacturing

This section presents the structure of genetic algorithm used for optimizing sustainable design and manufacturing of product in manufacturing systems. The essential ingredients of genetic algorithm are:

chromosome (solution) representation; generation of initial population; reproduction operators (crossover and mutation); fitness function; selection operator; and termination criterion. Figure1 illustrates the scheme of genetic algorithm which used for minimizing the cost of the final product in production facilities. Each part of the cycle creates a new generation which is considered as a potential solution for a specified problem and the cycle is iterative until a termination condition is achieved.

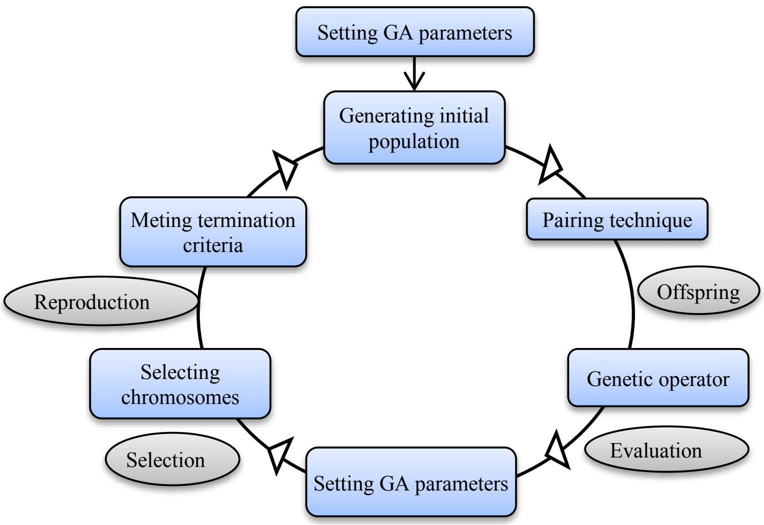


Figure 1. The GA scheme for optimization of sustainable product design and manufacturing

2.2.1 The Chromosome Representation

The search of GA for solutions which are optimal or (near-optimal), begins by the generation of a number of individuals at "initial random population of solutions". Every individual in the population is a representative chromosome for the problem solution. A chromosome is a series of symbols or a group of genes) that can be encoded in different forms (binary, integer, real, etc.). Figure (2) represent chromosome vector. This step is a key issue in GA work due to their significant effects on the subsequent steps. For the problem that is considered in this work, variables of real coded values are adopted for chromosome presentation. Every chromosome (solution) of Sustainable manufacturing and design of product includes a vector of real decision variables and it's close to the practical problem structure.

1	1	2	4	1	3	2	1

Figure 2. Example of chromosome real encoded

2.2.2 Generation of the Initial Population

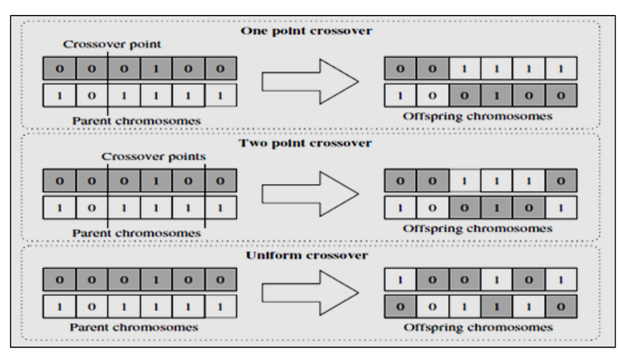
The number of chromosomes in population is called population size. The generation of initial population can be created randomly or according to heuristic procedures [12]. Anderson and Ferris (1994) have indicated that the performance of GA algorithms is not as good from well-adapted (seeded) population as it is from a random start. Based on that, the chromosomes in an initial population in this paper are all randomly generated.

