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ORIGINAL ARTICLE

Energy-efficient scheduling of flexible flow shop of composite recycling

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Abstract
Composite recycling technologies have been developed to tackle the increasing use of composites in industry and as a result of restrictions placed on landfill disposal. Mechanical, thermal and chemical approaches are the existing main recycling techniques to recover the fibres. Some optimisation work for reducing energy consumed by above processes has also been developed. However, the resource efficiency of recycling composites at the workshop level has never been considered before. Considering the current trend of designing and optimising a system in parallel and the future needs of the composite recycling business, a flexible flow shop for carbon fibre reinforced composite recycling is modelled. Optimisation approaches based on non-dominated sorting genetic algorithm II (NSGA-II) have been developed to reduce the time and energy consumed for processing composite wastes by searching for the optimal sub-lot splitting and resource scheduling plans. Case studies on different composite recycling scenarios have been conducted to prove the feasibility of the model and the developed algorithm.

Keywords Energy-efficient scheduling · Composite recycling · Flexible flow shop scheduling · Multi-objective optimisation · Genetic algorithms

1 Introduction

In the last 30 years, composites 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 [30, 31]. 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 carbon fibre reinforced composite (CFRC) scrap is around 3000 t [31]. By the year 2030, some 6000–8000 commercial planes are expected to reach their end-of-life [31]. Since 2004, most European countries have banned the landfill disposal of CFRC waste. It can be expected that future EU regulations will be imposed on the recycling of end-of-life aircraft [10, 30, 31]. Composite recycling is still an immature area that the current research mainly focuses on the technologies including mechanical, thermal and chemical recycling [30]. Some researchers also considered to improve the energy efficiency of the above processes [10]. Most existing works of reducing recycling energy consumption has focused so far on developing more energy-efficient operating parameters [17]. Improving the resource efficiency of composite recycling at the system level has never been investigated before.

Our research focuses on designing and optimising a flexible flow shop for the future composite recycling business through scheduling. The main aim is to model a flexible flow shop which can adapt to the composite material being recycled and to develop an optimisation approach which incorporates reducing time and energy into consideration. The flexible flow shop is selected as the fundamental model based on the requirement of the composite recycling to produce fibres with different length and quality. Compare to employing the normal flow shop, the flexible flow shop enables the improvement in recycling productivity. The CFRC is selected as the waste material to be processed. In the composite recycling procedures, splitting the large batches of wastes to smaller sub-lots is a crucial process, since the splitting plan and the

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recycling resource allocation for the sub-lots can affect the time and energy consumed for completing a certain amount of recycling work. Thus, the non-dominant sorting genetic algorithm (NSGA-II) [8] has been adopted for achieving the aforementioned bi-objective optimisation. The purpose for the developed optimisation approach is to search for the optimal sub-lot splitting plans and the corresponding scheduling plans to allocate the sub-lots to the recycling resources in the pre-defined flexible flow shop. A model for the flexible flow shop and the bi-objective problem to minimise the total energy and time consumed by all machines to process all jobs in a schedule has been developed. The NSGA-II algorithm is modified for solving the aforementioned optimisation problem. Simulation experiments which represent potential scenarios in the composite recycling workshop have been conducted to prove the effectiveness in saving time and energy of the developed approaches in different circumstances. The modelling and optimisation methods proposed in this paper can be applied to other flow shop production systems and may save significant amounts of energy as well as keeping a good performance on classical scheduling objectives. This work is done in the framework of the Efficient X-sector Use of Heterogeneous Materials in Manufacturing (EXHUME) project. The purpose of this EPSRC-funded project is to establish a sustainable and cost-effective strategy for the deconstruction, recycling and remanufacture of composite materials.

In the remainder of the paper, the research problem will be more formally defined after the background research and research motivation; then, the model will be presented, followed by an introduction to the NSGA-II and how it has been applied to optimised the bi-objective lot splitting and scheduling problem; then, simulation experiments based on three case studies are presented to demonstrate the effectiveness of the model and the algorithm for the research problem; finally, conclusions and discussion about the future research work are provided.

2 Background and motivation

The works focusing on composite recycling in terms of academic research, industrial application and business models are still in their infancies. The mechanical, thermal and chemical recycling processes are the major approaches which have been investigated. The mechanical treatment including cutting, crushing and milling is used to reduce the composite waste to fine particles [10, 30]. As the most mature one among all recycling methods, it is mainly used to recycle glass fibre reinforced polymer (GFRC). The applications for recycling CFRC also exist. However, the re-use of the mechanical recyclates is limited by the quality issue; it can only produce short milled fibres with poor mechanical properties used as filler reinforcement materials [18]. There are mainly two thermal processes: fluidised-bed combustion recycling process and pyrolysis recycling process [22]. Fluidised-bed combustion recycling process is to combust the resin matrix as energy and to recover the carbon fibres [23]. 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. Pyrolysis [13, 17, 23, 28, 30] is a thermal decomposition method for polymers at high temperature from 300 to 800 °C in the absence of oxygen. It allows the recovery of long, high modulus fibres. In some circumstances, a higher temperature can be applied; however, this will result in some serious degradation of the recyclates. Pyrolysis therefore appears to be more suitable to recover carbon fibres, since glass fibres retain less than 50% of their mechanical properties at the minimal temperature of 400 °C [19]. Microwave-assisted pyrolysis has also been used as a composite recycling method [15, 16]. This method costs less energy since the material is heated in its core so that thermal transfer is very fast [19]. Solvolysis is a chemical treatment using a solvent to degrade the resin [19, 32]. The solvolysis process can reclaim both the clean fibres and fillers as well as depolymerised matrix in the form of monomers or petrochemical feedstock [11, 30]. Based on a wide range of solvents, temperature, pressure and catalysts, solvolysis can offer a large numbers of possibilities. Generally, for solvolysis, lower temperatures are required to degrade the polymer compare to pyrolysis [19]. Water or alcohol is normally used as the solvent, which is relatively environmentally friendly [30]. The solvolysis recycling process can be used for both GFRCs and CFRCs. The reclaimed fibre retains most of its mechanical properties [30]. Based on the above, most existing research about composite recycling focuses on the recycling technologies. The work related to the workshop, factory or business model levels is scarce.

