An International Journal of Optimization and Control: Theories & Applications
ISSN: 2146-0957 eISSN: 2146-5703
Vol.X, No.X, pp.X-X (2025)
https://doi.org/10.36922/ijocta.1660

RESEARCH ARTICLE

A MILP model for one dimensional cutting stock problem with adjustable leftover threshold and cutting cost

Anett Rácz*

Department of Applied Mathematics and Probability Theory, University of Debrecen,Hungary
racz.anett@inf.unideb.hu

ARTICLE INFO

Article History:
Received: August 6, 2024
Accepted: January 15, 2025
Published Online: March 19, 2025

Keywords:
One dimensional cutting stock problem
Mixed-integer linear-programming
Optimization

AMS Classification:
90-08

ABSTRACT

This paper presents a MILP model for one dimensional cutting stock (CSP) problems that considers the most commonly used objectives all together. These are the minimization of the trim loss which is the leftover that is not large enough to be reused in the future, minimization of the total cutting cost and number of bars involved. We carried out computational experiments in order to find out the limitations of our model and to compare it with the most commom linear cutting software on the market.

1. Introduction

Optimization is an essential element of modern economic life. Increasing the efficiency of production is a key point of industrial optimization. There are studies from several areas of industry that focus on cost efficiency in business operations.[1–3]

In this paper I deal with one dimensional cutting problems. One dimensional Cutting Stock Problems (1DCSP) are real-world industrial optimization problems, where one dimensional stock pieces (bars) need to be cut in order to serve customers demand. In order to achieve efficiency, businesses must also think about the cost of cuts, the number of one dimensional items used and the amount of waste generated in the process. These factors may vary widely from one industry to another. In the metal industry, the cost of cutting is significant, while also shorter leftovers have a good chance of being recycled, while in the wood industry the cost of cutting could be lower, but typically only the longer trims can be sold. In each case, the number of rods needed to service the orders is an important consideration.

Various articles about the CSP can be found in the literature from the first formulation by Kantorovich[4] to the latest papers. These models can be diverse in terms of the objective. Most common goals are the three previously mentioned:

- Minimizing the number of bars involved in serving the orders.
- Minimizing the number of cuts.
- Minimizing the amount of waste.

The simplest models have only one objective. Most often, this is to minimize trim loss, considering a certain lower bound above which the leftover can be reused. Examples of such models are[5–7]:

There are models that combine different objectives, such as, [8] where the authors used two goals, one to minimize uncut orders and the other to minimize trim loss. Multi-objective approaches are often industry specific and vary widely due to different cost factors. Sinuany-Stern et al created a personalized model with two objectives for metal cutting problems in. [9] Primary objective of

*Corresponding Author

the mentioned model is to meet the requirements using minimal number of bars, secondary objective is to organize the cutting so that the maximum quantity of leftovers is accumulated in one bar. The model of Rahimi et al for rebar cutting optimization in conrete industry [10] has an objective with three component: purchase costs, cut costs and bend cost. In study,[11] the researchers introduced an approach to determine the optimal stock size to meet expected demand, aiming to minimize the overall costs associated with waste, storage, and unmet orders. Model created by Tanir et al[12] aims to minimize both trim loss and the number of welds while accommodating practical constraints in the steel industry.

The models mentioned above, as well as industry-specific solutions, are usually highly customised. My aim was to develop a general model that could combine the three objectives considering a user defined priority. In this way, the model would be parameterisable, customisable and widely applicable, taking into account different industry specific cost factors and objectives. The user can specify how much a cut costs, how large the financial loss is if a unit of waste is generated and the importance of the number of bars in the service process.

In Section 2, we describe our **M**ultiobjective, **A**djustable **C**ost and **R**ecycling parametric **OPT**imization model for **1 D**imensional cutting stock problems (MACROPT-1D) and give a step-by-step overview of the extensions with the different additional objectives. Section 3 is about computational requirements of the model and its limitations revealed by simulations.

Thousands of implementations and variants of CSP models are available in the literature, which is partly why we decided to compare our solution with the most popular software available on the market. Another criterion was to select the most common, most widely used software. That's why we looked at Google page ranking statistics and chose the top 3 most visited websites software on the topic. In the following sections we present a technical overview of the software (Section 4), a comparative numerical example (Section 5) and finally some performance tests focusing on runtimes and size limitations (Section 6).

