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Published in:
Procedia CIRP

DOI (link to publication from Publisher):
10.1016/j.procir.2022.05.167

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 107 (2022) 1415–1420

www.elsevier.com/locate/procedia

55th CIRP Conference on Manufacturing Systems

Automated Scheduled Nesting for Flexible Manufacturing

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Abstract

In the sheet metal industry, companies rely on nesting procedures to organise the cut patterns of sheet metal. Most of the current nesting algorithms and methods focus solely on laying out the cutting patterns only to reduce material usage. However, in dynamic manufacturing environments, such as engineer to order (ETO) companies, efficient nesting has to be addressed together with effective production scheduling. Therefore, reducing the trade-off between high material utilisation (to lower production cost) and effective production planning (to honour tight delivery deadlines) is essential. This paper presents a novel *scheduled nesting* approach for ETO companies. The framework is built on the existing "scheduled nesting" model, where material utilisation and variables implied from different operations around the nesting process are considered together. The proposed artefact, called *Scheduled Nesting System* (SNS), is based on a constrained optimisation objective function to be minimised and considers a wide range of variables, which are either directly or indirectly connected with nesting. These variables are material usage, operation of cutting machine cost, cost of changing metal sheets, cost of cutting orders to stock, and order due date, to name a few. The dynamic nature of the ETO operations is as such included by adapting pending nests based on incoming orders. Based on these variables, the framework finds a nest, which has a minimal cost. The study focuses on ETO companies' sheet metal nesting process, and test results show the SNS's potential for lead-time and production cost reduction.

Peer-review under responsibility of the International Programme committee of the 55th CIRP Conference on Manufacturing Systems

Keywords: Nesting; scheduled nesting; sheet metal industry; production cost reduction; flexible manufacturing

1. Introduction

Nesting is the process of placing multiple shapes to be cut on a work-piece (e.g. metal sheets). The typical objective is to optimise material utilisation by placing the shapes to be cut in a way that minimises the waste material. Nesting has many applications and is commonly used in the textile, paper and metal industries, to name a few. In mass production, the expected economic gains from optimising a nest can be substantial, and nests with a very high material utilisation are often standardised in order to reuse it over and over again. However, in engineer-to-order (ETO) companies, extensive nest standardisation is often not possible, due to the large product variety. Instead, the nesting process must be done under highly dynamic conditions, with a continuous flow of new orders, different order priorities, unknown shapes and sizes, and varying demands. Furthermore, if varying materials are used, changeover cost and cost of stock must also be considered. As a result, the nesting process itself becomes the smaller piece in a complicated scheduling problem. A problem that is often handled using experts with years of experience and deep insight into the surrounding company processes (both manufacturing and business).

In this paper, a systematic approach is proposed, named *scheduled nesting*, as a way to combine the various components of the scheduling problem into a joint cost-function that can then be used to optimise production and lower its cost. The work takes offset in eliminating the trade-off between high flexibility, associated with ETO manufacturing systems leaning towards job-shop production, and high efficiency, associated with mass production systems. It is desired to reduce this trade-off, in an effort to optimise the value chain through digital technologies [2, 7].

This paper consists of five sections. Following the introduction is a state of the art analysis. Based on these analyses, the scheduled nesting approach is developed in section 3. Section 4 presents a case study, exemplifying the application of the scheduled nesting approach on an ETO SME. Lastly, a conclusion and discussion of the proposed system and further work is presented in section 5.

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10.1016/j.procir.2022.05.167

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) [9, 12]. GAs were used for nesting problems for the first time in 1992 by [6], and are still today used to increase the efficiency in regards to nesting, sometimes in combination with other algorithms, as seen in the case of [13] and [11]. A common denominator for these studies is that the objective is to maximise material utilisation. However, at complex manufacturing sites optimising production planning and scheduling can yield a larger reduction in costs, than obtainable by better utilising the raw material.

Scheduled nesting was experimented with in the textile industries, where the objective was to optimise the production of carpets [4]. Another approach for scheduled nesting is a 2D bin packing problem with rectangles, as studied by [1]. Sakaguchi et al. [8] proposed a co-evolutionary GA-based scheduled nesting method, that operates in two environments; a nesting environment and a scheduling environment. 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. [4] applied a rule-based algorithm, where both [1] and [8] uses genetic algorithms. But where [1] considers only due date and processing time, [8] involve several manufacturing processes in the optimisation algorithm. However, the emphasis for both [8] and [1] 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. [3] proposes a framework for optimising 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.