For the aforementioned three recycling approaches, some researchers have considered optimising the recycling procedures to accelerate recycling rate, reduce the energy consumption and improve the quality of recyclate. Howarth et al. [10] developed a bottom-up model to describe the electrical energy consumption of the milling process when it is used as an option for carbon fibre reinforced composite recycling. The energy demand of CFRCs recycling using milling can be theoretically calculated when the material removal rate is known. To obtain the recovered fibres with properties close to new fibres, Meyer et al. [17] 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 Ye et al. [31] to optimise the steam thermolysis which is used for recycling the epoxy-based CFRC materials. Steam thermolysis is a

Table 1 A summary of past literature according to time

[32]; [23]; [28]; [15, 16];
[22]; [11]; [17]; [13];
[4, 5]; [14];
[21]; [30]; [31]; [10];
[18, 19]

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 Cheung et al. [5]. These research works can be used as reference for pyrolysis-based composite recycling to develop models and optimisation techniques. Cheung et al. [5] 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, Lam et al. [14] 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 Cheung et al. [4], which is capable to save about 22.5% energy consumption with a 100% increase in completion time compared to the conventional strategy. Oyedun and Lam [21] 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 the existing literature, the multi-objective optimisation techniques to improve the efficiency of composite recycling have not been applied on the workshop or factory level.

The motivation for this research is to design and optimise a workshop for future composite recycling businesses to improve its resource efficiency. This is a significant gap in the current research which needs to be addressed. The current trend of system development is to consider system optimisation in parallel. Thus, the time and energy consumptions for completing the recycling for certain amount of composite are set as the objectives to be minimised. Based on the existing knowledge about composite recycling [19], the workshop can be modelled as a flexible flow shop including two stages: pre-processing and the actual recycling. Parallel machines

Table 2 Energy usage and recycling rate of different recycling methods

Recycling method	Energy usage (MJ/kg)	Recycling rate (kg/h)
Microwave pyrolysis (MP)	10	5.4
Fluidised bed process (FBP)	25	342.5

Table 3 Comparison between different lot splitting and dispatching plans

Lot splitting and allocation		ECP (MJ)	Makespan (h)
MP (kg)	FBP (kg)		
500	500	17,500	92.6
200	800	22,000	37.0
800	200	13,000	148.1
100	900	23,500	18.5
900	100	11,500	166.7
300	700	20,500	55.6

are to be used for both stages. Pre-processing is used to break the waste to smaller pieces, and then, the waste will be sent to the recycling processes to obtain the fibres. Before the wastes are to be sent to the workshop, normally, they need to be split from comparatively large batch to smaller sub-lots. The allocation of all the sub-lots to parallel machines will affect the values of time and energy consumed for processing the waste. Thus, operations research and scheduling methods can be employed to realise the multi-objective optimisation. The optimisation work on this level is very important, since it can considerably reduce the negative impact of composite recycling system without changing the legacy system too much. The workshop design and optimisation work in this paper can be used a reference for the future composite recycling business. The mathematical model for the developed flexible flow shop model will be presented below (Table 1).

3 Notation and problem statement

The notation used in the problem statement is as follows:

	Flexible flow shop problem with lot sizing
J	A finite set of n jobs, $J = \{J_i\}_{i=1}^{n}$
J_i	A finite set of h ordered sub-lots of J_i, $J_i = [L_i^g]_{g=1}^{h}$
L_i^g	The gth sub-lot of job J_i after lot splitting
W_i	Weight of job J_i, $W_i = \sum_{i=1}^{h} w_i^g$
w_i^g	Weight of sub-lot L_i^g of job J_i
M	A finite set of m stages, $M = \{M_k\}_{k=1}^{m}$
M_k	A finite set of r ordered parallel machines, $M_k = \left[m_k^l\right]_{l=1}^{r}$
m_k^l	The lth parallel machine of stage M_k
p_k^l	Processing rate of machine m_k^l
e_k^l	Energy consumption rate of machine m_k^l
s	A feasible schedule
C_i^g	Completion time of the gth sub-lot of job J_i in schedule s
α_{ik}^{gl}	A decision variable that denotes the allocation of sub-lots on machines; $\alpha_{ik}^{gl} = 1$ if the gth sub-lot of job J_i is processed on m_k^l, 0 otherwise

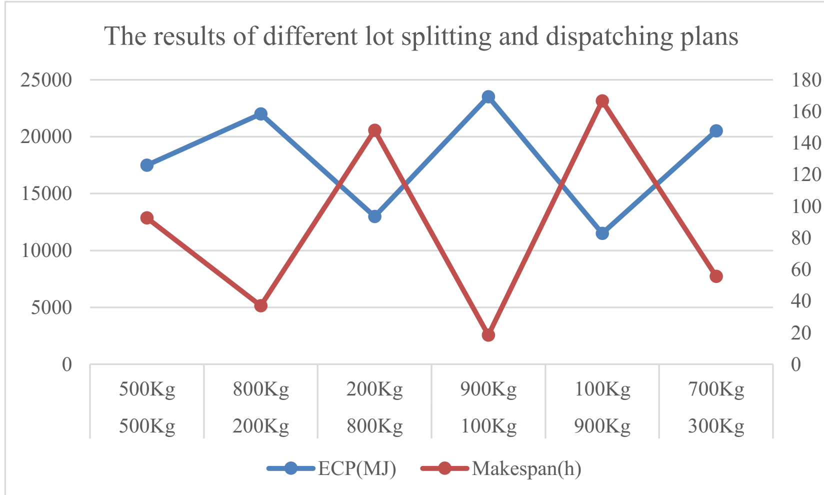

Fig. 1 The total energy and time consumptions for different lot splitting and dispatching plans