2.2.3 Fitness Evaluation Scheme

To assess sustainable design and manufacturing of product scenarios which are generated using GA implementation, a scheme for fitness function evaluation is designed to adequately assign a numerical value proportional to its overall quality. Basically the evaluation scheme in the GA search toward finding an optimal solution for multiple objective design problems requiring employing three key elements: the objective functions and imposed constraints, fitness function evaluation and a mechanism for handling the constraints .Based on this, the development of a fitness evaluation scheme comprises defining the objective functions to minimize or maximize defining the constraints of sustainable design and manufacturing of product that have to be dealt with, formulating the fitness evaluation function, and setting a mechanism to account for unsatisfied constraint solutions. The mathematical model of GA completes three objective functions. Depending on the preference of the measures in the system design, a list of three objective functions with applying GA to optimize Sustainable design and manufacturing of product in this paper includes:

1. Minimize the manufacturing cost
2. Minimize the carbon dioxide emission
3. Maximize the rate of recycling

Atiya et al., (2017) presented these objective functions with detailed formulation, assumptions, input



parameters, constraints, and decision variables. Since the objectives (1) and (2) must be minimized and (3) must be maximized (as stated above), then the converting of these multiple objectives to a single overall objective function is required, known as (resultant objective function). Fitness function which requires a final optimization will be considered from this resultant objective function. The converting of multiple objectives to single objective will be done by using the desirability function approach [13] and in two stages; (i) individual desirability's and (ii) overall desirability.

2.2.4 Selection Strategy

Establishing a strategy to select the best chromosomes (solutions) is required, since those chromosomes in the current generation are used to reproduce the next generation. With the GA implementing, there will be two strategies of selection for the chromosomes choosing which will be used for new chromosomes reproduction; elitist and non-elitist. To avoid losing best solutions in population elitist strategy is used here by saving a number of these solutions and later copying it into the next generation for the evolution process.

2.2.5 Genetic Operators

Currently, there are numerous known types of operators. However, the scope of this paper is beyond these operators. Following is a short background about every operator rule in the process of evolving of GA, along with the operators' types selected for this paper.

1. Selection process: the theory of Darwin's evolutionary for the fittest survival is applied in the process of parent selection for chromosomes in GA applications. Depending on this law, chromosomes that have high values of fitness function are chosen for genetic operations using the process of stochastic selection (Goldberg 1989). In this paper the roulette wheel technique is applied, because it is easy to implement and emulates nature faithfully, and therefore is much more attractive [14].

2. Crossover: crossover or recombination is the process most widely used by which a chromosome pair recombines to generate a new chromosome pair (offspring). As the name implies, this process involves swapping some parts (genes) between the pair selected chromosomes. The crossover operators have a very big chance of reproducing the parent chromosomes' desirable features, and consequently expect to improve the solution quality of the problem undertaken.

Figure 3. Crossover Operator

3. Mutation: it is another operator of genetic; a mutation is applied on single chromosome to create a modified mutant — addition of new offspring for the population. In the operation of mutation, one gene values or more of the chromosome that has been created is randomly selected as replacement for creating another offspring. With the new offspring, the GA could be capable of reaching more optimal solution than what was possible earlier with the using of crossover operator.

Figure 4. Mutation Operator

2.2.6 Mechanism of Constraints Handling

The feasibility of any design solution is must be known (especially if any conflict exists) before the evaluating of all design objectives as outcomes of the modeling process. Based on (the overall desirability function) mathematical model stated in [15] the overall desirability function is equal to (0) if any value of for anyone from the objective functions = 0. Thus, the GA exploration for reaching an optimal solution cannot involve infeasible solutions which include measured values located outside acceptable limits (e.g. = 0).

2.2.7 Stopping Criteria

When the quality of the problem solution on hand is not improved significantly per generation, GA is usually stopped. Thus, stopping criteria must be decided by the designer of the algorithms. Because letting the algorithms run too long will cause waste of time and computational power, also the solutions that has previously searched out by algorithms will be revisit. The suggested stopping criteria are:

- The process of algorithmic search will be stopped if acceptable design solution is reached for Sustainable manufacturing and design of product.

- The GA search should be stopped if no significant variations are appreciated in the average values of fitness function for a certain generations number.

3. Illustrative Example: Using Designed GA to Determine Optimal Design of Product and its Manufacturing Process

The illustrative example relates to one of leading manufacturers of hydraulic cylinder products where the chief products being manufactured by the production system (see Figure 5).

Figure 5. Hydraulic cylinder

Responding quickly and economically to the diversification of customer needs has forced manufacturing companies to improve the existing production system that target a number of performance measures in sustainable products including reducing manufacturing cost; reducing Co2 emission; increasing recycling rate. The manufacturers decided to implement link between the design or the manufacturing processes and other key elements of sustainability; economic, environmental, and social. Decision variables within the model represent the search engine of GA were previously detailed out in [15]. Table 1 summary the search range and the number of levels of the nine decision variables.

