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An Investigation into Minimising Total Energy Consumption and Total Completion Time in a Flexible Job Shop for Recycling Carbon Fiber Reinforced Polymer

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Abstract

The increased use of carbon fiber reinforced polymer (CFRP) in industry coupled with European Union restrictions on landfill disposal has resulted in a need to develop relevant recycling technologies. Several methods, such as mechanical grinding, thermolysis and solvolysis, have been tried to recover the carbon fibers. Optimisation techniques for reducing energy consumed by above processes have also been developed. However, the energy efficiency of recycling CFRP at the workshop level has never been considered before. An approach to incorporate energy reduction into consideration while making the scheduling plans for a CFRP recycling workshop is presented in this paper. This research sets in a flexible job shop circumstance, model for the bi-objective problem that minimise total processing energy consumption and makespan is developed. A modified Genetic Algorithm for solving the raw material lot splitting problem is developed. A case study of the lot sizing problem in the flexible job shop for recycling CFRP is presented to show how scheduling plans affect energy consumption, and to prove the feasibility of the model and the developed algorithm.

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Keywords: flexible job shop; energy efficiency; composite; recycling

1. Introduction

In the last 30 years, CFRP have been increasingly used in a wide range of applications such as automotive, aerospace and renewable energy industry. However, difficulties in recycling have become their major drawback due to their inherent nature of heterogeneity, especially for the thermoset-based polymer composite [1, 2]. Historically, most composite waste has been disposed in landfills. Nevertheless, the demand for developing more environment-friendly composite recycling approaches is growing. In Europe and the USA, the annual generation of CFRP scrap is around 3,000t [2]. By the year 2030, some 6,000-8,000 commercial planes are expected to reach their end-of-life [2]. Since 2004, most European countries have banned the landfill disposal of CFRP waste. It can be expected that, future EU regulations will be imposed on the recycling of end-of-life aircraft [1, 2, 3].

Current research on recycling technologies mainly focuses on mechanical, thermal and chemical recycling [1]. Some researchers also considered to improve the energy efficiency of the above processes. Most existing works of reducing recycling energy consumption has focused so far on developing more energy efficient operating parameters. However, using scheduling method to reduce the recycling energy consumption on the system-level has not been well explored.

The aim of this work is to develop an approach to incorporate energy reduction into consideration while making the scheduling plans for a CFRP recycling workshop. This research sets in a flexible job shop with lot sizing circumstance. Model for the bi-objective problem that minimise the total energy consumed by all machines to process all jobs in a schedule and total completion time is developed. The modelling and optimisation methods proposed in this paper can be applied to discrete event production system and may save

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significant amounts of energy as well as keeping a good performance on classical scheduling objectives. In following content, the research problem will be raised after the background research and research motivation; then the model will be presented, followed an introduction to Non-dominant Sorting Genetic Algorithm (NSGA-II) [4] and a newly developed encoding schema for this problem. Finally, a case study is presented to demonstrate the effectiveness of the model and the proposed solution.

Nomenclature

J	a finite set of n jobs, $J = \{J_i\}_{i=1}^{n}$
M	a finite set of m machines, $M = \{M_k\}_{k=1}^{m}$
O_i	a finite list of u_i ordered operations of J_i, $O_i = [O_i^l]_{l=1}^{u_i}$
O_i^l	the l-th operation of job J_i processed on machine M_k
p_{ik}^l	processing time of single unit of job J_i's operation O_{ik}^l on machine M_k
s	a feasible schedule
$C_i(s)$	completion time of job J_i in schedule s
SL_i	a finite list of t_i ordered sub-lots of J_i, $SL_i = [SL_i^r]_{r=1}^{t_i}$
ss_i^r	the size of job J_i's sub-lot SL_i^r
γ_{ik}^{lr}	a decision variable that denotes the predefined allocation of operations on machines; $\gamma_{ik}^{l} = 1$ if operation O_{ik}^l of job J_i's sub-lot SL_i^r is processed on machine M_k; 0, otherwise
E_k	energy consumption per hour of machine M_k
P_0	the initial population with the size of N individuals
Q_0	the first offspring set
P_t	the t-th generation of population
Q_t	the offspring of P_t
R_t	the union of the parents P_t and their offspring Q_t
F_f	the set of non-dominated solutions of level f

2. Background and Motivation

A considerable amount of research has been conducted in the area of recycling CFRP. The mechanical, thermal and chemical recycling approaches have been widely investigated [1].