In the flexible flow shop for composite recycling, a finite set of n jobs $J = \{J_i\}_{i=1}^{n}$ are to be processed on a finite set of m stages $M = \{M_k\}_{k=1}^{m}$ following the same order, i.e. they have to be processed first at stage 1, then at stage 2, and so on. A stage functions as a bank of parallel machines that M_k is a finite set of r ordered parallel machines, $M_k = \left[m_k^l\right]_{l=1}^{r}$. The lth parallel machine of stage M_k is denoted as m_k^l with a processing rate of p_k^l (weight/time) and energy consumption rate e_k^l (energy/time). At each stage job J_i requires to be processed on only one machine and any machine in parallel can do. Considering the background of composite recycling, parallel machines at stage 1 are used to pre-process the waste composite, i.e. using mechanical treatments such as shredding or milling to transfer the large pieces of materials to smaller ones. At stage 2, parallel machines are used to complete the actual recycling which separates fibres from the resin. All jobs in this research are ready to be processed at time point 0. Before releasing to the flexible flow shop, job J_i which weights W_i can be spliced to h sub-lots. The gth sub-lot of job J_i is denoted as L_i^g, and it weights w_i^g. Each sub-lot are treated as an independent new 'job' to be processed by the workshop. The order of these sub-lots (new jobs) to be released to the workshop and the recycling resource allocation for them can affect the time and energy consumed for processing all jobs. A simple example is given below to demonstrate the aforementioned effect. In this case, microwave pyrolysis and fluidised bed process are used as the recycling methods. One thousand kilograms of CRRC waste material are to be processed, which can be split to certain number of sub-lots and processed by any of the recycling process. The energy usage and recycling rate of the two methods are shown in Table 2; the values are calculated based on Lester et al. [15, 16], Carberry [3] and Shuaib [27].

As shown in Table 3 and Fig. 1, different lot splitting plans and dispatching decisions can deliver different scheduling plans. Each scheduling plan has its own performance on total processing energy consumption and time (makespan). It can be noticed that the scheduling plan which reduces energy consumption does not necessarily reduce makespan. The complexity of searching for optimal scheduling plans which minimise the total energy consumption and time increases along with the increasing numbers of jobs and machines. When the resource allocation rules are pre-defined, it is crucial to identify the optimal lot splitting plans and the orders for all sub-lots to be released to the workshop, thereby finding the optimal scheduling plans.

It can been defined that the first sub-lot on the sequence is released to the flexible job shop at time point 0. Dispatching rules are used to decide the processing route of each sub-lot after it has been released. In Table 4, all the dispatching rules used in this research and the appropriate circumstance for each of them to be applied are listed. A decision variable α_{ik}^{gl} is used to denote the allocation of sub-lots on machines; $\alpha_{ik}^{gl} = 1$ if the gth sub-lot of job J_i is processed on m_k^l, 0 otherwise. Thus, given a feasible schedule s for completing certain number of jobs, let C_i^g indicates the completion time of sub-lot L_i^g of job

Table 4 Dispatching rules used in this research [24]

Dispatching rules	Application
Earliest available machine (EAM)	EAM is used when dispatching a sub-lot to parallel machines at any stage
First-in, first-out (FIFO)	FIFO is applied which gives the first sub-lot in the waiting queue in front of a specific machine the priority to be processed

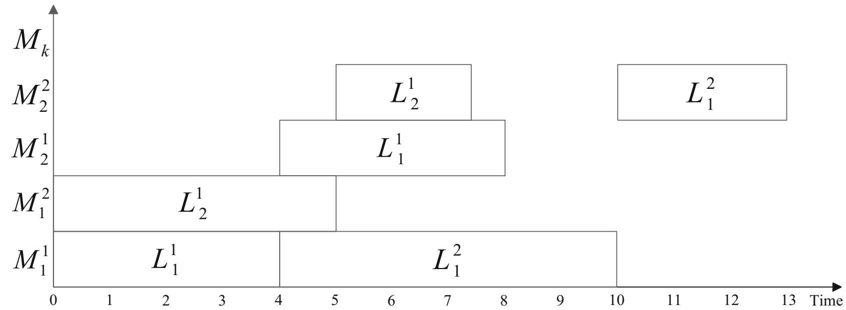

Fig. 2 Gantt chart of chromosome [121]

J_i in schedule s. The two optimisation objectives are to minimise the total time (makespan) and energy consumed to process all jobs, which can be expressed as

$$\text{Minimise}(\max C_i^g, E(s)) \tag{1}$$

$$E(s) = \sum_{i=1}^{n}\sum_{k=1}^{m}\sum_{g=1}^{h}\sum_{l=1}^{r}\alpha_{ik}^{gl}\cdot w_i^g\cdot e_k^l \tag{2}$$

where $E(s)$ is the total energy consumption of all machines, which is a function of schedule s.

