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Optimal directional nesting of planar profiles on fabric bands for composites manufacturing

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ABSTRACT

The nesting problem of planar (2D) parts into 2D sheets is common among many applications and thus industry branches. This work focuses on manufacturing of polymer composites reinforced by woven fabric where constraints such as part orientation and mirroring apply. A nesting procedure was developed combining a genetic algorithm as an optimization tool for part sequencing and a new Bottom-Left-Fill-Left (BLFL) heuristic for 2D nesting that considers a predetermined part sequence. The BLFL heuristic is a two-step placement method where each part is first roughly placed according to the Bottom Left Fill rules on an appropriately rasterized band and then it is finely moved left so as to eliminate discretization error. This is both a fast and accurate procedure due to a novel shape representation by four equivalent forms, namely vector, raster, simple polygon and high definition polygon. The effectiveness of the proposed approach is tested for nesting orthogonal quadrilateral, orthogonal edged (tetris™-like) and, most importantly, irregular free-form 2D shapes. The approach proved much faster than other known approaches, because of the computationally light evaluation function of the genetic algorithm and more flexible, too, since it allows the user to balance between speed and accuracy, as desired, chiefly by fine-tuning the essential shape representation parameters.

Introduction

Nesting of simple and irregular shapes on 2D sheets is an important topic that is common among many industry sectors. Given a stock cutting problem the ideal nesting solution minimizes the wastage of the stock material. Traditionally, specially trained experts were responsible to find a near optimum solution. However, in the last two decades various computational approaches have been proposed. The problem becomes more complicated and hence more difficult to solve when factors such as the degree of shape complexity and irregularity, allowed angles of shape rotation and shape mirroring are introduced. Suitability of the approach is dependent on various factors such as shape and size, type of stock and restrictions applicable and available computational resources and time.

This paper proposes a generic nesting approach of 2D irregular parts, which is suitable for normal parts, too, on a continuous 2D textile band to solve the textile stock cutting problem, with particular motivation coming from the textile composites industry. In the case of composite textiles high material cost is a much stronger motivation to obtaining optimum nesting compared to normal fabric.

An important class of composites parts, typically consisting of a polymer matrix reinforced by carbon, aramid or glass fibers, are built in layers by stacking up suitably cut profiles of sheets (plies) either pre-impregnated with resin or infused by resin at a later stage. There are a number of pertinent manufacturing processes such as automated Tape/Fiber Laying, Resin Transfer Molding (RTM), Vacuum-Assisted RTM (VARTM), Vacuum/Pressure Molding (VPM), Metal Mould Forming, Rubber Forming, Diaphragm Forming (Johnson and Rudd, 2000). Mechanical properties of the final part depend on the stacking sequence but also on orientation of fibers, i.e. on the stacking angle, hence on the relevant orientation of the profile on the stock from which this is cut.

The stock is assumed to be a rectangular band with predefined width and infinite length representing fabric rolls. Foremost, limitations include weave orientation of both stock material and parts. Typically, nesting may require rotation and/or mirroring of the parts which, however, have limited rotation ability as allowed by the stock's specific weave orientation and possibly also different properties on each side (i.e. front versus back).

The shape of parts to be nested can range from simple to highly irregular as it may have been generated by textile draping

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simulation software packages, which is common in technical textiles for composites parts. Therefore, shapes can be defined by straight lines, circular arcs and polynomial spline curves. In addition, they may have internal features of any shape. Moreover, each shape may appear more than once in a given nesting problem, i.e. multiple identical copies must be supported.

Computational approaches for nesting can be categorized according to the general shape of the parts or the sheets, the number of sheets and the rules or restrictions that govern the nesting procedure. Furthermore, the various methods employed can be separated into simple methods based on heuristics and more complex methods combining heuristics with optimization techniques such as genetic algorithms or simulated annealing.

A hybrid GA–heuristic algorithm is presented in this work, fast and accurate enough for practical application in the composites textile industry, which is largely enabled by a multiple accuracy shape discretization representation.

The state-of-the-art is reviewed in Section "State-of-the-art". Sections "BLFL nesting heuristic" and "Genetic optimizer" present the developed solution concerning heuristic and optimization, respectively. Section "Results and discussion" presents sample results including performance data and Section "Conclusions" outlines the conclusions reached.

