# **Towards Automated Scheduled Nesting for Flexible Manufacturing**

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# Abstract

Companies in the sheet metal industry relies on nesting, which is the process of creating cutting patterns to reduce material waste. In many cases, nesting and production scheduling must be addressed simultaneously, due to a trade-off between high material utilization and effective production planning. This is especially true for ETO companies, where the production is both complex and flexible, due to a high variety in products and varying demand. ETO companies in high cost countries are competing against companies low-wage countries, causing them to be challenged on lead times and manufacturing costs. Implementing flexible automation can be the competitive edge these companies need. This paper presents a new framework for automating the nesting process in ETO companies, where not only material utilization is considered, but also variables implied from different processes around the nesting process. The proposed framework, called *Scheduled Nesting System* (SNS), is cost-based and considers a wide range of costs, which are either directly or indirectly connected with nesting. These costs are: material usage, cutting cost, cost of changing sheets, cost of cutting orders to stock, and order due date. Based on these costs, the framework proposes a nest, which has the minimal cost. The study focuses on the sheet metal nesting process of ETO companies, and thus applies to the manufacturing industries concerned with heavy machinery, ships, aircrafts and aerospace, to mention a few.

Keywords: Automation, Nesting, Scheduling, Optimization, Genetic algorithm

# 1. Introduction

Nesting is the process of creating cutting patterns on a working piece. It has a vast array of applications and is commonly found in e.g. textile, paper and manufacturing industries. The objective of nesting is to minimize the cost of manufacturing. This is done by strategically placing the shapes to be nested in a way, that maximizes the material utilization and thus reduces the amount of scrapped material. In mass production, the expected economic gains from optimizing a nest can be substantial, and nests with a very high material utilization are often standardized in order to reuse it over and over again. However, not all companies can benefit from using standardized nests, and Engineering-to-order (ETO) companies are an example of this. ETO companies develop products for and in collaboration with their customers, and have the uniqueness of their products as one of the main selling points that differentiates them from typical mass production. This however entails dealing with a high variety in the production, thus not being able to reuse standardized nests. Furthermore, ETO companies are often challenged by long lead times [1]. If the lead time is too long, the customer will either choose a different vendor, or might be willing to compromise on the product, and opt for a standard product instead. Since the nesting process has an impact on both the lead time and the cost of manufacturing, automating the nesting process can lead to enhanced competitiveness. However, the automation must be able to handle the complexity and flexibility of the production.

This paper consists of six sections. Following the introduction is a state of the art analysis. Based on these analyses, the scheduled nesting system is developed in section 3. The outcome hereof is shown in section 4, which is followed by a discussion of the proposed system and further work in section 5. Lastly, the conclusion on the paper is presented in section 6.

#### 2. State of the Art

The nesting problem is a combinatorial problem, that has been an ongoing research topic for several decades. One of the more prevalent methods for handling these problems is *Genetic Algorithms* (GAs), e.g. used by [2] and [3]. GAs were used for nesting problems for the first time in 1992 by [4], and is still today used to increase the efficiency in regards to nesting, sometimes in combination with other algorithms, as seen in the case of [5] and [6]. A common denominator for these studies is that the objective of the nesting is to maximize material utilization. However, at many manufacturing sites there exists a trade-off, which is that nesting with the highest possible material utilization might have a negative impact on production planning and scheduling, and ultimately lead to a higher manufacturing cost. While the objective of nesting is to maximize material utilization, the objective of scheduling is to maximize the value of the produced parts while minimizing the cost of manufacturing. Value is added when meeting or surpassing customer expectation, e.g. by having the products ready by their due date in the agreed quality and quantity. Cost is minimized by enabling a constant flow of materials and products through the production, such that the utilization rate of the machines is high. Considering both nesting and scheduling is referred to as scheduled nesting.

Due to the high variety of products in ETO companies, focusing solely on material utilization as the optimization objective might have negative consequences on the subsequent manufacturing processes, and the reduced flexibility of using standardized nests often hinders ETO companies from using them. In general, ETO companies have a harder time adopting automation, as it often lacks the flexibility that is needed when producing high variety [7], and automation within these companies often end up as automated isles with a very low degree of coupling. The same goes for the nesting process, that is often handled by experts, who uses their expertise and experience to not only nest shapes with a high material utilization, but also to handle the planning of which shapes to nest onto which sheets, and whether to nest to stock or save surplus sheet for later nesting. This high degree of complexity entails that for ETO companies the nesting process is not only a combinatorial nesting problem, but is also a scheduling problem.