4 NSGA-II and its related operators

The non-dominated sorting and crowding distance sorting procedures are the two main operators for the NSGA-II algorithm. NSGA-II is selected as the fundamental structure for the solution in this research since it normally outperforms other popular meta-heuristics for solving optimisation problems with two or three objectives. Non-dominated sorting procedure ranks the solutions in different Pareto fronts, while the crowded distance sorting procedure calculates dispersion of solutions in each front and preserves the diversification of the Pareto front [25]. More information can refer to Deb et al. [8]. The working procedure of NSGA-II is shown in following [29].

An initial population P_0 with the size of N is randomly generated when the algorithm begins. All the individuals in the population are sorted using the above two procedures. Then, selection, crossover and mutation operators are used to create the first offspring set Q_0 ($|Q_0| = N$). The selection is a binary tournament: between two individuals, to select the one with the lower rank on Pareto front. The one with the larger value in the crowding distance wins when the two individuals are on the same front. At a given generation t, R_t is the union of the parents P_t and their offspring Q_t. Therefore, $|R_t| = 2N$. Individuals of R_t are sorted by the two procedures as above. Frontier F_f is the set of non-dominated solutions of level f. The individuals in the following generation P_{t+1} are the solutions of frontiers F_1 to F_λ with λ such that $\sum_{i=1}^{\lambda}|F_i| \le N$ and $\sum_{i=1}^{\lambda+1}|F_i| > N$ plus the $N - \sum_{i=1}^{\lambda}|F_i|$ first solutions of $F_{\lambda+1}$ based on their descending value in crowding distance.

4.1 Encoding schema for lot sizing and dispatching rule to build a schedule

Inspired by the operation-based encoding schema (OBES) [6], the sub-lot-based encoding schema (SLBES) is developed for this research. SLBES is known as 'permutation with repetition', where each job's index number is repeated h times (h is the number of sub-lots of J_i). By scanning the permutation from left to right, the gth occurrence of a job's index number refers to the g-th sub-lot of J_i to be released into the flexible flow shop for composite recycling. For instance, [321233] is a feasible chromosome when 3 jobs are to be processed by the flexible flow shop, 3 on the first gene position stands for L_3^1, which is the first sub-lot of the third job (J_3) with weight w_3^1; 3 on the fifth gene position stands for L_3^2 with weight w_3^2; 3 on the sixth gene position stands for L_3^3 with w_3^3. There are two sub-lots for J_2 and just one sub-lot for J_1. Thus, the chromosome can be translated to a list of ordered sub-lots as $[L_3^1 L_2^1 L_1^1 L_2^2 L_3^2 L_3^3]$. Then, the sub-lots can be sent to the

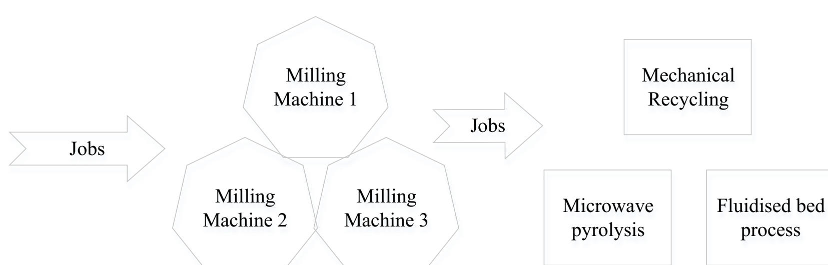

Fig. 3 The schematic diagram of the composite recycling problem based on flexible flow shop

Table 5 Energy consumption and recycling rates for all machines

Pre-processing	Energy usage (MJ/kg)	Recycling rate (kg/h)
Milling machine 1	1.00	7.00
Milling machine 2	2.00	8.00
Milling machine 3	3.00	10.00
Recycling method	Energy usage (MJ/kg)	Recycling rate (kg/h)
Mechanical recycling	2.03	10
Microwave pyrolysis	10.00	5.4
Fluidised bed process	25.00	343

pre-processing and recycling stages. Following the 'earliest available machine' and 'first-in, first-out' dispatching rules, the sub-lots can be allocated to proper machines, thus the chromosome can be transformed into a feasible schedule. A schedule building procedure is depicted in Fig. 2 using a simple chromosome [121] with weight [40,50,60 kg]. Two pre-processing parallel machines M_1^1 and M_1^2 are used. Both of them have a processing rate of 10 kg/h. M_2^1 and M_2^2 are used for recycling with processing rates of 10 and 20 kg/h, respectively.

Based on the SLBES, two permutation methods are used in this research, one is job-focused and the other is sub-lot-focused. For a chromosome, the sub-lots of a specific job are not to be separated when the job-focused permutation method is used, while all the sub-lots can be randomly placed on all the loci when the sub-lot focused permutation is used. For instance, chromosome [333122] is a job-focused permutation, while the aforementioned [321233] is a sub-lot focused one. The performance of the two permutation methods are to be compared in Sect. 5.

4.2 Crossover and mutation operators (for two types of operators)

4.2.1 Crossover operator

The job-based order crossover (JOX) is adopted and modified for its advantage of avoiding producing illegal chromosome in offspring [20]. Given parent 1-A_1 and parent 2-A_2, the crossover generates child 1-$A_1^{'}$ and child 2-$A_2^{'}$ by the following procedure:

1. Randomly, choose the same jobs including their corresponding sub-lots from both of the parents A_1 and A_2. The loci of the unselected jobs are preserved.
2. Move the jobs and their corresponding sub-lots chosen at step 1 from A_1 to $A_2^{'}$, A_2 to $A_1^{'}$, the loci of the unselected jobs are preserved in the offspring $A_1^{'}$ and $A_2^{'}$.

