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A review of optimisation techniques used in the composite recycling area: State-of-the-art and steps towards a research agenda

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ABSTRACT

The increased use of carbon fibre and glass fibre reinforced polymer in industry coupled with restrictions on landfill disposal has resulted in a need to develop effective recycling technologies for composites. Currently, mechanical, thermal and chemical approaches have been use to recycle composites. This paper seeks to examine the applications of engineering optimisation techniques in the composite recycling and re-manufacturing processes and their relevant systems, providing an overview of state-of-the-art. This paper is based on a comprehensive review of literature covering nearly all the research papers in this area. These papers are analysed to identify current trends and future research directions. The composite recycling is a relatively new area, and the modelling and optimisation work for composite recycling and re-manufacturing techniques and their relevant systems is still in its infancy. Currently, the optimisation work developed in composite recycling mainly focus on the applications of design of experiments methods. These approaches have been applied to improve the quality of recyclates such as carbon fibres. Some of the soft-computing algorithms have been applied to optimise the re-manufacturing at the system level. Based on the existing research, the area of optimisation for composite recycling and re-manufacturing haven't been well explored despite the fact that many opportunities and requirements for optimisation exist. This means significant amount of modelling and optimisation work is required for the future research. More significantly, considering optimisation at the early stage of a system development is very beneficial in terms of the long term health of the composite recycling industry.

1. Introduction

In the last 30 years, fibre reinforcement resins, thermoplastics as well as thermosets have been increasingly used in a wide range of applications such as the automotive, aerospace and transportation industries. However, the major drawback of composites is that they are difficult to recycle. This is based on their inherent nature of heterogeneity, especially for the thermoset-based polymer composite (Yang et al., 2012; Ye et al., 2013). The traditional way to deal with the composite waste is disposal in landfills or incineration. These methods are still acceptable due to the relatively low amount of production waste and the fact that most Carbon Fibre Reinforced Composites (CFRCs) produced so far are still in operation. However, the cost of the traditional approaches is high. For instance, the cost for disposal of CFRCs waste, where not illegal, is around 0.2 GBP/kg (Pimenta and Pinho, 2011). By the year 2030, around 6000–8000 commercial planes are expected to reach their end-of-life (Ye et al., 2013). This will bring a large amount of composite waste. On the other hand, the amount of production waste will increase as the demand for composites and the amount of composites parts produced is growing rapidly. For instance, in Europe and the USA, the annual generation of CFRCs scrap is around 3,000t (Ye et al., 2013). Hence, the demand for developing more cost effective and sustainable composite recycling approaches is growing. Besides future problems with composite disposal, it is also economically beneficial to implement composite recycling. For instance, carbon fibres are an expensive raw material. The price of it as of 2015 is 20 USD/kg. Recycling activities provide the potentiality to use cheap carbon fibres for applications which do not require high strength, and will also ultimately open up new sustainable and secure sources of carbon fibre material. To securely use the recycled carbon fibres, relevant applications and specific standards are needed to be developed (Oliveux et al., 2015a).

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Comparatively, it is easier to recycle thermoplastic matrix composites. Since they can be re-shaped by re-melting and remoulding (Yang et al., 2012). For the thermoset matrix composites, current research on recycling technologies mainly focuses on mechanical (Oliveux et al., 2015a; Howarth et al., 2014), thermal (Pickering, 2006) and chemical recycling (Yang et al., 2012). In the mechanical recycling process, the composites are milled or ground to particles with a length from 10 mm to 50 μm. The thermal recycling processes can combust the resin matrix, thereby recovering the glass or carbon fibres. Chemical recycling uses the dissolution reagents to depolymerise the matrix of composites. Some of these technologies have reached an industrial scale. For instance, the Filon Product Ltd. in United Kingdom use grinding to recycle Glass Fibre Reinforced Composites (GFRCs), ELG Carbon Fibre Ltd. in United Kingdom use pyrolysis, Adherent Technologies Inc. in USA use a wet chemical breakdown of composite matrix resins to recover fibrous reinforcements (Oliveux et al., 2015a) and SGL Carbon in Germany employs a solvolysis process to recycle carbon fibres which can be used in the roof of the new BMW i models and in the rear seat of BMW i3 (Gardiner, 2014; SGL, 2016). The recyclates can be used as filler or reinforcement in new composites. The existing composite recycling techniques have their own advantages and drawbacks. The emerging trend is: mechanical recycling is more suitable for glass fibre reinforced composites while thermal and chemical approaches are more for carbon fibre reinforced composites, since glass fibres are tend to be damaged during thermo-chemical processes (Yang et al., 2012).