Chryssolouris et al. [8] conducted a study on scheduled nesting in the textile industries, where the objective was to optimize the production of carpets. They built a rulebased algorithm with inputs from knowledge workers within the industry and data from a manufacturing site. The algorithm suggests an optimal nest based on due dates, material and machine utilization, while minimizing manufacturing costs. Another approach for scheduled nesting is a 2D bin packing problem with rectangles, as studied by [9]. Here, the scheduling consisted of a due date and processing time for each part. Using genetic algorithms, they sought to optimize on both material utilization and lateness of the parts. Sakaguchi et al. [10] proposed a coevolutionary GAbased scheduled nesting method, that operates in two environments; a nesting environment and a scheduling environment. The coevolutionary GA is used to optimize in one environment, either scheduling or nesting, before outputting into the other environment, where it optimizes again in order to reduce the overall cost, which is the sum of the costs for the two environments. The study included multiple processes in the scheduling, such as punching, welding and bending operations. Common for these are, that the nesting problem is handled as a 2D bin packing problem, where all parts are treated as rectangles for simplicity. [8] opts for a rulebased algorithm, where both [9] and [10] uses genetic algorithms. But where [9] considers only due date and processing time, [10] has chosen to involve several manufacturing processes in the optimization algorithm. However, the emphasis for both of these studies are on mass production, e.g. with sheet metal processed by punching. Here, a more flexible model that caters for the variety in ETO companies are considered beneficial.

Manufacturing products of great variety is often the case within additive manufacturing, e.g. 3D printing. [11] proposes a framework for optimizing the scheduling of additive manufacturing jobs, i.e. assigning print jobs to different machines based on build-time, due dates and availability of the machines. The objective of the framework is to maximize machine utilization, while producing the parts before the specified due date. Although the objective is different, due to the nature of additive manufacturing, the production planning and scheduling is relevant and serves as inspiration for this study.

Gahm et al. studied the efficiency of applying machine learning for solving a scheduled nesting problem [12]. Their approach takes offset in irregular shapes nested onto sheet metal. They argue that due to the complex nature of scheduled nesting, the large number of possible solutions for the nests makes a heuristic nesting algorithm inefficient computation-wise. Therefore, they batch the shapes before nesting, such that only a set of batched shapes are nested onto the specific sheet, thereby reducing the number of possible solutions. The batches are determined using machine learning to predict whether a certain amount of shapes will fit onto a specified sheet and thereby be a part of the specific batch. The batched shapes are then nested using heuristic methods. The main objective of the study is to investigate the use of machine learning methods, and the implications of hyperparameters, to solve the scheduled nesting problem, but with little emphasis on other manufacturing processes.

In the literature, little attention is paid to the complexity, that companies are facing in their productions. This paper introduces a new approach to the scheduled nesting problem, where a *Scheduled Nesting System* (SNS), based on individual cost functions is defined. The nesting of shapes is handled by a genetic algorithm, while the cost functions are defined based on flexible manufacturing processes, i.e. laser, plasma, and flame cutting. These processes are often found in ETO companies within metal industries due to their flexible nature, and thus the proposed SNS is considered to be of general interest to ETO companies involved with sheet metal manufacturing. The cost functions are compound to one main cost function, which is minimized in order to determine the nest with the least manufacturing cost.

#### 3. Scheduled Nesting

The section presents a framework for the scheduled nesting system, which is used to determine which sheet to nest on. The objective of the SNS is to introduce a mathematical description that prioritizes the sheets in terms of the costs surrounding the nesting, in order to nest with the highest possible cost-efficiency. The different costs that are taken into account are material usage, cost of changing sheets, cost of cutting parts to stock, the cost of cutting with the cutting machines and due date of the shapes. Table I lists the variables used in the cost functions, that are designed in this section, together with a description of the variable.