For mechanical treatment, cutting, crushing and milling are used to reduce the CFRP to fine particles [1, 3]. However, the energy intensity of mechanical processing is high, and it can only produce short milled fibres with poor mechanical properties used as filler reinforcement materials. There are mainly two thermal processes: Fluidised-bed combustion recycling process and pyrolysis recycling process [5]. Fluidised-bed combustion recycling process is to combust the resin matrix as energy and to recover the carbon fibres [6]. The organic resins are used as energy source in this process. The recovered fibres are clean and have a mean length of 6-10 mm. The recovered carbon fibre has 20% loss in stiffness degradation after the thermal treatment at 550°C. The mechanical properties of the recyclates have been described in detail by [6].

Pyrolysis is a thermal decomposition of polymers at high temperature from 300°C to 800°C in the absence of oxygen, allowing for the recovery of long, high modulus fibres [7]. In some circumstances, a higher temperature can be applied [8]. However, this will result in more serious degradation of the recyclates [8, 9]. When using pyrolysis as a recycling treatment of polymer matrix composites, the matrix is transferred into smaller molecules at temperatures above 350°C in an oven [1].

Chemical recycling uses the dissolution reagents to depolymerise the matrix of composites [1]. This process can regenerate both the clean fibres and fillers as well as depolymerised matrix in the form of monomers or petrochemical feedstock [1].

Based on the aforementioned recycling approaches, some researchers have considered optimising the recycling procedures to reduce the energy consumption of them. [3] modelled the electrical energy requirements of milling process to recycle carbon fibre composite. Based on the developed model, the energy demand of carbon fibre composite recycling can be theoretically calculated for any milling process.

To obtain the recovered fibres with properties close to new fibres, [9] have investigated and optimised different process parameters during pyrolysis to remove the residue as much as possible without oxidation of the carbon fibre itself. The variation of pyrolysis temperature, oven atmosphere and isothermal dwell time had been studied.

The Taguchi method has been used by [2] to optimise the steam thermolysis which is used for recycling the epoxy based CFRP materials. Steam thermolysis is a combination of vacuum pyrolysis and mild gasification. Operational parameters including target temperature, isothermal dwell time and steam flow-rate have been investigated.

A series of modelling and optimisation work for pyrolysis process which is used for treating waste tyres have been developed by [10]. These research works can be used as reference for pyrolysis based composite recycling to develop models and optimisation techniques. [10] have found that the heating rate and the operation temperature can affect the overall energy consumption, the product quality and yield of the pyrolysis process. Based on the fact that pyrolysis is an overall endothermic process but preformed exothermically at its early stage, [11] proposed an approach to trap the exothermic heat released in the beginning of the pyrolysis process and using it to fulfil the energy requirement of the endothermic reactions at the end of the process.

A four-stage operation strategy for the tire pyrolysis has been proposed by [8], which has the sequence of heating, adiabatic, heating and adiabatic. The approach is capable to save about 22.5% energy consumption with a 100% increase in completion time compared to the conventional strategy. [12] proposes an optimisation method to tune the operating parameters in the developed multi-stage pyrolysis. Finally, this approach can achieve a 29% reduction in energy usage with just 36% increase in completion time.

Based on above, it can be found that the energy reduction for recycling CFRP has never been considered at the workshop level. Therefore, the new problem can be raised as: The Multi-objective Total Processing Electricity Consumption and Makespan Flexible Job Shop with Lot Sizing Scheduling problem based on CFRP recycling. The flexible job shop and lot sizing environment are selected since this model is more close to the real manufacturing circumstance. The modelling method for this problem is presented below.