The composite recycling is still an immature area. This means the developing techniques mentioned above still need to be optimised to produce higher quality recyclates and improve resource efficiency. Within the existing work, some research focuses on achieving higher quality products in less time. The authors normally try to optimise the recycling techniques with the design of experiment approaches (Meyer et al., 2009; Ye et al., 2013). The basic objective is to find the values of a group of parameters which lead to the optimal decomposition rate and decomposition time. Some other research considers the resource efficiency, energy efficiency for instance, for the aforementioned recycling processes. The existing work of reducing recycling energy consumption has focused so far on searching for more energy efficient operating parameters (Howarth et al., 2014). How to optimally use the recyclates to improve the performance, or reduce the cost of the remanufactured product is also a very important issue worth investigating. Research works have also been developed focusing on this topic (Meira et al., 2014; Pohlak et al., 2010). Optimisation is important for the development of composite recycling techniques as it can help to improve recyclate quality and process efficiency, as well as reduce cost. Currently, there is no paper focusing on the state-of-the-art of the applications of optimisation techniques on composite recycling. The aim of this paper is to examine a number of optimisation approaches used in the composite recycling area and outline the future research issues that optimisation in composite recycling as a practice should cover.

This review 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 deconstructing, recycling and remanufacture of composite materials. In the remaining of the paper, the methodology used to deliver this review and the optimisation techniques used in the mechanical, thermal and chemical recycling are presented in Section 2; then, in Section 3, optimisation approaches used at the re-manufacture stage is presented; finally, the research gaps and important research opportunities for the future are proposed in Section 4.

2. Techniques used to optimise the recycling approaches

According to Roy et al. (2008), the engineering optimisation is a process of identifying the right combination of the product and associated process parameters for the best solution. Traditionally, the process is often done manually. The manual approach can be very time consuming, and the searching ability of it is limited and can often lead to sub-optimal solutions. Some automatic searching approaches have been developed in recent decades such as Genetic Algorithms (Holland, 1975) and Swarm Intelligence (Blum and Li, 2008) and offer alternative methods to the more traditional manual approaches. The mathematical modelling for a specific process is normally developed before the application of optimisation techniques. The purpose of this paper is to search the applications of modelling and engineering optimisation in the composite recycling and re-manufacturing areas.

The composite recycling or re-manufacturing system can be studied at different levels. These levels range from the entire factory to the recycling techniques (the y axis in Fig. 1). As shown in Fig. 1, each of these levels has its corresponding optimisation objectives (the x axis). At the recycling techniques level (mechanical, thermal and chemical recycling methods), improving the quality of recyclates, increasing the recycling rate (decomposition rate) and shortening the processing time are the main issues for consideration. At the equipment level, resource efficiency is the main performance indicator to be improved. This means resources consumption such as energy and water need to be reduced for recycling certain amount of composites. Furthermore, at the enterprise level, the trade-off between quality, resource and time within the whole recycling/re-manufacturing system are to be realised. Fig. 1 also presents the potential approaches to realise the optimisation at each level. For instance, at the enterprise level,

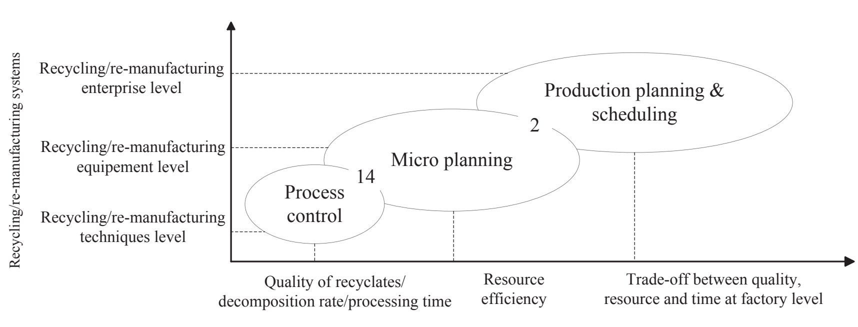

Fig. 1. The levels of composite recycling/re-manufacturing system (based on Vijayaraghavan and Dornfeld (2010)).