A system overview of the SNS is illustrated in Figure 1. The input to the scheduling part of the SNS, is information about sheets on stock and shapes that are to be nested, coming from the ERP system. The scheduling algorithm, which is illustrated in Figure 2, then assigns the incoming shapes to sheets based on their thickness. After a sheet has been assigned with shapes, it is sent to the nesting part of the SNS. A diagram of the nesting algorithm is shown in Figure 3. The nesting part nests the shapes, outputs a cutting diagram and sends back the material usage of the sheet to the scheduling part. The scheduling algorithm then assigns a cost to the sheet for each process that it undergoes, and a total cost from the scheduling algorithm together with a cutting diagram

Variable	Unit	Description
$c_s$	DKK/sheet	Sheet cost
p	DKK	Selling price for scrap material
C	m	Sum of circumferences
$v_{cut}$	m/s	Cutting speed
$c_m$	DKK	Machine cost
$r_h$	DKK/h	Hourly rate for production worker
$c_f$	DKK/h	Operating cost of the forklift
$t_s$	S	Time for changing a sheet
n(x)	parts	No. of high runner shapes for a
		given sheet
$pen_1$	-	Penalty term
U(x)	parts/year	Yearly consumption of a certain
		high-runner part
$t_d$	day-month-year	Due date for nesting
$t_n$	day-month-year	Actual nesting date
$pen_2$	-	Penalty term
$t_{sheet}$	m	Thickness of sheet
t	m	Specified thickness
$m_u$	%	Material usage found by GA

**Tab. I** Overview of variables and their respective units used in the cost function.

from the nesting algorithm are further processed. This process is done for each of the sheets, and all the cutting diagrams with their appurtenant costs are prioritized according to the lowest cost. The cutting diagrams that have the lowest costs are then outputted to fitting cutting machines, so that each of the cutting machines cuts the sheets with the lowest costs first.

The SNS deals with only one decision variable; which sheet to be nested on next. Each sheet has a number of properties that are included in the system. These properties are:

- Length
- Width
- Thickness
- Sheet price
- Shapes to nest
- Due date
- High-runner shapes

For the nesting, the dimensions of the sheet, as well as the shapes to be nested, are used to find a cutting layout that provides a high degree of material utilization. The input to the scheduling algorithm, composed by all the smaller cost functions, is the shapes and sheets from the ERP system. The input shapes are assigned to the sheet based on their thickness and area. Each sheet is then given an initial cost of  $c_0 = 0$  and for each of the processes it undergoes, a cost, +c, is added to the total cost of the sheet. This is done for all of the sheets with the use of the SNS, and the sheet with the lowest cost



Fig. 1 System overview of the SNS.

is the one that should be nested next.

As shown in the Figure 2, the scheduling algorithm can take two different paths, depending on an inequality between material usage and a threshold, which has a piecewise linear relationship with the price of the sheet. Depending on if the material usage is greater or less than the threshold, different costs are included in the total cost of the sheet. The first cost function is based on the material usage.

#### Material usage

The purpose of the nesting process is to make the shapes take up as little space on the sheet as possible, which is defined as the material usage. The material usage of a sheet is determined by using a nesting algorithm, which is included into the SNS. The nesting algorithm is based on the use of a GA for finding the best possible solution, i.e. the nest that minimizes the material usage of the sheet in question. The GA does not find an optimal solution, but it searches for the best possible solution until it reaches a pre-defined stopping criterion, which is a maximum number of generations. The nesting algorithm is able to handle irregular shapes, in order to meet the demands of ETO companies producing a high variety of products.

When searching for the best possible solution, the GA computes a fitness score that improves as the area, that the parts occupy, becomes smaller. The number of parts for each of the sheets is fixed, and it is therefore the area they occupy that is minimized by the algorithm. The lowest material usage of the sheet in question is established when the GA has found the nest that minimizes the occupied area of the sheet. The cost of the material usage is calculated with Equation 1.