3. Problem definition

The first part of the model describes the problem of flexible job shop scheduling with lot sizing. A finite set of independent n jobs $J = \{J_i\}_{i=1}^{n}$ and a finite set of m machines $M = \{M_k\}_{k=1}^{m}$ are given. Each job is defined as a finite set of u_i ordered operations $O_i = \{O_i^l\}_{l=1}^{u_i}$. Each operation O_i^l can be executed on any among a subset $M_i^l \in M$ compatible machines. The flexibility of the job shop can be defined as partial if there exists a proper subset M_i^l of M for at least one operation O_i^l. Comparatively, the job shop can be defined as total flexible if $M_i^l = M$ for each operation O_i^l. In the flexible job shop, the processing time for each operation is machine-dependent. Thus, p_{ik}^l is used to denote the processing time of O_i^l when it is executed on machine M_k. Pre-emption is not allowed, i.e., each operation must be completed without interruption once started. Furthermore, machines cannot perform more than one operation at a time. All jobs and machines are available at time 0. Given a feasible schedule s, let $C_i(s)$ indicate the completion time of job J_i. When considering about lot sizing in flexible job shops, the job J_i is defined as a batch of v_i identical parts (unit) where $J_i = \{J_i^j\}_{j=1}^{v_i}$. Based on this, the definition of processing time needs to be adjusted that p_{ik}^l means the time consumed to process a single unit of job J_i's operation O_{ik}^l on machine M_k. Job J_i can be divided into a finite list of t_i ordered sub-lots that $J_i = SL_i = [SL_i^r]_{r=1}^{t_i}$, where SL_i^r is the r-th sub lot for J_i. There are ss_i^r units in the sub lot SL_i^r. It can be referred to [13] and [14] for more information about flexible job shop and lot sizing modelling.

The first part of the problem is lot splitting which deals with the decision that when and how to split a job into sub lots. In this paper, all jobs are split at time 0 since the model used is a static one. Hence, the splitting decision making will focus on two sides: how many sub lots each job should be split into and how many units in each sub lot. By solving the above two problems, the second part of the problem is to assign each sub-lot to an appropriate machine (routing problem), and to sequence the sub-lots on the machines (sequencing problem) [15]. The purpose of solving the four sub problems is to minimise the makespan, i.e., the time needed to complete all jobs, and the total energy consumed by all machines to process all jobs for schedule s ($ECP(s)$). The ECP is a function of the scheduling plan which needs to be expressed by the sequence of different operations of sub-lots which have been scheduled to be processed on machines. The energy consumption per hour of machine M_k is denoted by E_k. A decision variable γ_{ik}^{lr} is used to denote the predefined allocation of operations on machines; $\gamma_{ik}^{l} = 1$ if operation O_{ik}^l of job J_i's sub-lot SL_i^r is processed on machine M_k; 0, otherwise. In summary, the two objective functions for the minimisation of both makespan ($f_1(s)$) and ECP ($f_2(s)$) can be expressed by Equation 1, 2 and 3:

$$minimise\ F(s) = \left(f_1(s), f_2(s)\right)\ \ s \in S \tag{1}$$

$$f_1(s) = Makespan = max\{C_i(s)\} \tag{2}$$

$$f_2(s) = ECP = \sum_{k=1}^{m} E_k \sum_{i=1}^{n} \sum_{l=1}^{u_i} \sum_{r=1}^{t_i} p_{ik}^l \times ss_i^r \times \gamma_{ik}^{lr} \tag{3}$$

4. NSGA-II and its related operators

The non-dominated sorting procedure and crowding distance sorting procedure are two main operators of the NSGA-II. The solutions in different Pareto fronts are ranked by non-dominated sorting procedure. The crowding distance sorting procedure calculates dispersion of solutions in each front and preserves the diversification of the algorithm. In each generation of this algorithm, these two functions form the Pareto fronts [16]. [17] provides a summary for the working procedure of NSGA-II, as in following. For more information refer to [4].

3.1. Non-dominant sorting procedure

As shown in Fig. 1, all the solutions within a certain population P_t are evaluated according to the non-dominated sorting method. All the dominant individuals within the population locate at Level 1. If these individuals are not considered, the second set of dominant individuals constitutes Level 2. The sorting procedure iterates until each individual is classified to one of the levels. The most important factor of an individual's fitness is the level where it locates. The individual with lower rank is preferable.