In the literature, only few contributions on nesting address the complexity that surrounds the nesting itself. This paper therefore introduces a new approach to the scheduling problem, where a *Scheduled Nesting System* (SNS) is defined based on individual cost functions for the scheduling constraints.

3. Scheduled Nesting Cost Function

This section presents the approach for the scheduled nesting problem within the heavy sheet metal industry, embedded into an SNS. The objective of the SNS is to introduce a mathematical description that prioritises the sheets in terms of the costs surrounding the nesting, in order to nest with the high cost-efficiency. The different costs that are taken into account are material usage, cost of changing sheets, cost of cutting parts to stock, the time cost on the cutting machine and the due date of the shapes.

An overview of the process flow 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, illustrated in Figure 2, 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. The nesting part nests the shapes, outputs a cutting diagram and returns 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 from the nesting algorithm are obtained. This process is done for each of the sheets, and all the cutting diagrams with their appurtenant costs are prioritised according to the lowest cost. The cutting diagrams that have the lowest costs are then released to a suitable cutting machine.

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 (shapes which are used for multiple products)

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 utilisation. 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 is the one that should be cut next.

As shown in Figure 2, the scheduling algorithm can take two different paths depending on an inequality between material usage and a threshold, which has a piece-wise linear relationship with the price of the sheet. Depending on whether 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 place the shapes to be nested in such way that the difference between the total area they occupy on a sheet and the sum of their areas is minimal. This in turn yields the maximum possible material usage. The nesting algorithm finds the best possible solution in terms of material usage of the sheet in question. The nesting algorithm chosen for SNS is "libnest2d" [10]. Although, SNS is not dependent on any particular nesting algorithm, the nesting algorithm must be able to handle irregular shapes, in order to meet the demands of ETO companies producing a high variety of products. The cost of the material usage, is calculated with

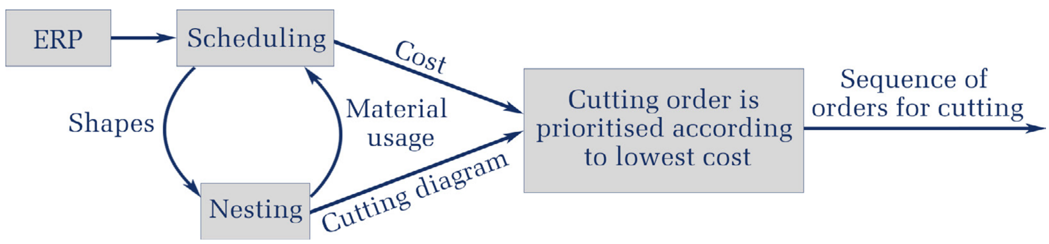

Fig. 1. System overview of the SNS.

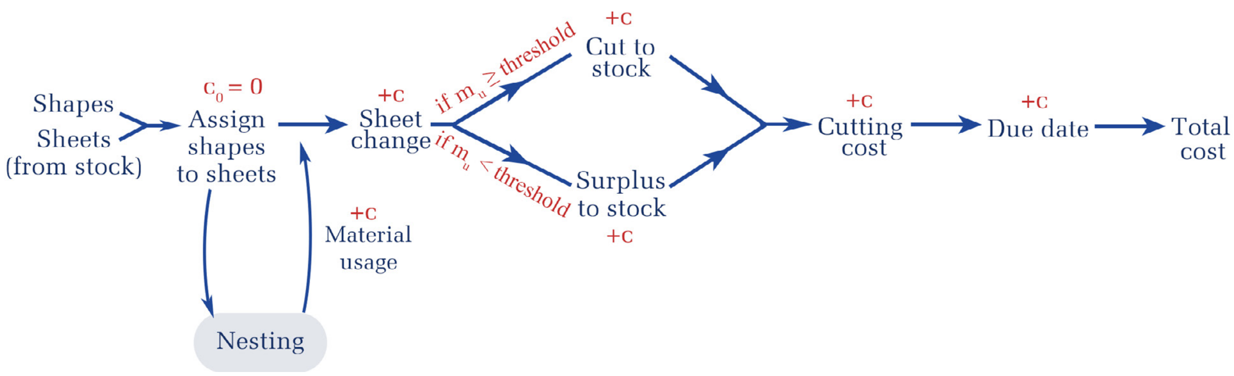

Fig. 2. Principal sketch of the scheduling algorithm. C_0 is the initial cost and for each process the sheet undergoes, a cost, $+c$, is added to the total cost of the sheet.