$$f_1(x) = c_s(x) - (1 - m_u) \cdot p \tag{1}$$

#### **Sheet Change**

The cost of changing sheets depends on whether it is considered that the current sheet should be put back into stock again after cutting the parts or used for nesting of high-runner parts. These parts are not originally assigned as parts to nest, but they are parts which are frequently used in production, so it may be advantageous to have some of them in stock. This is assessed on the basis of the amount of material which is left after cutting the parts along with the price of the sheet. If working with a more expensive sheet, the algorithm should show a greater propensity to put the sheet back in stock again, rather than when working with a cheaper sheet, where it is probably more costeffective just to nest the high-runners. If the algorithm determines that the sheet should be put back to stock, a cost for returning the sheet should be added to the total cost. Equation 2 is designed to describe the cost of changing sheets.

$$f_2(x) = (r_h + c_f) \cdot t_s(x) \tag{2}$$

## **Cutting to Stock**

The cost of cutting parts to stock is only calculated if it is chosen to cut high-runner parts on the remaining area of the sheet. If so, a cost will be added, which is dependent on the number of high-runners to be cut, as well as the annual consumption of the high-runner part in question, where a high annual consumption result in a lower cost. A function is set up describing the cost of storing high-runner parts:

$$f_3(x) = c_s(x) + \left(\frac{n(x)}{U(x)}\right)^{pen_1} \tag{3}$$

# **Cutting Cost**

To find the cost of cutting the parts, first of all, the thickness of the sheet is used to determine which cutting method is best suited for the dimensions of the sheet, as both the time and cost of cutting the parts in dependent on the choice of cutting method. The circumferences of



Fig. 2 Principal sketch of the scheduling algorithm.  $C_0$  is the initial cost and for each process the sheet undergoes, a cost, +c, is added to the total cost of the sheet.

the parts to be nested are used to determine the length of the cut. The cost of cutting the parts can then be derived form the selection of cutting method and the cutting length. The cost function for running the cutting machines are set up:

$$f_4(x) = \frac{C(x)}{v_{cut}(x)} \cdot c_m(x) \tag{4}$$

#### **Due Date**

The due date for all the parts is also included in the cost optimization by adding a cost that is dependent on the due date. Each sheet is assigned a due date by applying the due dates that each of the parts of the sheet has, where the earliest date is chosen as the due date for the sheet. The cost for each sheet is then varied so that it gets higher the later the due date is, which is expressed in Equation 5.

$$f_5(x) = \left(t_d(x) - t_n(x)\right) \cdot pen_2 \tag{5}$$

#### **Main Cost Function**

All of these different cost functions are composed to one main cost function in this section, which form the scheduling algorithm. The scheduling algorithm should be minimized in order to determine the best possible nest, when all the aforementioned manufacturing processes are considered, in order to lower manufacturing costs. The sheet that implies the lowest cost is the sheet that will be nested next. The scheduling algorithm is as follows:

$$C(x) = \sum_{n=1}^{N} f_n(x) = f_1(x) + f_2(x) + f_3(x) + f_4(x) + f_5(x)$$
(6)

The following optimization problem can therefore be set up:

$$\underset{x}{\text{minimize}} \quad C(x) = \sum_{n=1}^{N} f_n(x) \tag{7}$$

subject to:

$$h_1(x) = t_{sheet} = t(x) \tag{8}$$

$$g_1(x) = t_d(x) - t_n(x) \ge 0$$
(9)

$$g_2(x) = t(x) > 0 \tag{10}$$

Where  $f_n(x)$  denotes the cost functions that are based on the manufacturing processes, from which the main cost function, C(x), for the scheduling algorithm is composed. The scheduling algorithm is subject to a number of constraints, which are explained in the following.

The equality constraint,  $h_1(x)$ , implies that the thickness of the sheet used,  $t_{sheet}$ , must be equal to the specified thickness of the part, t(x). The first inequality constraint,  $g_1(x)$ , states that nesting of the shapes must take place before or at due date for the respective shapes.  $t_n(x)$  is the actual date the shapes are nested, wherefore the specified due date,  $t_d(x)$ , minus the nesting date must be larger than or equal to 0. The last inequality constraint,  $g_2(x)$ , simply implies, the fact that, the thickness of the sheet must be larger than zero, as a negative thickness is not possible.