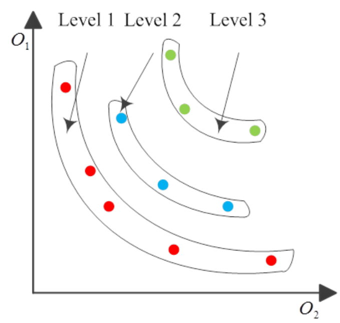

Fig. 1 Non-dominated levels [4]

3.2. Crowding distance sorting procedure

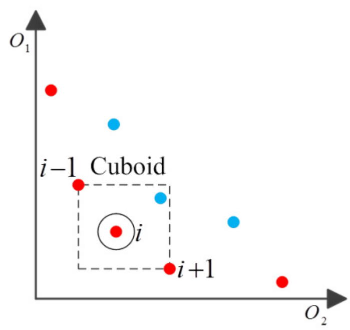

Fig. 2 Computation of the crowding distance [4]

The crowding distance of an individual is defined by [4] as: ''an estimate of the perimeter of the cuboid formed by using the nearest neighbours as the vertices''. By using the crowding distance sorting procedure, the diversity of the population is preserved. For an individual, the crowding distance is the sum of the normalized distance between the right and left neighbours for each objective function. The extreme solutions have a crowding distance equal to infinity (see Fig. 2).

3.3. NSGA-II algorithm

An initial population P_0 with the size of N individuals is randomly generated at the beginning of the algorithm. All the individuals of P_0 are sorted using the above two procedures. Then, the selection, crossover and mutation operators are used to create the first offspring set Q_0 ($|Q_0| = N$). Binary tournament selection operator is employed: the one with lower rank is selected between two individuals. When two individuals have the same rank, the winner is the one with the larger value in the crowding distance. At a given generation t, R_t is defined as the union of the parents P_t and their offspring Q_t. Thus, $|R_t| = 2N$. Individuals of R_t are sorted following the above two procedures. Frontier F_f is defined as the set of non-dominated solutions of level f. The individuals constitute P_{t+1} are the solutions of frontiers F_1 to F_λ with λ such that $\sum_{i=1}^{\lambda}|F_i| \leq N$ and $\sum_{i=1}^{\lambda+1}|F_i| > N$ plus the $N - \sum_{i=1}^{\lambda}|F_i|$ first solutions of $F_{\lambda+1}$ according to their descending value in crowding distance. The remaining individuals are rejected. The new offspring population Q_{t+1} is generated from individuals from P_{t+1}. Fig. 3 illustrates the generation of population P_{t+1}.

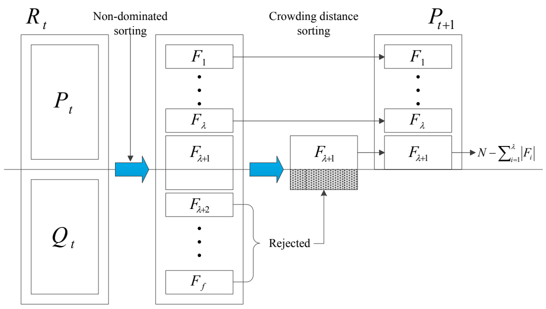

Fig. 3 Construction of population P_{t+1}

3.4. Encoding schema and schedule builder

Two stages of NSGA-II are applied as the solution. The first stage is to split original large job into a number of flexible sub-lots.

A splitting approach using cursor [14] is employed. At the beginning of the algorithm, a number of cursors are generated for each job. The units between two cursors belong to one sub-lot. The size of sub-lot between the two cursors is defined as 0 when two cursors are in the same position. Fig. 4 depicts a typical splitting scheme for a job. The number of cursor is three which means the pre-set number of sub-lot is four. The job has finally been split into three sub-lots since the second and the third cursor locate at the same position. The sizes of the sub-lots are 4, 4 and 2.