2. MACROPT-1D

Our goal was to create a model, that combines all the mentioned objectives and allows the users to personalize the cutting cost, waste limit and waste penalty parameters.

2.1. Problem definition

Using the notations from Table 1., the problem can be described as follows: A company sells one dimensional cut-to-size materials. They have a stock of raw materials, bars: $B1, B_2, \ldots, B_n$ given by their length $l_1, l_2, \ldots, l_n$. An $O_1, O_2, \ldots, O_m$ group of orders should be served with required length $r_1, r_2, \ldots, r_m$. The cost of a cut is indicated by the parameter CC. Bars that are longer than W are worth to stock and can be sold. They want to minimize the non reusable leftovers, that are identified as a waste. So, we are using two definition for the remainder: leftover $LOl_1, LOl_2, \ldots, LOl_n$ on the bars, that can be reused and those that are shorter than the limit W,that is the waste on the bars $WL_1, WL_2, \ldots, WL_n$. Thus, after the optimization the variables $LOl_1, LOl_2, \ldots, LOl_n$ determines the new stock for the next process. The waste means a financial loss to the company, that is described by a loss coefficient CW. They also have a setup cost, which appears when a new bar is put under the saw. Therefore, they would like to minimize the number of bars involved. In summary: The company wants to minimize the costs of cutting, setup and the loss of waste, while serving the orders.

Table 1. Notations

Symbol	Description
Input data	
$B_1, B_2, \ldots, B_n$	Bars in stock.
$l_1, l_2, \ldots, l_n$	Length of bars.
$O_1, O_2, \ldots, O_m$	Orders.
$r_1, r_2, \ldots, r_m$	Requested length of orders.
CC	Unit cutting cost.
W	Smallest length of retail
CW	Waste loss per unit
Variables	
$\|\|x_{ij}\|\|_{m \times n}$	Binary variables to assign orders and bars.
$YL_1, YL_2, \ldots, YL_n$	Binary variable to indicate leftovers.
$LOl_1, LOl_2, \ldots, LOl_n$	Length of leftover on the bars.
$YR_1, YR_2, \ldots, YR_n$	Binary variable to indicate reusable leftovers.
$WL_1, WL_2, \ldots, WL_n$	Length of waste on the bars.
$YU_1, YU_2, \ldots, YU_n$	Binary variable to indicate the bar is used or not.
Constants	
M, M_2	Large positive numbers.

2.2. Minimization of cutting cost

In this initial version of our model we consider the total cost of cuts as an objective (in (1)), subject to serving all orders. The objective function 1 defines the total cost of the cuts by counting them and multiplying with the user defined cutting cost, coeffitient CC.

The number of cuts is determined by the number of orders assigned to the bar as follows:

Number of cuts on bar B_j is

$$\begin{cases} \sum_{i=1}^{m} x_{ij}, & \text{if there is some leftover,} \\ \sum_{i=1}^{m} x_{ij} - 1, & \text{else.} \end{cases}$$

Where x_{ij} binary variable denotes the assignement between orders and bars, so that $x_{ij} = 1$, if the order O_i is served by the bar B_j, else $x_{ij} = 0$.

According to the notations in Table 1, binary variable YL_j determines whether there is a remainder on bar B_j or not.

The model allows the user to define a cutting fee CC parameter, that can be inserted into the objective function. So the model can be formulated as follows:

$$min \;\; CC \cdot \sum_{j=1}^{n} \left(\sum_{i=1}^{m} x_{ij} - 1 + YL_j \right) \quad (1)$$

st.

$$\sum_{i=1}^{m} x_{ij} r_i + LOl_j = l_j \quad j = 1, 2, \ldots, n \quad (2)$$

$$YL_j \geq \frac{LOlj}{l_j} \quad j = 1, 2, \ldots, n \quad (3)$$

$$\sum_{j=1}^{n} x_{ij} = 1 \quad i = 1, 2, \ldots, m \quad (4)$$

Constraint (2) ensures that the length of a bar should be equal to the leftover and the sum of the orders assigned to it.

Constraint (3) sets the value of YL_j binary variables to reflect the existense of leftover on bar B_j.

Finally, constraint (4) ensures that, an order can only belong to exactly one bar.