Table 1
The keywords and their combination used for literature search.

Keywords used for recycling methods	Keywords used for materials	Keywords used for modelling and optimisation
Mechanical	Composites	Optimisation
Thermal		
Pyrolysis	Carbon Fibre	Optimise
Fluidised-bed		
Microwave		
Chemical	Glass Fibre	Model
Solvolysis		
Extended search		
Mechanical + Polymer + Optimisation/Optimise/Model		
Pyrolysis + Polymer + Optimisation/Optimise/Model		
Fluidised-bed + Polymer + Optimisation/Optimise/Model		
Microwave + Polymer + Optimisation/Optimise/Model		
Solvolysis + Polymer + Optimisation/Optimise/Model		
Carbon Fibre/Glass Fibre + Re-manufacture/Re-use		

production planning and scheduling methods can be used to achieve the trade-off between quality, resource and time (Liu et al., 2015). These approaches are not absolutely independent. They overlap each other, filling the whole process for the composite recycling or re-manufacturing systems. The model developing and optimisation techniques can be applied on any level. The review of existing research works on composite recycling presented in this paper is based on the levels shown in Fig. 1. The search strategy consisted of looking for relevant studies within scientific literature sources, represented by academic studies published in peer-reviewed journals and conferences. The online databases including Web of Science and ScienceDirect have been searched to identify the relevant articles published on the topics of applications of optimisation techniques on composite recycling with different keywords combination as shown in Table 1.

The keywords are selected based on some comprehensive review papers about the current status of recycling of composites (Oliveux et al., 2015a; Pimenta and Pinho, 2011; Yang et al., 2012). According to these reviews, mainly, keywords used for recycling methods are defined and shown in Table 1. Every keyword in each category ('Keywords used for recycling methods', 'Keywords used for materials', 'Keywords used for modelling and optimisation') show in Table 1 is combined with each other to form a string for searching. For instance, 'Mechnical + Carbon Fibre + Optimisation' is a representative string for literature search. Seven and three keywords are selected for the category of 'Keywords used for recycling methods' and the category of 'Keywords used for materials' respectively since they can cover nearly all names for recycling technologies. 'Model' is selected as a keyword besides 'optimisation' and 'optimise' in the category of 'Key words used for modelling and optimisation'. Since for the engineering optimisation problems, normally a mathematical model is developed before any optimisation techniques can be applied. As a result, research work that focuses on modeling the composite recycling process can be defined as the basement for applying optimisation techniques. Besides the search based on the three keywords categories, some extended search using 'Recycling method' + 'Polymer' + 'Optimisation/Optimise/Model' combination have been accomplished. There are mainly two reasons for extending the search. Firstly, the publication identified in the first round of search is scarce. Secondly, the techniques used to optimise the recycling approaches when they are applied for other purposes are potential useful references for their application in composite recycling. The numbers of optimisation research works identified on each level are shown in Fig. 1. The number of research works identified in each keywords category is show in Table 2. All research reported in this paper is based on analysis of published papers referred to in the paper.

The research work focusing on optimisation techniques applied in composite recycling and re-manufacturing and its relevant system is identified in the literature search. They will be presented in the rest of this section and Section 3.

2.1. Techniques used to optimise the mechanical recycling method

Molnar (1995) evaluated the potential of using mechanical method to recycle Kevlar® aramid and carbon fibre reinforced scraps and cured prepreg composites. During the mechanical recycling process, materials are ground or milled to finer products ranging from 10 mm down to 50 μm in size after a first crushing or shredding into smaller pieces (Oliveux et al., 2015b; Morin et al., 2012). The recyclates can be separated into resin-rich powders and fibres of various lengths that are still embedded in resin (Oliveux et al., 2015b; Palmer et al., 2009). The resin-rich powders can be reused as active fillers in either bulk molding compound (BMC) or sheet molding compound (SMC) composites (Morin et al., 2012; Pickering, 2006; Schinner et al., 1996; Palmer et al., 2010; Pimenta and Pinho, 2011). Recovered fibrous fractions can be reused in thermoset composites (Morin et al., 2012). However, the re-use of the mechanical recyclates is limited by the cost and quality issue. Virgin fillers such as calcium carbonate or silica have very low costs (Oliveux et al., 2015b). Meanwhile, the most important obstacle for using the fibrous fractions as the reinforcement is that the bonding between the recyclates and the new resin is poor. This would cause the decreasing mechanical properties of the final product, such as tensile strength of the fibre, Young modulus and surface quality (Oliveux et al., 2015b). The mechanical recycling technique is the most mature one among all recycling methods. It is mainly used to recycle GFRC. The applications for recycling CFRC also exist. Based on the literature search, the optimisation works considering the relationship between recyclates quality and machining parameter variance are scarce. Schinner et al. (1996) used the milling approach to recycle the carbon fibre reinforced polyether-ether-ketone (PEEK) resin. The authors found that cutting mills, gave more homogeneous fibre length distribution and longer fibres than hammer mills, although the cutting blades wore out faster than the former.