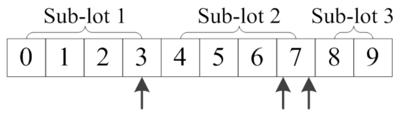

Fig. 4 Chart of lot splitting [14]

The chromosome designed for the lot sizing problem is presented in Fig. 5. The chromosome is used to represent the splitting plan for each job. For instance, the first four gene position depicts how the first job J_1 been split. The number 3 at the first position means 3 cursors has been set for J_1. The following number 4, 7 and 11 means the 3 cursors locate at the 4th, 7th and 11th unit of J_1. Following the splitting plan for J_1, the chromosome starts to depict the plan for J_2 until the splitting method for all jobs has been set.

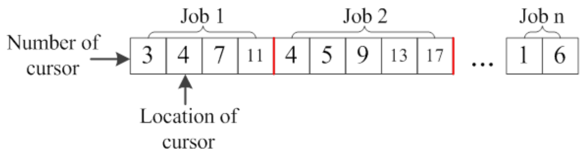

Fig. 5 Chromosome for lot splitting problem

By finishing the lot splitting, the sequencing problem needs to be solved, which means all the sub-lots need to be dispatched into the manufacturing system following a predefined sequence. The operation-based encoding schema (OBES) is adopted for this research which is mathematically known as "permutation with repetition" [18], where each job's index number is repeated u_i times (u_i is the number of operations of J_i). Normally, by scanning the permutation from left to right, the l-th occurrence of a job's index number refers to the l-th operation in the technological sequence of this job. However, the method needs to be adjusted in this research to adapt the lot sizing problem.

According to an example provided by [19], [32112321313332] is a feasible chromosome for a 3×2 job shop. In this model, each job needs 2 operations to be completed. The first job J_1 has been split to 2 sub lots, while J_2 has 2 sub lots and J_3 has 3. Thus, 3 on the first gene position stands for the first operation of the first sub lot of the third job J_3. 3 on the sixth gene position stands for the second operation of the first sub lot of the third job J_3. 3 on the ninth gene position stands for the third operation of the first sub lot of the third job J_3. 3 on the eleventh gene position stands for the first operation of the second sub lot of the third job J_3. The same translating method is applied to all the 1 and 2 in the chromosome. The schedule are developed by the active schedule builder [18]. Then any operation of the sub lot is dispatched to the earliest available machine for it.

3.5. Crossover and mutation operators

Referring to [19], [20] and [21], the crossover and mutation operators in this research are defined as below:

Crossover operator for lot sizing part:

The one point crossover operator is adopted. Given parent A_1 and parent A_2, the one point crossover operator generates child A_1' and child A_2' by randomly choose the same crossover point from both of the parents, and then exchange all the genes before the crossover point in A_1 and A_2. As shown in Fig. 6.

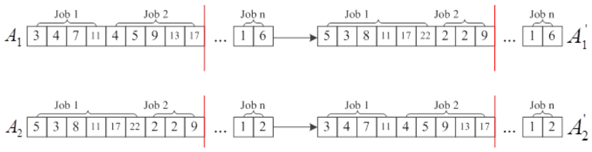

Fig. 6 Crossover operation for lot splitting chromosome

Crossover operator for flexible job shop scheduling part:

The operation-based order crossover (OOX) which is developed based on the job-based order crossover (JOX) is adopted as the crossover operator. For example, in a 3×3 job shop, [321123321] and [222333111] are feasible parent chromosomes. The loci of operations in the boxes are preserved. More details of the OOX can be refer to [19].

$$B_1 = [\boxed{3}211\boxed{2}332\boxed{1}]$$
$$B_2 = [2\boxed{2}2\boxed{3}3311\boxed{1}]$$

B_1' and B_2' are feasible child chromosomes as shown below:

$$B_1' = [\boxed{3}223\boxed{2}311\boxed{1}]$$
$$B_2' = [2\boxed{2}1\boxed{3}1332\boxed{1}]$$

Mutation operator for lot sizing and flexible job shop scheduling parts:

The swap mutation operator is employed in this research which means two difference arbitrary genes of the parent chromosome are chosen and swap the values. Following the above example, A_1'' is the final child chromosome of A_1 after applying mutation on A_1' while B_1'' is the final child chromosome of B_1 after applying mutation on B_1'. As shown in Fig. 7.