Equation 1, where the variables m_u, p, c_s, and x are explained in Table 1.

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

Sheet Change

The cost of changing sheets depends on the efforts required to perform the change. For thick, heavy steel plates, this cost can be substantial. The decision to be made is whether 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 is 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 cost-effective just to nest the high-runners and place them in part-stock. 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.

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

Variable	Unit	Description
x	set	All shapes to be nested
$c_s(x)$	DKK/sheet	Sheet cost
m_u	%	Material usage found by nesting algorithm
p	DKK	Selling price for scrap material
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	Number of high runner shapers for a given nest
$U(x)$	parts/year	Yearly consumption of a certain high-runner part
$P(x)$	m	Sum of perimeters
$v_{cut}(x)$	m/s	Cutting speed
$c_m(x)$	DKK	Machine cost
$t_d(x)$	day-month-year	Due date for nesting
$t_n(x)$	day-month-year	Actual nesting date
t_{sheet}	m	Sheet thickness
t	m	Specified thickness

Table 1. Overview on all the variables considered for performing scheduled nesting. The variables are grouped based on their order of appearance in the cost functions.

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:

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

Cutting Cost

To find the cost of cutting the parts, first of all, the thickness of the sheet is used to determine the best suited cutting method. The circumferences of the parts to be nested are used to determine the length of the cut. The cost of cutting the parts can then be derived from the selection of cutting method and the cutting length as:

$$f_4(x) = \frac{P(x)}{v_{cut}(x)} \cdot c_m(x) \quad (4)$$

Due Date

The due date for all the parts is also included in the cost optimisation by adding a cost that is dependent on the due date. Each sheet is assigned a due date by applying the earliest due date amongst the parts on it. 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.

$$f_5(x) = (t_d(x) - t_n(x)) \quad (5)$$

Main Cost Function

All of the different cost functions are composed into one main cost function in this section, which form the scheduling algorithm. The scheduling algorithm should be minimised 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 main cost function becomes:

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

The following optimisation problem can therefore be set up:

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

subject to:

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

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

$$g_2(x) = t(x) > 0 \quad (10)$$

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 the 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 that the thickness of the sheet must be larger than 0, as a negative thickness is not possible.

4. Case Study

Having modelled the cost function covering the variables in Table 1, it was implemented by developing an SNS software capable of taking in shape orders and providing the best nesting option at a given moment. The software was then tested in collaboration with a Danish SME involved in the heavy steel industry and having an ETO-based business model. SNS is as such tested and bench-marked against the manual methods used by the SME ETO: manual scheduling performed by workers using their tacit knowledge and manual software aided nesting.

4.1. Implementation of Scheduled Nesting System

To implement the cost function for scheduled nests (Equation 6), a Python software has been developed that is able to take in data about the shapes orders and output the nest diagram that is best to perform in terms of cost and due date, thus obtaining a nesting schedule dependent on continuous incoming orders. The flowchart in Figure 3 illustrates how the scheduling algorithm receives data on sheets and shapes from the enterprise resource planning (ERP) system and transfers the data to nesting, from which it calculates the total costs of each sheet, as described in the previous section. 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