Take a 4 jobs case as an example, [314323] and [42313] are feasible parent chromosomes. Job J_3's corresponding sub-lots are selected to be swapped, as show in the boxes. Other loci of sub-lots are preserved.

$$A_1 = [\boxed{3}14\boxed{3}2\boxed{3}]$$

$$A_2 = [42\boxed{3}1\boxed{3}]$$

$A_1^{'}$ and $A_2^{'}$ are feasible child chromosomes as shown below:

$$A_1' = [\boxed{3}14\boxed{3}2]$$

$$A_2' = [42\boxed{3}1\boxed{3}\boxed{3}]$$

4.2.2 Mutation operator

The swap and single point mutation operators are used. The swap mutation means two different arbitrary genes of the parent chromosome are selected and swap the values. Following the above example, $A_2^{''}$ is the final child chromosome of A_2 after applying mutation on $A_2^{'}$.

$$A_2' = [4\boxed{2}31\boxed{3}3]$$

$$A_2'' = [4\boxed{3}31\boxed{2}3]$$

Single-point mutation means one arbitrary gene of the parent chromosome is chosen and split to two, or two genes represents different sub-lots within a specific job are chosen and combined to one. As an example, $A_2^{''}$ is

Table 6 The weight for each job in three groups of jobs

$W_i(Kg)$	J_1	J_2	J_3	J_4	J_5	J_6	J_7	J_8	J_9	J_{10}	J_{11}	J_{12}
Group 1	1000	2000	3000	2000	1000	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Group 2	1000	2000	3000	2000	1000	2000	3000	2000	n/a	n/a	n/a	n/a
Group 3	2000	1000	3000	2000	1500	4000	5000	2500	1000	3000	4000	2000

Table 7 Case study and scenarios comparison

Scenarios	Lot splitting plan	Encoding schema	Mutation operator	Optimisation approach
Scenario 1	Fixed number of sub-lots	Job-focused SLBES	Swap mutation	NSGA-II
Scenario 2	Developed unfixed lot splitting	Sub-lot-focused SLBES	Swap and single mutations	NSGA-II
Scenario 3	The weight upper bound for each sub-lot is 500Kg; unfixed lot splitting	Sub-lot-focused SLBES	Swap and single mutations	NSGA-II
Scenario 4	The weight upper bound for each sub-lot is 500Kg; unfixed lot splitting; some of the processing route is fixed for the purpose of quality control	Sub-lot-focused SLBES	Swap and single mutations	NSGA-II

the final child chromosome of A_2 after applying single-point mutation on A_2'. In the splitting case, the weight of the selected sub-lot is separated to two values which are the weights for the two new sub-lots.

$$A_2' = [4\boxed{2}31\boxed{3}3]$$

$$A_2'' = [4\boxed{2}\boxed{2}31\boxed{3}3]$$

5 Performance evaluation of the algorithm

5.1 Experiment setting and test scenarios for comparison

A flexible flow shop for composite recycling which incorporates energy and time consumption profiles for all processors is designed for this research to carry out the case study and performance evaluation of the algorithm (Fig. 3). According to the objectives of minimising the total energy and time consumption, the energy consumption and processing rates for parallel machines both at pre-processing and recycling stages need to be defined. Suppose that all pre-processing machines are automated milling ones, the relevant data can be abstracted from research works developed by Avram and Xirouchakis [1], Baniszewski [2], Dahmus [7], Drake et al. [9], Kalla et al. [12] and Rajemi [26]. The data for the three recycling methods are abstracted from works of Lester et al. [15, 16], Carberry [3] and Shuaib [27]. The details of the flow shop are shown in Table 5.

Three groups of jobs are developed as the test cases to validate the effectiveness of the proposed lot splitting and sub-lots sequencing method. The details of the three groups are shown in Table 6. The number of jobs increases from 5 to 12 from group 1 to group 3. This is designed to validate the general applicability of the developed algorithm.

To demonstrate the effectiveness of the developed approaches in different circumstances of the flexible flow shop of composite recycling, the following comparison experiment is carried out based on the following four scenarios as shown in Table 7:

Scenario 1 The jobs in each group are split to a fixed number of sub-lots, and the weight for each sub-lot is also a constant, as shown in Table 8. For instance, for the J_1 in group 1, its first

Table 8 The fixed sub-lot splitting plan for three groups of jobs

Jobs	Sub-lot weight ratio (%)				
Group 1					
J_1	10	10	20	20	40
J_2	10	30	30	10	20
J_3	25	25	20	20	10
J_4	10	30	30	10	20
J_5	10	10	40	10	30
Group 2					
J_1	10	10	10	70	
J_2	10	20	10	60	
J_3	10	30	10	50	
J_4	10	40	10	40	
J_5	10	20	20	50	
J_6	10	30	20	40	
J_7	20	20	20	40	
J_8	20	30	20	30	
Group 3					
J_1	10	20	10	30	30
J_2	10	20	10	30	30
J_3	10	10	10	50	20
J_4	10	40	10	20	20
J_5	10	20	20	20	30
J_6	10	30	20	10	30
J_7	20	20	20	20	20
J_8	20	30	10	30	10
J_9	10	30	20	30	10
J_{10}	10	10	10	40	30
J_{11}	10	20	10	50	10
J_{12}	10	30	10	30	20