#### 3.1 Nesting Algorithm

In section 3 about *material usage*, it is explained that the material usage,  $m_u$ , of the sheets are determined by a nesting algorithm. This section seeks to explain how the nesting algorithm works, and describe how the GA is designed, more specifically which GA parameters that have been selected for the algorithm. The overall system overview of the nesting algorithm is illustrated in Figure 3. The diagram shows that the scheduling algorithm provides an input to the nesting algorithm, which is the different sheets that have been assigned with shapes. For each sheet, the algorithm then nests the shapes, outputs a cutting diagram and calculates the material usage, which is outputted back to the scheduling algorithm.



Fig. 3 System overview of the scheduled nesting system.

The GA used in the nesting algorithm is explained in the following. The size of the population in the GA, is determined from a tuning experiment, so the number of chromosomes in a population is three times the number of shapes for the given instance. The number of genes in each chromosome is the same as the number of shapes to nest, so that each gene represents the location of separate shapes. 2,000 generations are run for each nest, which is also determined from a tuning experiment.

The fitness function aims to minimize the area that the nested shapes occupy, which is set up as in Equation 11, where  $x_{s_n}$  and  $y_{s_n}$  express the x- and y- coordinates of the vertices of the shapes,  $s_n$ . By minimizing the product of the sum of all the shapes' maximum x- and y-coordinates, it is ensured that the shapes are placed as far to the bottom-left as possible, which is advantageous when trying to make the shapes take up as little space as possible of the sheet. The smaller the denominator in Equation 11, the larger becomes the fitness function, and the better is the nest. The fitness function is subject to some constraints, which hinders the shapes from being placed outside the sheet or overlapping each other.

fitness = 
$$\frac{1}{\sum_{n=1}^{N_s} \max(x_{s_n}) \cdot \sum_{n=1}^{N_s} \max(y_{s_n})}$$
 (11)

When generating chromosomes for the next generation in the algorithm, a single-point crossover operation is performed. By this operation, the algorithm randomly picks a point in the parent's chromosomes and the genes to the right of that point are then swapped between the two chromosomes to generate an offspring. The parents are selected as the two chromosomes with the best fitness score. After the crossover operation, the offspring chromosomes are mutated to maintain diversity from one generation of chromosomes to the next. Adaptive mutation is here performed, where chromosomes with a low fitness score are exposed to greater mutations than chromosomes with a high fitness score. In this way, large mutations can increase the quality of low-quality solutions, while small mutations prevent disruption of high-quality solutions.

## 3.2 Implementation of Scheduled Nesting System

This section describes how the implementation of the scheduled nesting system is carried out. The flowchart in Figure 4 illustrates how the scheduling algorithm imports data on sheets and shapes from an ERP system and transfers the data to nesting, from which it calculates the total costs of each sheet. The algorithm calculates the total costs by running each sheet through the different processes in the flowchart, and then the algorithm outputs a log on the nesting containing the total cost, time consumption, material usage and information about the nested shapes. Additionally, the algorithm also outputs a cutting diagram for each sheet, containing the best possible nest that the nesting algorithm was able to find. The two outputs, nesting log and cutting diagram, are then sent to a priority system, as illustrated in Figure 1, where the cutting order of the sheets is determined. This cutting order is determined based on the total cost of each sheet, where the sheet with lowest total cost is cut first.

#### 4. Results

This section seeks to examine the performance of the SNS through a case study. In the study, the performance of the system is compared to the performance of a nesting expert at an ETO company and a commercial nesting software for automated nesting, i.e. the software computes the optimum placement of the shapes. The experiment involves an establishment of a low-scale simulated ERP system, which is specified in the following.

# 4.1 Validation

In order to test the SNS, a low-scale simulated ERP system was designed to mimic the behaviour of an ERP system, that handles incoming orders from which the orders are redistributed to production planning. The simulated ERP system is based on three basic shapes, a rectangle, a triangle and a pentagon.



Fig. 4 Flowchart describing the back-end of the scheduled nesting system. The ERP system is illustrated with dotted lines, as it is not an actual part of the system, but just where the data is imported from.

The validation is carried out by nesting on six different sheets. The shapes are generated by the simulated ERPsystem and assigned to their corresponding sheet, i.e. sheets that have the same thickness as the part. The exact same shapes are used in the commercial nesting software, and by the nesting expert at the ETO company, thereby making it possible to compare the results.