Table 1. Search Range for Decision Variables and the Corresponding Number of Levels

Decision variables	Range	Number of levels
Variable x_1 Production process method	1-3	3
Variable x_2 Logistic mod transportation	1-3	3
Variable x_3 Place of factory	1-4	4
Variable x_4 Skill levels of workers	70%-100%	4
Variable x_5 No. of workers	2-6	6
Variable x_6 No. of machine	2-5	4
Variable x_7 Type of material	1-3	3
Variable x_8 Lead time	1-30	30

4. Genetic Search Results for Optimal Design Solutions of Sustainable Product Design and Manufacturing Problem

Depending on the levels set of the variables in Table 1 the number of combinations is almost 25 million. Evaluating all these combinations will take nearly 20 hours of calculation time. Therefore the developed mathematical model for evaluating system performance in [15] is not capable of solving the example design problem due to very large design space. However, an optimal design solution can still be obtained by investigating, by means of the GA, only a small portion of the 25 million possible combinations. The developed GA is used to find the optimal solution for sustainable product design and manufacturing problem of the hydraulic cylinder production line under study. The proposed GA was coded using Matlab and run on a PC Intel® Core™ i5-5200UM processor working at speed 2.2 GHz and RAM of 4GB.Application of GA begins with a population of random chromosomes representing decision variables. The chromosomes represent the alternative solution for sustainable product design and manufacturing problem. The basic parameter values are listed in Table 2.

Table 2. Parameters of Genetic Algorithms

The parameter	The value
Max. No. of generation	500
Population size	100
Crossover probability	0.5
Mutation probability	0.06

The developed GA in this paper is executed using the parameter values to solve the problem of sustainable product design and manufacturing. The fitness values of all 300 are shown graphically in Figure 6 and indicates that the values of fitness; best, worst and average, are approximately equalized after 81 generations. Thus, the GA execution is terminated at the 300th generation.

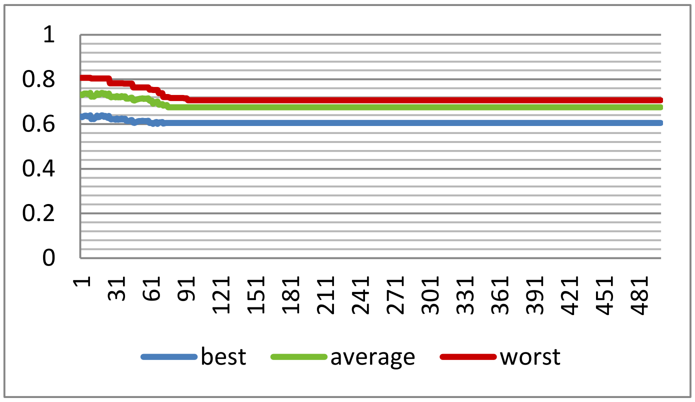


Figure 6. The GA progress toward the optimal design solution of Sustainable product design and manufacturing

As indicted in Figure 6, the GA converged to the optimal solution in 72 generations with the optimal design having a minimize fitness value 0.602647. This solution is considered the global optimum. The resulting values for decision variables and objective functions for this solution are presented in Table 3.

Table 3. Decision Variables and Objective Functions Values for Optimal Design Solution of Sustainable product design and manufacturing

Decision variables								Objective functions		
x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	y_1	y_2	y_3
1	3	2	80%	4	3	2	26	149.92	0.077	0.0138

5. Conclusion

The development of GA for sustainable product design and manufacturing problem has been described in this paper. The GA fundamental structure was outlined. It included selection strategy, fitness function, representation of chromosome, genetic operators (e.g. Selection, crossover and mutation operators), generation of initial population, constraints handling, and stopping criteria. The representation of chromosome real number coded was adopted as representation of the internal object for the search of solutions in the GA of this paper. The algorithm is designed for applying the developed GA to find sustainable product design and manufacturing based on the given design variables and input parameters to make this task systematic and flexible as possible. To demonstrate the developed algorithm effectiveness for handling the sustainable product design and manufacturing optimization problem, GA was run to find an optimal design and associated manufacturing processes with high sustainability index that is required for the designed problem. Because the design of solution (chromosome representation) is quite problem domain dependent in any GA, thus using the developed GA procedure here will not be effective to solve different optimization problems elsewhere. Depending on the above this paper introduced successfully a unique GA.

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