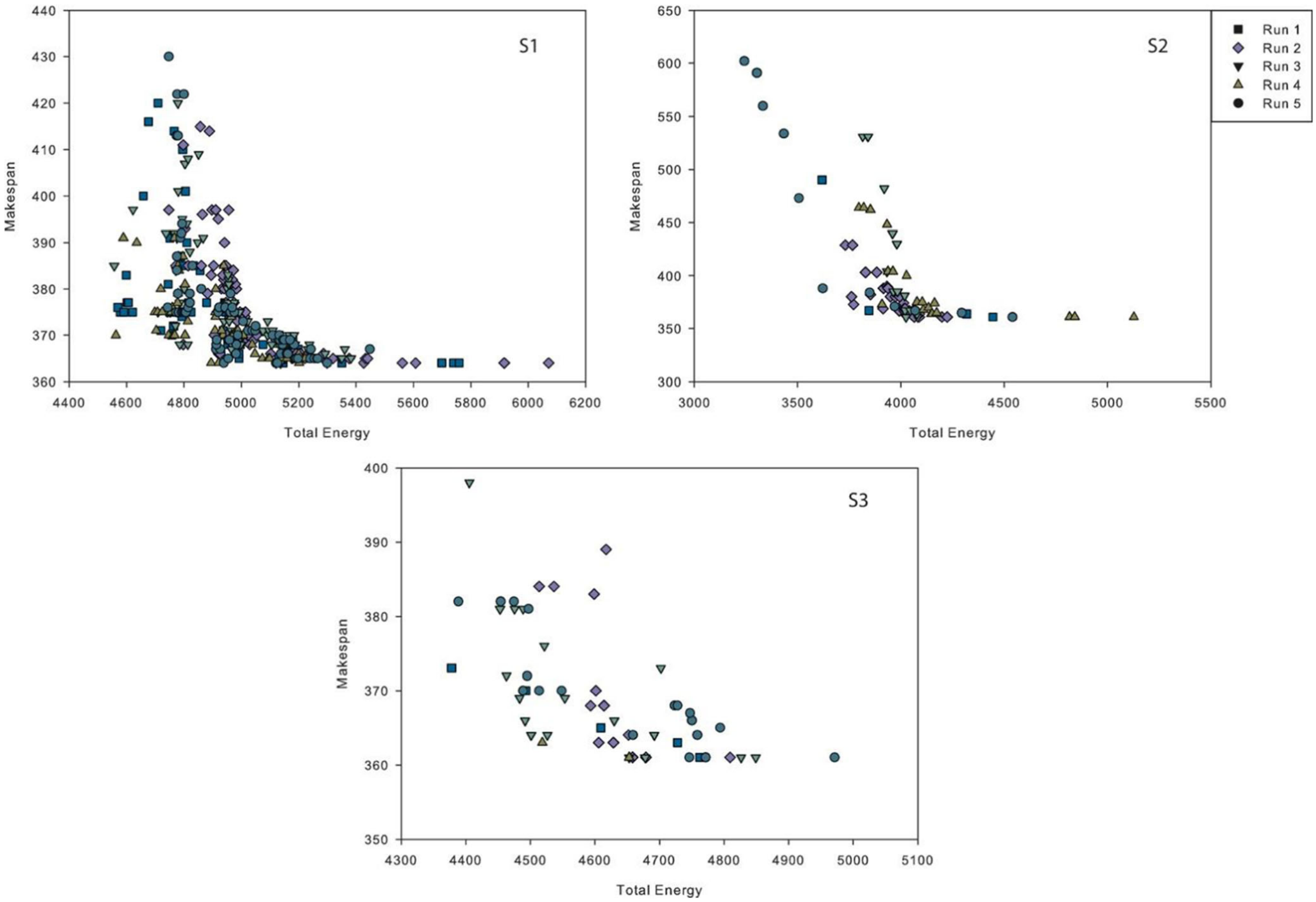

Fig. 4 Performance comparison of the fixed and unfixed lot splitting (group 1–5 jobs)

sub-lot weights 100 kg which is 10% of the weight of J_1. The NSGA-II and job-focused SLBES are used as the optimisation approach and encoding method, respectively. The swap mutation is adopted in this scenario. This represents the traditional lot-sizing approach which is used as the benchmark scenario.

Scenario 2 The developed unfixed lot splitting approach and the sub-lot-focused SLBES are used in this scenario, which represents the optimised way for operating the composite recycling flexible flow shop. Both of the swap and single mutation operators are employed in this scenario.

Scenario 3 Normally, in the real manufacturing circumstance, there are restrictions for lot splitting. One of the typical restrictions is the size of the sub-lots. Considering the composite recycling background, in this scenario, the weight upper bound for each sub-lot is set to 500 kg. The unfixed lot splitting approach and the sub-lot-focused SLBES are used. Both of the swap and single mutation operators are used.

Scenario 4 The quality of the recyclates is to be considered in this scenario. In the real recycling circumstance, sometimes a job needs to be allocated to a certain recycling method when there are requirements on the quality of recyclates. The quality of recyclates, such as tensile strength, varies when applying different types of recycling methods. Thus, in this test scenario, for the 8 jobs case, the sub-lots of the third job J_3 has to follow a pre-defined processing route which is milling machine 2 and microwave pyrolysis; for the 12 jobs case, the sub-lots of J_1 and J_2 follow the processing route of milling machine 2 and microwave pyrolysis, and the sub-lots of J_8 and J_{12} follow the processing route of milling machine 3 and fluidised bed process. For all the sub-lots, the weight upper bound for each sub-lot is set to 500 kg. The unfixed lot splitting approach and the sub-lot-focused SLBES are used. Both of the swap and single mutation operators are adopted.