The purpose of the nesting process is to minimize the material usage of the sheet. As the working principle of the SNS is to nest the shapes as close to the bottomleft corner as possible without overlapping, the nesting expert is instructed to do the same. In addition, the nesting expert has the possibility of rotating the shapes freely. In the commercial nesting software, the setting for *optimal nesting* without time constraint is ticked off, meaning the software will continue searching the solution until an optimum is found. Apart from this, the default settings are kept, i.e. the shapes can rotate in angular increments of  $90^{\circ}$  and must have a spacing of 10 mm apart from each other. The material usage is determined by calculating the area of the convex hull, i.e. a polygon, that surrounds the nested shapes. The area of the nests from the ETO company and the nesting software is calculated using the same method, and from these, the material usage of each sheet is determined.

The time for performing each nest is output from the SNS via a log-file, and for both the ETO company and the commercial nesting software it is measured, when the nesting is performed. The ETO company and the commercial nesting software are close when comparing material usage, while the SNS is higher for all six nests, as shown in Figure 5. The total time consumption is highest for the SNS, lowest for the nesting software, with the manual nesting at the ETO company in between. The nesting software spent approximately 13 minutes computing the six nests,



**Fig. 5** Bar chart illustrating the differences in the material usage for the three nesting setups. The blue bars symbolize the material usage for the SNS, the red bars for the nesting experts at the ETO company and the green bars for the commercial nesting software.



**Fig. 6** Bar chart to illustrate the differences in the time consumption for the three nesting setups. The blue bars symbolize the time consumption for the SNS, the red bars for the nesting experts at the ETO company and the green bars for the commercial nesting software.

which the ETO company and the SNS exceeded by 60 and 140 minutes, respectively. The time is shown on the bar chart in Figure 6. Here it can be seen, that some of the times for the SNS is closer to the times of the ETO company than others. More specifically, on the nests involving fewer shapes (40 and 50 mm), the SNS is closer to the times of the ETO company, than in nests with more shapes. Furthermore, the time for each method varies considerably between nests.

The number of shapes is plotted against time, as shown in Figure 7. The time is normalized in order to see the variations of each method. This shows, that the number of shapes impacts the computation time for the SNS and the nesting software, which is caused by more shapes



**Fig. 7** Bar chart illustrating the relation between the number of shapes and time consumption. The time consumption has been normalized. The blue bars symbolize the time consumption for the SNS, the red bars for the nesting experts at the ETO company and the green bars for the commercial nesting software.

leading to a larger solution space, that the algorithms needs to search. The nesting expert at the ETO company is less affected by this. This is considered to be due to the heuristic approach by the nesting expert, which shows as patterns in the nests. Rectangular shapes are packed together, if possible filling out the width of the sheet. Triangles are packed together, with every other shape rotated  $180^{\circ}$ . The nests performed by the nesting software shows some of these patterns as well, but to a lesser extent.

#### 5. Discussion and Further Work

# **Proposed Method**

The SNS handles irregular geometrical shapes, i.e. consisting of line, circle and arc entities, but can not handle more complex geometries, such as splines and inner geometries. This is a problem in regards to deployment of the SNS, as most ETO companies handle shapes with a great amount of variation in shape, size, and complexity. Therefore, the part of the program that imports DXF-files needs to be further developed, such that more complex geometries can be imported and nested. The algorithm in the current form is not able to rotate the shapes either. This is chosen, as rotating the shapes implies a trade-off between computation time and material usage. When the shapes are able to rotate, the computation time increases heavily. This is due to the increase in solution space, i.e. the increase in the possible combinations of positions and rotations for each shape, that the rotation implies. The commercial nesting software is able to rotate the

shapes in increments, which is considered to be part of the reason it delivers better results in terms of material usage. Making the SNS able to rotate the shapes is a topic for further development, as it is considered to lower the costs. However, it must not be at the expense of a severely prolonged computation time, as this might hinder the use of the SNS in a production.