Table 2
Numbers of optimisation research works identified for each keyword category.

Comprehensive review for composite recycling techniques	Mechanical recycling	Thermal recycling	Chemical recycling	Re-manufacturing
6	2	7	3	4

Currently, the mechanical recycling approach has not been optimised on the system level. This means the trade-off between the recyclates quality, cost and resource consumption has not been investigated. Howarth et al. (2014) 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 CFRPs recycling using milling can be theoretically calculated when the material removal rate is known. It has been discovered that at a recycling rate of 10 kg/hr, the recycling energy consumption (2.03 MJ/kg) is significantly less than the embodied energy of virgin carbon fibre (183–286 MJ/kg) (Howarth et al., 2014). This model suggested that there is potential environmental benefit of using recycled fibres in short fibre composites where mechanical performance is less important. Based on this model, further optimisation approaches for mechanical recycling to improve the energy efficiency can be developed. For instance, the application of heuristics can be considered to achieve multi-objective optimisation in terms of recyclates quality, energy consumption and processing time. Based on the above, for the mechanical recycling methods, modelling work has been developed in this area. However, there is still a lack of application of optimisation approaches.

2.2. Techniques used to optimise the thermal recycling methods

Pyrolysis (Meyer et al., 2009; Pickering et al., 2000; Kaminsky, 2010; Yang et al., 2012; Torresa et al., 2000) is a thermal decomposition method for polymers at high temperature from 300 °C 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 (Oliveux et al., 2015a). When using pyrolysis as a recycling treatment of polymer matrix composites, the matrix is transformed into smaller molecules at temperatures above 350 °C in an oven. These smaller molecules evaporate from the material and, can be used as energy source for the process due to their high calorific value. Some pyrolytic carbon (residue) bonded to the fibre surface remains in the oven together with the fibres. The amount of residue can influence the mechanical properties of the reclaimed fibres such as fibre strength, electrical properties and fibre-matrix adhesion. The amount of residue strongly depends on process parameters as oven atmosphere, temperature, heating rate and others. Controlling the value of these parameters in the pyrolysis reactor is crucial for achieving the complete depolymerisation and higher cleanliness level of the recovered fibres.

To obtain the recovered fibres with properties close to new fibres, Meyer et al. (2009) have used thermogravimetric analysis (TGA) to investigate and optimise different process parameters during pyrolysis to remove the residue as much as possible without oxidation of the carbon fibre itself. Based on lab scale pyrolysis experiments, the variation of pyrolysis temperature, oven atmosphere and isothermal residue time had been studied. It was found that in the synthetic air environment, within the temperature range from 580 °C to 600 °C, nearly all the matrix can be removed.

For the oven atmospheres, nitrogen and synthetic air environments have been investigated based on a fixed heating rate of 10 °C/min. When the temperature is between 400 °C and 550 °C, the residues exist in both atmospheres. However, the nitrogen environment provides better results in this temperature range. Above 550 °C the results are changing, as synthetic air provides the condition for residue to be oxidised. It is safe to conclude that pyrolysis in nitrogen is tending toward residue production, even at very high temperatures. With synthetic air a complete removal of the former matrix can be achieved at around 600 °C. However, at 650 °C and above, the carbon fibres start to be oxidised. This results in a strong decrease of the mechanical properties of the fibres. Consequently, temperatures higher than 650 °C should be avoided when oxygen is used.

The influence of isothermal residue time at maximum pyrolysis temperatures between 400 °C and 600 °C was examined. In a nitrogen atmosphere, an increase in the matrix weight loss was detected for the first 30 min at 400 °C. This increase became much smaller at 500 °C. It even disappears at 600 °C. Hence, the reaction is time dependent only in the lower temperature range. Therefore, neither high temperatures above 600 °C, nor long residue time of more than 30min are required when pyrolysis is performed in nitrogen atmosphere. Comparatively, the oxidation reaction is much more time dependent. An increase in weight loss with residue time was observed in synthetic air, and therefore the exposure time of the carbon fibres in this temperature should be short in order to avoid oxidative fibre damage.