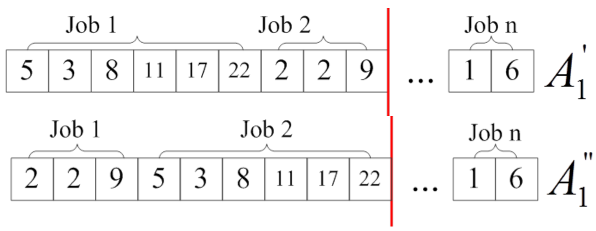

Fig. 7 Mutation operation for lot splitting chromosome

$$B_1' = [32\boxed{2}3231\boxed{1}1]$$
$$B_1'' = [32\boxed{1}3231\boxed{2}1]$$

4. Conceptual framework and case study

The conceptual framework which descripts how the above algorithm can be applied to solve the multi-objective optimisation problem is presented in Fig. 8.

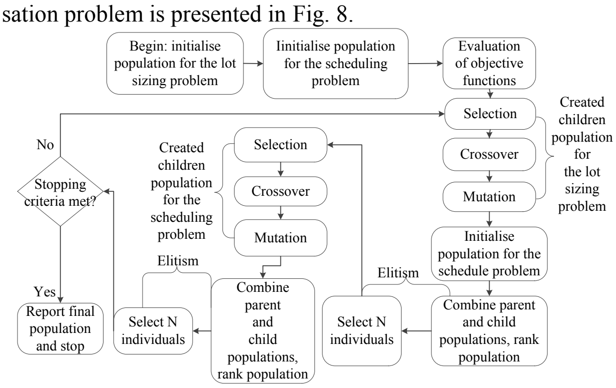

Fig. 8 Conceptual framework of the solution

A simple example is given below to demonstrate the proposed model and solution are effective. It can be supposed that in a flexible workshop, there are two types of recycling methods: microwave pyrolysis and fluidised bed process. 1000Kg CRRP waste material are available at time 0 to be processed. The 1000Kg can be split to certain amount of sub-lots, and can be processed by any of the aforementioned recycling process. The energy usage and recycling rate of the two methods are shown in Table 1, the values are calculated based on [22], [23] and [24].

Table 1. Energy usage and recycling rate of different recycling methods

Recycling method	Energy usage (*MJ/Kg*)	Recycling rate (*Kg /hr*)
Microwave Pyrolysis (MP)	10	5.4
Fluidised bed process (FBP)	25	342.5

Table 2. Comparison between different lot splitting and dispatching plans

Lot splitting and allocation		ECP (*MJ*)	Makespan (*h*)
MP	FBP		
500Kg	500Kg	17500	92.6
200Kg	800Kg	22000	37.0
800Kg	200Kg	13000	148.1
100Kg	900Kg	23500	18.5
900Kg	100Kg	11500	166.7
300Kg	700Kg	20500	55.6

As shown in Table 2, different lot splitting methods and dispatching decisions can lead to different performance of the scheduling plans on objectives like total processing energy consumption and makespan. It can be noticed that scheduling plan which reduces energy consumption does not necessarily reduce makespan. This simple case could demonstrate the feasibility of the aforementioned model and proposed solution. The complexity of the problem will increase along with the increasing numbers of jobs and machines, various energy characteristic of recycling methods.

5. Conclusion and Future Work

Reducing energy consumption for CFRP recycling at the workshop level as well as keeping good performance in classical scheduling objectives is a difficult problem that can take a large amount of time to search optimal solution. The model for the above problem had been developed based on the flexible job shop with lot sizing circumstance in this paper. An optimisation approach developed based on NSGA-II is proposed. A case study had been presented to show the effectiveness of the model and proposed solution. In future work, more complicated job shop instance will be studied based on the aforementioned model and developed optimisation approach. In addition, various situations about job arrival patterns will also be taken into consideration in the future work.

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