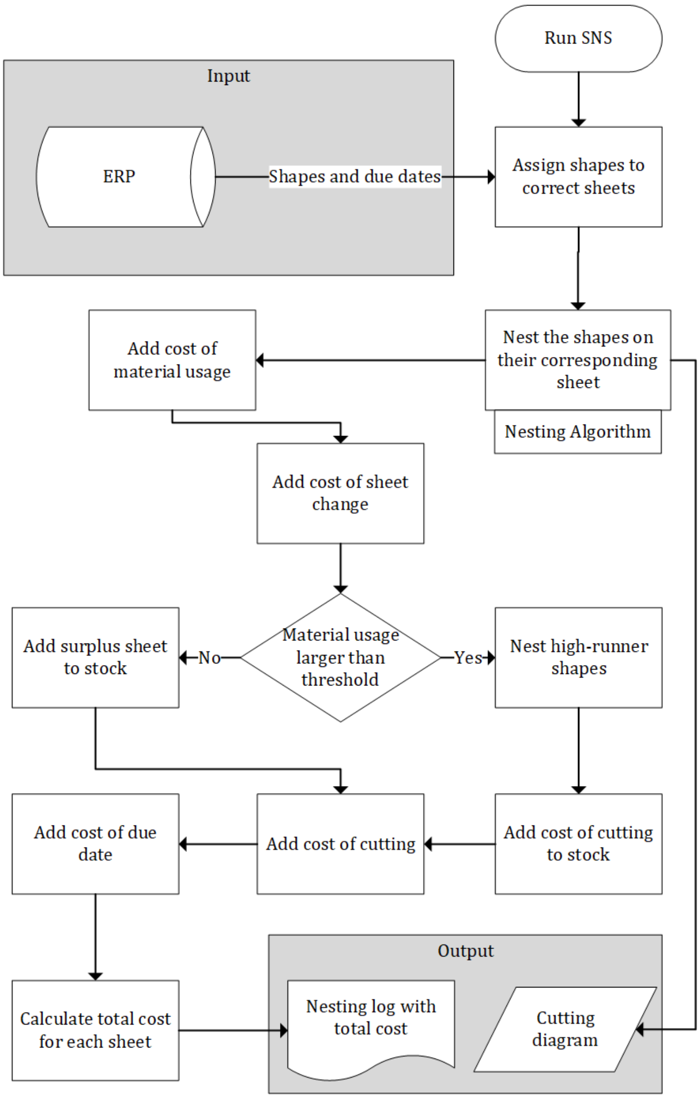

Fig. 3. Flowchart representing the data flow within SNS. Information about orders is received from the ERP system, namely what shapes are required to be cut and their due dates. SNS processes the order and outputs the cutting diagram that is the most cost-effective, together with a nesting log that contains all the cost related data for the nest.

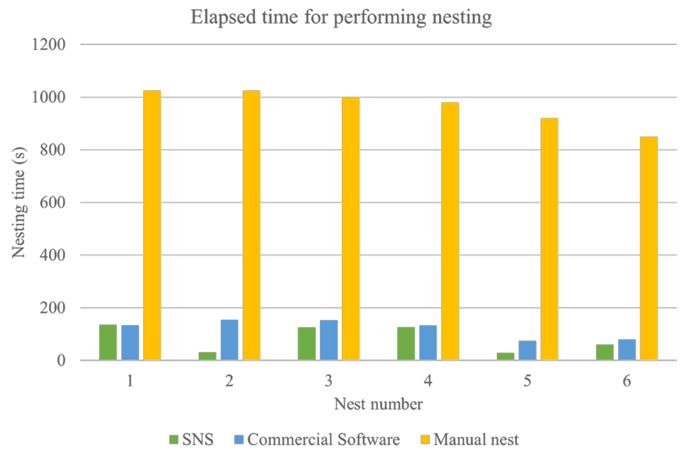

Fig. 4. Experiments were made to determine the time-effectiveness of SNS in comparison with manual nesting and nesting using a commercial software. The results show that SNS brings a major improvement when compared with the manual methods, while having a similar performance with the commercial software in use at the case-company.

sheet, containing the least expensive nest that the nesting algorithm was able to find. The two outputs, nesting log and cutting diagram, are prioritised, as illustrated in Figure 1, thus obtaining the necessary schedule to obtain cost-effective nests. This cutting order is determined based on the total cost of each nest, where the nest with lowest total production cost is cut first.

4.2. Validation

In order to test the SNS, a low-scale simulated ERP system is 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. The validation is carried out by nesting on six different sheets. The shapes are generated by the simulated ERP-system and assigned to their corresponding sheet, i.e. sheets that have the same thickness as the part. The exact same shapes are nested by 1) the SNS, 2) the nesting expert at the ETO company, and 3) through a commercial nesting software. Thus, making it possible to compare the results between SNS and the traditional approaches. On the one hand, the SNS use the cost-function to determine the nested sheet that is cheapest to cut at a given moment, and thus constrained by the included parameters. On the other hand, the nesting expert applies his tacit knowledge to do the same, but is constrained by his ability to manage the large input complexity.