The above research work focuses on the process level of recycling/re-manufacturing techniques. It had been delivered based on experiments. This means there is a lack of mathematical model to describe the pyrolysis process used for CFRP recycling, and no automatic optimisation techniques have been applied. This work only considered to optimise the mechanical properties of the recyclates based on parameter tuning. The cost and environmental impact factors have not been considered yet.

Cheung et al. (2011a,b); Lam et al. (2011) had developed a series of modelling and optimisation work for pyrolysis process which is used for treating waste tyres. These researches can be used as reference for pyrolysis based composite recycling to develop models and optimisation techniques. Furthermore, this work has included energy consumption as one of the objective to be optimised. Lam et al. (2011) 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 performs exothermically at its early stage, Cheung et al. (2011a,b) proposed an idea to reduce the pyrolysis energy consumption in order to reach its full potential to produce bio-fuels. This approach suggests trapping 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.

Cheung et al. (2011b) developed a mathematical model that considers the mass loss kinetics, exothermic kinetics, and heat flow together based on tyre pyrolysis experiments. A multi-stage pyrolysis operation approach is then proposed with the aid of the developed model. The approach starts the pyrolysis with a heating stage to initialise the exothermic reactions. This is then changed to an adiabatic stage where the captured exothermic heat is used to facilitate the endothermic reactions afterwards. A significant energy saving has been achieved by employing the multi-stage operation strategy comparing with the conventional operation strategy.

In the industrial pyrolysis process, the heating rate is difficult or often not necessary to be kept constant (Lam et al., 2011). This is termed as 'dynamic heating' that the heating rate varies at different reaction stages. Lam et al. (2011) studied the pyrolysis with dynamic heating to understand the effect of heating rate on production rate, energy consumption and product quality, etc. Based on experiments, the production rate and reaction heat of tyre pyrolysis at different heating rates are obtained. A transient model considering the effect of dynamic heating was then developed and compared with the conventional static heating model. It has been shown that a higher heating rate favours the production of volatiles fractions and shifts the overall pyrolysis heat flow to more endothermic.

Based on the aforementioned work, the authors (Cheung et al., 2011a,b) proposed a four-stage strategy for the tyre pyrolysis, which has the sequence of heating, adiabatic, heating and adiabatic. The approach is verified by the model, and it is capable to save about 22.5% energy consumption with a 100% increase in completion time compared to the conventional strategy. Oyedun et al. (2012) proposes an optimisation method to tune the operating parameters in the developed four-stage pyrolysis. Finally, this approach can achieve a 29% reduction in energy usage with just 36% increase in completion time. Some of the modelling work for pyrolysis had been delivered at this stage, however, the optimisation work still based on experiments. None of the advanced automatic optimisation techniques had been applied.

Ye et al. (2013) used Taguchi method (Roy, 2001) 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. The process is operated with a maximum temperature of 600 °C and under atmospheric pressure. Superheated steam is used as the soft oxidant. Operational parameters including temperature, isothermal residue time and steam flow-rate have been investigated. Two levels for each of them were tested to determine their influence on the decomposition rate of the polymer matrix and the mechanical property of the recycled carbon fibres. Taguchi method is used in this research to reduce the number of experiments based on the full factorial design to a practical level. Normally, two types of factors are defined in the Taguchi method: control factors and noise factors. An inner design constructed over the control factors is used to find the optimum settings (Ye et al., 2013). It can be referred to Roy (2001) for more details about Taguchi method and its relevant applications. The analysis of variance and standard least squares linear regression are used to analysis the experiment results. It has been identified that the decomposition rate of matrix is directly related with the mass ratio of steam/sample, the heating temperature, and the presence of steam at higher temperature during the later stage of the thermal treatment. The influences of the process parameters on the tensile strength of the recovered carbon fibres, however, cannot be determined within attributed levels.