State-of-the-art

Depending on the practicalities of the industry branch tackled, including the stock form and cutting procedures adopted, optimizing stock utilisation may be interpreted differently thereby leading to a need for different nesting algorithms (Xie et al., 2007). For instance, it might be typically desired either to reduce scrap areas on a fixed dimension sheet or to reduce the length of a roll band (which is adopted in this work, too) or even to apply a combination of both. There are also variants of these criteria, e.g. differentiating between scrap areas located at the bottom and those at the left side of the stock sheet/band or taking into account the contact length of nested features (Uday et al., 2001). In addition, different constraints may need to be accommodated, e.g. in nesting of packages a specific columnar arrangement may need to be considered as well as specific search spaces horizontally, vertically and between profiles (Selow et al., 2008).

Starting in the mid-1990s nesting research emphasis was laid in rectangular shaped parts, whilst suggesting further work concerning irregular parts, and was based on heuristics so as to contribute to the needs of clothing, furniture and aerospace industries (Cheng et al., 1994). Dowsland et al. (2002) provide a good account of the classic Bottom Left (BL) heuristic which led to other variants, such as the Bottom-Left-Fill (BLF) algorithm (Hopper and Turton, 1999). Even today, there are stand-alone applications based on BLF thereby trying to avoid optimization as such (Weng and Kuo, 2011). Another popular heuristic concerns total potential energy (HAPE), i.e. minimization of the distance between an edge of the sheet and the centroid of the nested parts (Savio et al., 2012).

In the last decade it became apparent that combinatorial complexity of the nesting or packing problem necessitated stochastic search (metaheuristics) in combination to either existing or new heuristics, i.e. hybrid AI-based methods (Hopper and Turton, 2001). New heuristics have been reported within such hybrid approaches. Examples include human packer mimicking (HPM) which gradually places new shapes towards the border of the stock (Tay et al., 2002); this, however, seems to be sensitive to part sequences. Another example is the Compact Neighborhood Algorithm (CAN) that considers the relationship between the number of neighbors and the sharing space between them, being suitable for large scale packing involving a large number of identical parts (Cheng and Rao, 2000). Furthermore, a Quick Location and Movement (QLM) heuristic has also been reported (Lee et al., 2008).

Within hybrid approaches, shape representation is quite influential both in terms of speed and in terms of accuracy or, more generally, quality of the solution. Orthogonal parts are the simplest to deal with (Jain and Chang, 1998). Discretisation approaches provide for speed in subsequent evaluation at the price of accuracy, hence they might be applied to both length and width of the stock (Babu and Babu, 2001) or across width only (Burke et al., 2006). Exact approaches may rely on subsequent evaluation using no-fit polygons (Bennell and Oliveira, 2008).

As far as the metaheuristic method employed is concerned, GAs are dominant, one of the first influential works published being that of Jakobs (1996). Crispin et al. (2005) provide a systematic investigation into GA coding methods for both packing-based nesting and the less popular connectivity-based nesting based on no-fit polygons. Further next-of-kin metaheuristics include: evolutionary strategy methods (Wong and Leung, 2009), simulated annealing, for instance including part clustering (Wu et al., 2003), and also parallel GAs involving subpopulations communicating with each other according to selected patterns (Uday et al., 2001). Improvements to genetic evolution have been reported, too, namely: (a) hierarchical subgroups together with new genetic operators (Fischer and Dagli, 2004), (b) Neural Networks that essentially select scrap areas already formed between nested parts that may be reallocated to part nesting (Poshyanonda and Dagli, 2004) and (c) shrinking algorithms to enhance good solutions

Table 1
Main characteristics of the nesting problem and solutions.

Problem characteristics			Solution characteristics		
Part shape	Degrees of freedom	Criterion	Nature	Part geometry	Flexibility
Rectangular	Translation	Length covered	Heuristic: • BL • BLF • HAPE • HPM • CAN • QLM	Accurate	Accuracy-dictated
Linear	Rotation • Full • Restricted • Specific • No	% Empty area	Hybrid AI-heuristic, AI being: • GA • Parallel GA • Evolutionary • Sim.annealing • Cuckoo search	Discretised	Solution time-dictated
Freeform	Mirroring	Contact length of nested profiles		Hybrid	None