5.2 Experiment results and discussion

The parameter values used in the algorithm in all experiments obtained by tuning, are as follows: population size $N = 100$, crossover probability $P_c = 0.8$, mutation probability $P_m = 0.05$, and generation $t = 100$. The

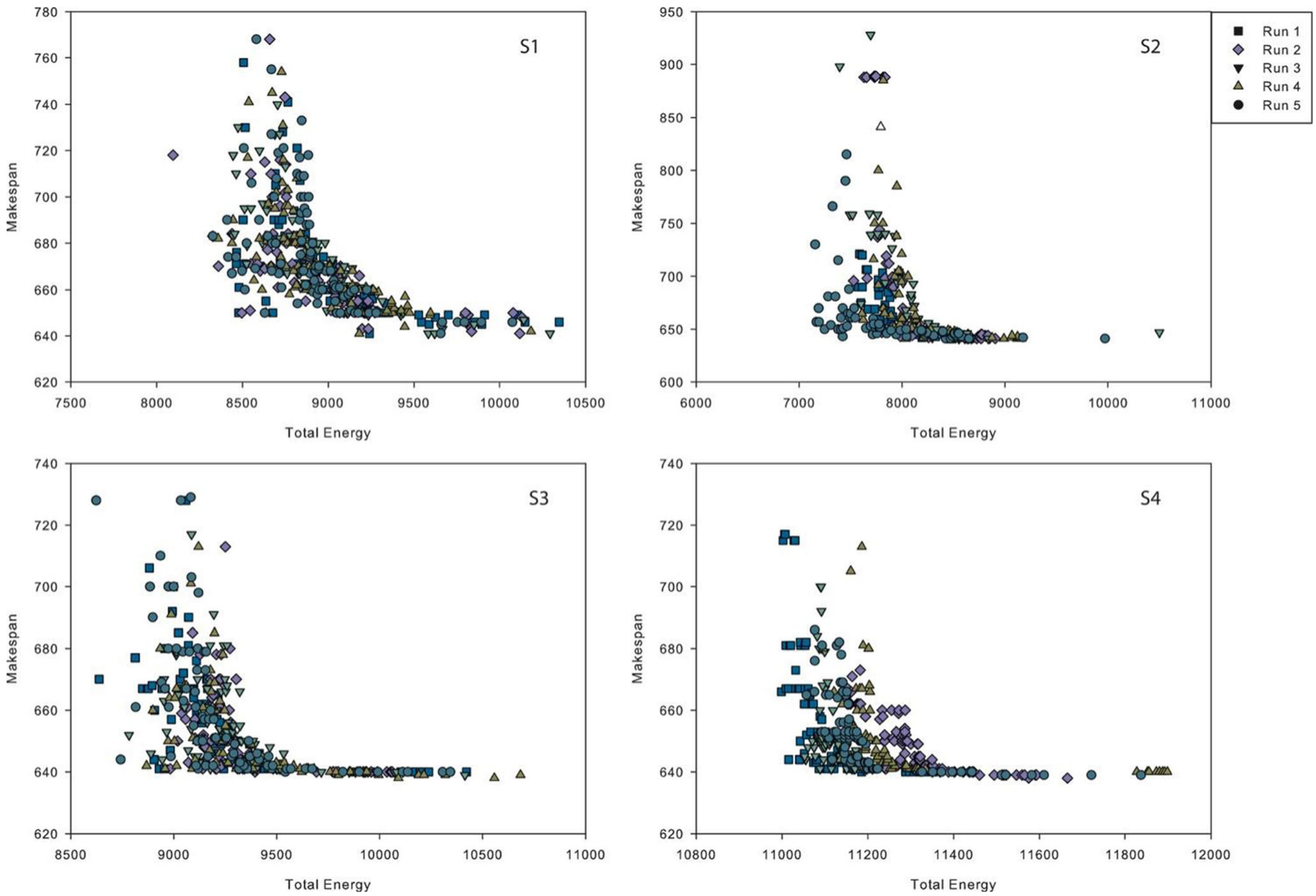

Fig. 5 Performance comparison of the fixed and unfixed lot splitting (group 2–8 jobs)

algorithm is run five times. The comparisons among solutions in the aforementioned four scenarios are presented in Figs. 4, 5 and 6.

In Figs. 4, 5 and 6, S1 to S4 are used to notify that their corresponding figures present the solutions in scenario 1 to scenario 4, respectively. The five different shapes of points represent the Pareto sets obtained in each run. When comparing the solutions in S2 to S1 in each group, it can be identified that on average, the developed unfixed lot splitting combined with the sub-lot-focused SLBES outperforms the fixed lot splitting combined with the job-focused SLBES in terms of total time and energy consumed to recycle all jobs when NSGA-II is used as the optimisation algorithm for both scenarios. However, when the upper bound of 500 kg for the weight of the sub-lot is applied, the average performance of solutions based on unfixed lot splitting is not necessarily better than the ones based on the fixed lot splitting. It can be observed that only for group 1, the solutions in S3 can outperform the solutions in S1. By comparing S4 to S1, it can be observed that when the processing routes for some jobs have been pre-defined, to achieve similar value in makespan, the solutions in S4 normally need larger value in total energy consumption. Based on the above experiments, it can be observed that the unfixed lot splitting combined with the sub-lot-focused SLBES is more effective in minimising the time and energy consumed in composite recycling in the flexible flow shop environment when there is no restriction on the sizes of sub-lots and the process routine. When restrictions such as the weight upper bound for sub-lots or the intrinsic processing routes for certain jobs are applied, the combination of unfixed lot splitting and the sub-lot-focused SLBES not necessarily generates better solutions than the combination of fixed lot splitting and the job-focused SLBES. From the managerial perspective, adopting optimised lot splitting plan could effectively save the time and energy consumption in composite recycling based on the flexible flow shop model. The developed lot splitting, dispatching and optimisation approaches are also applicable for other workshops which seek the optimal lot splitting to achieve optimisation. A more thorough investigation of the effects of applying the aforementioned two combinations needs to be complete in the future. More types of combinations between the lot-splitting approaches (fix or unfix) and the permutation methods are also need to be tested.