The time performance of SNS was evaluated by measuring the difference between the start and the beginning of the process. For SNS, the time required to perform the nest was measured using the ”timeit” Python method. For both the ETO company and the commercial nesting software it was measured, when the nesting was performed. Six experiments were performed and represented in Figure 4. In average, SNS has almost 30% better performance than the nesting procedure using the commercial software. This can be explained by the fact that SNS does not need any user input to perform the actual nest, but it needs time to process the best possible nest.

To evaluate the ability to reduce the overall cost, the SNS is benchmarked against the plain nesting algorithm which does not consider the variables described in Table 1. For every experiment, a pool of shapes (triangles, pentagons, squares) of random sizes, random due dates and thicknesses are generated. Both the SNS and the plain nesting algorithms are executed in parallel during the experiments. The results from the plain nesting algorithm are then evaluated with the cost function described in Equation 6. The results are represented in Figure 5 and they indicate a significant cost reduction potential of using the SNS to generate the nests taking the variables in Table 1 into account.

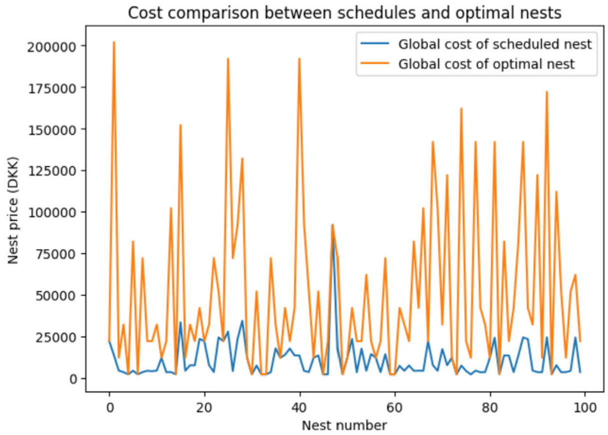

Fig. 5. Cost comparison for performing nests between a plain nesting algorithm and the SNS software. The cost is estimated using Equation 6. 100 experiments were performed. As observed, SNS can radically reduce the production cost of incoming orders by generating a schedule for the order in which the nests should be performed. The cost of the nests when using plain nesting algorithm is presented with orange. The cost of the nests when using SNS is represented with blue.

5. Discussion and conclusion

This paper presented a value-chain optimisation initiative through digital technologies targeting the nesting procedures performed within ETO SMEs involved in the heavy steel industry. As explained in section 2, the field of nesting algorithms is very mature and many high-performance nesting algorithms are available both commercially and freely. However, this research was motivated by the lack of literature focusing on other factors that influence the total cost of a nest. The proposed novel method takes in consideration a number of possible variables around the nesting procedure, and shows that production cost can be reduced by considering these, without hurting the lead-time. The developed artefact serves as a proof-of-concept for the possibility of scheduling or prioritising certain nests using the modelled cost function presented in section 3.

The proposed cost function was implemented in a software system developed in Python. The software was used to carry out experiments to validate the scheduled nesting approach proposed. An industrial-partner was involved in this process, by having engineers perform nests using traditional methods. The software was bench marked in terms of time-performance and cost performance per nest, as presented in section 4. The experiments show a positive potential of the system, albeit only controlled experiments were made using basic shapes. Although the complexity of the shapes is not expected to influence the behaviour of the cost function, it is highly desired to deploy the system in a real industrial context in order to obtain more reliable results in terms of validation.

The system also shows potential in regards to digitalisation of human labour and overall improvement of the connectivity dimension of the company's value adding operations [5]. It is desired for further development to look into how the SNS can be integrated deeper into the company's digital infrastructure, as it can also provide a comprehensive overview on stock usage, production costs and other resource management performance indicators. Machine learning algorithms could be used to give better scheduled nests alternatives based on previous results. The tacit knowledge of the engineers is another possible source of valuable information in the effort to digitally integrate the nesting operations.

Acknowledgements: This work is supported by Manufacturing Academy of Denmark (MADE). MADE is an association of Danish universities and private companies. The association seeks to bring the Danish manufacturing industry at the highest technological level possible through research and development initiatives.

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