Fluidised-bed process is a pyrolysis-based approach using a bed, of silica sand for example, fluidised by hot air. It enables a rapid heating of the materials and release the fibres by attrition of the resin (Oliveux et al., 2015a; Pickering et al., 2000). This method has been applied to recycle both GFRCs and CFRCs. Pickering et al. (2000) has implemented a rotating sieve separator to separate fibres from fillers of GFRCs recylates. The tensile strength of glass fibre was reduced by 50% at 450 °C, while the reduction achieved 80% at 500 °C. The strength degradation of carbon fibres is around 25% at 550 °C (Oliveux et al., 2015a; Pickering et al., 2000). Microwave-assisted pyrolysis has also been used as a composite recycling method (Lester et al., 2004). This method costs less energy since the material is heated in its core so that thermal transfer is very fast (Oliveux et al., 2015a). However, both of the processes have not been optimised. Based on above, mainly, the manual approaches such as Taguchi method and sensitive analysis have been applied to optimise the thermal recycling approaches.

2.3. Techniques used to optimise the solvolysis recycling method

Solvolysis is a chemical treatment using a solvent to degrade the resin (Oliveux et al., 2015b; Yoon et al., 1997). The solvolysis process can reclaim both the clean fibres and fillers as well as depolymerised matrix in the form of monomers or petrochemical feedstock (Yang et al., 2012; Hydea et al., 2006). 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 (Oliveux et al., 2015a). Water or alcohol is normally used as the solvent, which is relatively environmentally friendly (Yang et al., 2012). The solvolysis recycling process can be used for both GFRCs and CFRCs. The reclaimed fibre retains most of its mechanical properties (Yang et al., 2012). To reach higher dissolution efficiency and faster dissolution rate, catalysts are normally used, and the solvent properties are also been tuned and optimised. Normally, the factorial design method is used to tune the solvent properties (Oliveux et al., 2015a; Kleinert et al., 2009). The solvolysis process has not been optimised on the system level. Actually, expensive reactors which can withstand high temperatures and pressures as well as corrosions are required when supercritical conditions are used (Kritzer, 2004). As a result there is a trade-off problem between the cost of facilities and the solvent properties that needs to be solved before applying the solvolysis to industrial scale.

Perrin et al. (2008) used the experimental design and statistical process control techniques to find the optimal values of solution concentration and agitation time for maximizing the dissolution of $CaCO_3$ to reclaim glass fibres from the SMC waste. In this research, the authors aimed at obtaining the longest fibres and the highest fibre content in the final recyclates. The optimisation approaches applied to the chemical recycling methods are very similar to the ones applied to the thermal recycling approaches. They are still manual approaches such as factorial design.

3. The optimisation used at the design and re-manufacturing stage

Optimal usage of the recyclates during the re-manufacturing is another very important issue in the composite recycling and remanufacturing system. According to the existing work, researchers have considered to use the recyclates to achieve cost reduction while guaranteeing the necessary mechanical performance.

Meira et al. (2014) uses the mechanical recycling method to reclaim the thermoset based glass fibre reinforced polymer rejects derived from the pultrusion manufacturing industry. The recyclates are used as aggregates and reinforcement replacements into concrete-polymer composite materials. The authors found that the recyclate content and size grade, and the effect of the incorporation of an adhesion promoter can be considered as factors which influence the flexural and compressive strengths of final composite. The authors used the Fuzzy Boolean Nets method to find the best balance between material parameters that maximizes both flexural and compressive strengths of final composite based on limited experiment result. Fuzzy Boolean Nets is a universal approximator with excellent generalisation capability which is able to predict the response of parameter-dependent systems (Carvalhoa and Tomé, 2007). This technique has been selected for the aforementioned study due to its good performance based on sparseness of available trial data (Meira et al., 2014). It can be referred to Carvalhoa and Tomé (2007) for more information about the working procedure of this technique.

Shah et al. (2010) developed a reinforcement learning algorithm (Gosavi, 2003, 2007) to help the plant manager to optimally use the recycled materials, thereby reducing the cost of the final products. Reinforcement learning allows machines and software agents to automatically determine the ideal behaviour within a specific context, in order to maximise its performance (Gosavi, 2003). The reason for using this technique to optimise the above problem is that it can generate near-optimal solutions to stochastic dynamic programs without probability transition (Shah et al., 2010). Gosavi

(2003) introduced how a typical reinforcement learning algorithm works. Normally, it is environmentally and costly beneficial to use recyclates. However, the service level can be negatively influenced by using recyclates since they usually need additional pre-processing which results in an increasing in the production time. Hence, it is necessary to use virgin materials when the supply of finished products is running low, to satisfy service levels. The authors modelled the aforementioned material selection as a semi-Markov decision problem. The developed reinforcement learning algorithm identified an optimal strategy of switching between the two sources of material. The simulation result shows a 65% cost improvement over a policy that uses only virgin materials. This research provides a general material selection strategy when recyclates are used as one type of the raw material. It is a very good reference on the optimisation work on the workshop level when automatic optimisation techniques are employed.