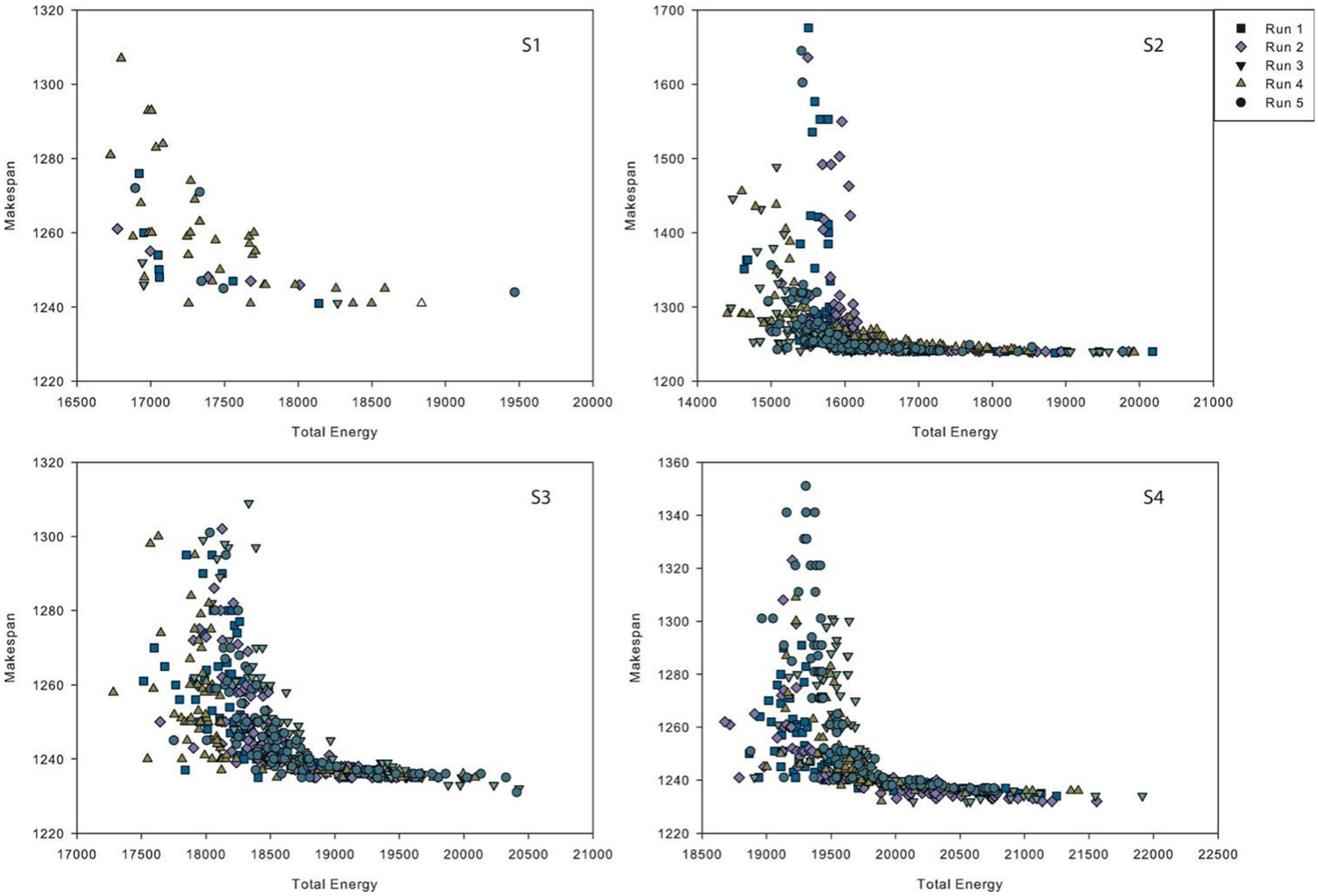

Fig. 6 Performance comparison of the fixed and unfixed lot splitting (group 3–12 jobs)

6 Conclusions and future work

The increased use of carbon and glass fibre reinforced composites in industry coupled with restrictions on landfill disposal has resulted in a development of recycling technologies for composites. Mechanical, thermal and chemical approaches are the main existing technologies. It also has been identified that the engineering optimisation techniques had rarely been applied in the composite recycling area, especially on the workshop level. Considering the current trend of designing and optimising a system in parallel and the future needs of the composite recycling business, this paper seeks to develop a workshop for the carbon fibre reinforced composite recycling, and improve its efficiency. A flexible flow shop model has been delivered to fulfil the aforementioned requirement. Based on this, a bi-objective optimisation problem has been raised to reduce the time and energy consumed for processing certain amount of composite wastes. Lot splitting and sub-lot dispatching are crucial operations in the developed system. Thus, the optimisation approaches based on the NSGA-II have been developed to search for the optimal sub-lot splitting plans and the corresponding scheduling plans to allocate the sub-lots to the recycling resources in the pre-defined flexible flow shop, thereby achieving the minimisation of time and energy consumption. By comparing the simulation experiment results based on different scenarios, it has been identified that the developed optimisation approach is effective in achieving the bi-objective optimisation. More types of combinations between the lot-splitting approaches and the permutation methods need to be test in the future. The developed approaches also need to be further tested with more cases to prove its general applicability. Thus, in future work, more flexible flow shop instances and groups of jobs will be studied. More types of combinations between the lot splitting approach and the permutation methods will also be tested. In addition, various situations about job arrival patterns will also be taken into consideration.

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