In section 4, it is mentioned, how the nesting expert at the ETO company, and to some degree the nesting software, is using heuristics, when nesting the shapes. The heuristics are seen as patterns in the nests, where certain shapes are nested in a specific way or packed together. An example of this is triangles packed together to form a large rectangle. The GA used for nesting in the SNS, initially places the shapes randomly, and then optimizes their positions. This hinders the shapes from being packed together in a similar manner, as the relative position of the shapes will not change considerably. If heuristics, similar to the ones seen on the validation nests, could be adopted into the nesting algorithm of the SNS, the quality of its nesting could be improved considerably. This would overcome the initial random placement of parts, and lead to a lower material usage, as shapes can be packed together. Furthermore, if the initial placement of parts are improved, the computation time is also considered to be drastically improved, as the solution space is reduced.

# Implementation of the Scheduled Nesting System

In order for the SNS to provide value for ETO companies, the steps for implementing the SNS must be considered. The input to the system comes from the ERP system, in the form of shapes with due dates from orders and sheets from inventory. Therefore, it has to be ensured, that the SNS is able to import the data from the ERP. Furthermore, it should be able to write to the ERP, e.g. in the case of updating the inventory with surplus sheet. This is handled by integrating the system with the ERP system, either as an application inside the ERP or by applying a seamless interface between the system and the ERP. By seamless it is meant, that the data flow is not blocked by the need of making file conversions or manual extraction of files. Thus, the orders, with shapes and due dates, should be assigned to a sheet, as soon as the data is input in ERP.

#### Validation

In section 4, a case study was conducted in order to compare the nesting performance of the SNS with the performance of nesting experts at an ETO company and a piece of commercial nesting software. The performance was measured in terms of material usage and time consumption. The study found that both the nesting experts and the nesting software were able to generate nests with a lower material usage than the SNS. In addition, the other two methods also spent less time performing the task, where it was quite clear that it was the nesting software that spent the shortest time. A reason for the SNS is nesting with a higher material usage than the other two, might be due to the fact that the genetic algorithm in the SNS is a search algorithm. It might not have searched the entire solution space and thereby not been able to find the optimal solution, before it reached the maximum number of generations. The differences in material usage are also partially due to the nesting expert being able to rotate the shapes when nesting, so that they can fit the different shapes between each other and thereby use less material.

The performance of the three different methods is measured on time consumption and material usage. However, the SNS is not designed to directly optimize on these measures, instead it searches for the solution that entails the lowest costs. Neither the nesting experts nor the nesting software include costs in their nesting, which is why it has only been possible to make a complete comparison with the selected performance measures.

# Novelty

In the state of the art study in section 2, it was found that optimization algorithms for scheduled nesting have already been researched. However, they pay little attention to the complexity of manufacturing. With the introduction of the SNS, a new framework for scheduled nesting is presented, which is based on due dates and the different costs associated with the nesting process. The framework is intended for automating the nesting process at ETO companies, in order to reduce the lead time and manufacturing costs.

# 6. Conclusion

The focus in this paper has been on the development of a framework for performing scheduled nesting in ETO companies. In order to gain a broader understanding of the nesting process, a state of the art study on nesting was conducted. From the study, it was found that nesting is a combinatorial problem, which is frequently handled through the use of Genetic Algorithms seeking to optimize the material usage of the nesting. However, only optimizing on the material usage might affect the scheduling of the production negatively. Therefore, it is decided to develop a system that combines nesting with scheduling to take account of both aspects.

The developed system, the SNS, consists of two parts; a scheduling part and a nesting part. The scheduling part of the system is based on a number of cost functions, where some different aspects associated with nesting imply different costs. These costs include, for example: cost of material usage, cost of sheet change and cost for cutting. The SNS can then be used to estimate the cost of nesting on different sheets and thus contribute a basis for decision-making in relation to which sheet to nest on next. The system's nesting part uses genetic algorithms for performing nesting of the shapes on the different sheets, which are outputted to the scheduling part, which then can use the material usage of the given nest for calculation of the costs.

In subsection 4.1, the performance of the SNS is validated against nesting experts at an ETO company and a commercial nesting software. The performance of the SNS was unable to keep up with the performance of the two other methods. The performance was measured in terms of material usage and time consumption, which are parameters that are not considered in the SNS, as discussed in section 5. However, as many different aspects of the manufacturing processes are taken into account in the SNS, i.e. in the form of the costs, it is believed that the use of it will lead to cost savings as well as a reduced lead time. In addition, the SNS can aid in automating the nesting process, as well as serving as a decision making tool for employees.

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