Zhao et al. (2008) investigated the feasibility of manufacturing wood-rubber functional composite panels with a polymeric methylene diphenyl diisocyanate and urea-formaldehyde combination binder. The response surface method was used to determine the significant independent variables among board density, pressing time and pressing temperature and their influence on the board performance including internal bond strength, modulus of rupture and modulus of elasticity. A mathematical simulation or response surface models were developed to predict the board properties. This work is not directly related with the optimisation research in composite recycling. However, the response surface method used in it can be used as a reference for the design optimisation research focusing on using recyclates during re-manufacturing.

Pohlak et al. (2010) developed a multistage optimisation procedure to find the optimal thickness of the glass fibre polyester resin layer in the composite bathtub. The objectives of the optimisation procedure are to minimise the total cost of the bathtub and the production time. The ratio of polyester resin to the curing agent has significant influence on curing time, and both objectives considered. The curing time decreases with increasing layer thickness. Compare to structure with constant thickness, the structure with optimal thickness distribution of the reinforcement layer has several advantages. The stresses and displacements are reduced several times and have more uniform distribution. This work can be very beneficial for research focusing on optimising the product quality at the design stage when using recyclates as the reinforcement. In the recyclates re-manufacturing sector, both of the manual and automatic searching approaches (Fuzzy Boolean Nets and reinforcement learning algorithm) has been applied as the optimisation approaches. More automatic searching approaches are expected to be applied in this sector since the re-manufacturing is more focused on the system level.

4. Conclusions and future work

Based on the literature presented in this paper, it can be found that on most levels of composite recycling and re-manufacturing system, the application of optimisation techniques can be identified. However, these applications are still scarce considering the potentialities to be optimised. Meanwhile, most of the techniques applied are the experimental design approaches to tune the parameters. The following research gaps are identified:

1. There is a lack of mathematical models to depict the influence of variance of processing parameters on the quality of recyclates for all recycling approaches. Based on the models, more efficient optimisation techniques can be applied. Currently, most of the existing optimisation work on the composite recycling technology level is developed based on experiments and experiences. The development of mathematical models for these recycling techniques is crucial for researchers to better understand and optimise them.
2. There is a lack of mathematical models to depict the influence of variance of processing parameters and other relevant factors on the cost and environmental impact of all recycling approaches. Cost and environmental issues during the composite recycling is very important, therefore the developed approaches should not only be technically feasible, but also cost effective and environmentally friendly.
3. There is no work that focuses on optimising the composite recycling on the workshop level. Based on existing research in the sustainable manufacturing area, operations research and scheduling methods had been proved to be very effective tools to reduce energy consumption and environmental impact of a specific manufacturing system. However, in the literature identified in the composite recycling area, energy and cost saving haven't been considered on the workshop level. 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. Even if a new factory for recycling composites were going to be developed, considering optimisation on the operations level would also be very beneficial.
4. The re-use of recyclate is as significant as recycling the composites. The work focuses on the optimal usage of the recyclates to improve the quality, or reduce the cost of a specific product is scarce. The feasible and economical applications of recyclates still need to be considered at the current stage of investigation. At the same time, the modelling and optimisation techniques can be applied at any level in the re-manufacturing system. For instance, the optimal parameter combination used for the re-manufacturing technologies is worth to be investigated; the optimal combination of virgin and recycled fibres could also be considered; on the workshop level, optimising the dispatching of recyclates for production can also effectively reduce the production cost.
5. In terms of the optimisation techniques, in the existing research, very little optimisation algorithm (automatic approaches) has been applied to complete the optimisation tasks. The design of experiments methods are widely used in the existing research. However, more preferable results could have been achieved if techniques like Genetic Algorithm (Holland, 1975) or Artificial Neural Networks (Yegnanarayana, 2009) had been applied. The efficiency of the composite recycling and re-manufacturing system can be largely improved by applying the optimisation algorithm. This area is worth to be investigated in the future.

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