2.3. Extending the model with leftover threshold and trim loss

In this version of our model, we extended the cost function with losses/penalties from waste. First, we need to introduce the definition of waste. Leftover with a length that is below the user-defined limit, $LOl_j < W$ is considered as waste. We also introduced binary variables $WL_j, \; j = 1, \ldots, n$ to indicate whether the leftover are reusable or waste. Value of variable WL_j should be determined as follows:

$$WL_j = \begin{cases} 0 & \text{if } LOl_j >= W, \\ LOl_j, & \text{else.} \end{cases}$$

Decision makers are also able to define the waste cost: CW, that is the unit loss on waste. Depending on their length, trim losses may be added to the total cost.

The new objective function is:

$$\begin{aligned} min \quad & CC \cdot \sum_{j=1}^{n} \left(\sum_{i=1}^{m} (x_{ij}) - 1 + YL_j \right) \\ & + CW \cdot \sum_{j=1}^{n} WL_j \end{aligned} \quad (5)$$

with previously defined constraints (2) - (4):

$$\sum_{i=1}^{m} x_{ij} r_i + LOl_j = l_j \quad j = 1, 2, \ldots, n$$

$$YL_j \geq \frac{LOlj}{l_j} \quad j = 1, 2, \ldots, n$$

$$\sum_{j=1}^{n} x_{ij} = 1 \quad i = 1, 2, \ldots, m$$

and extended with two more:

$$LOl_j - WL_j \leq M \cdot YR_j \qquad j = 1, 2, \ldots, n \quad (6)$$

$$W - LOl_j \leq M \cdot (1 - YR_j) \qquad j = 1, 2, \ldots, n. \quad (7)$$

Where M is a constant that is large enough so that $W - LOl_j \leq M$ and $LOl_j - WL_j \leq M$, $\forall j \in \{1, 2, \ldots, n\}$.

Constraints (6) and (7) are the regular formalization of if-then logical constraints (for more details see[13] Chapter 9.1.) in the following contex:

If the length of the leftover (LOl_j) is shorter than the reuse limit (W), **then** it is a waste $WL_j = LOl_j$, else there is no waste on bar B_j , $WL_j = 0$. In other words:

If $LOl_j < W$, then $WL_j = LOL_j$,
else $WL_l = 0$.

Since the minimization objective function 5 includes the variables WL_j and these variables are limited only by the mentioned constraint 6, they will be assigned to the smallest value allowed by the constracted lower bound.

Remarks:

If $LOl_j < W$, then in (7) $W - LOl_j > 0$, thus $0 < M \cdot (1 - YR_j)$. Since YRj is a binary variable, the previous inequality force it to be 0. If $YR_j = 0$, constraints (6) looks like $LOl_j - WL_j \leq 0$, that is $LOl_j \leq WL_j$.

If $LOl_j \geq W$, then (6) does not limit the value of YR_j, so there is no lower bound for WL_j, except the sign restriction $0 <= WL_j$.

Because of the minimization in (5) and the fact that WL_j is not contained by any other constraint, so it does not affect the value of any other variables, optimal value of it is the smallest possible value which is $LOlj$ if the leftover is under the waste limit and 0 if it is reusable.

2.4. Extending the model with the minimization of affected bars

It may also be reasonable to consider how many bars are involved in serving the orders. Thus, in the final version, we have extended the model so that its objective contains the minimization of the bars used during the process too.

A new binary variable is therefore introduced that shows if the correspoding bar is used or not. This variable is labeled by YU_j (see Table 1) and

$$YU_j = \begin{cases} 1 & \text{if } B_j \text{ is used,} \\ 0, & \text{else.} \end{cases}$$

Let us extend the objective function according to the previous formula.

$$\begin{aligned} min \quad & CC \cdot \sum_{j=1}^{n} \left(\sum_{i=1}^{m} (x_{ij}) - 1 + YL_j \right) \\ & + CW \cdot \sum_{j=1}^{n} WL_j \\ & + \sum_{j=1}^{n} YU_j \end{aligned} \tag{8}$$

The above function is essentially a multiobjective linear function containing the linear combination of three objectives:

- Minimization of the cost of cuts.
- Minimization of loss from waste.
- Minimization of involved bars.

Decision maker is able to weight these goals by setting the appropriate value of the correspoding parameters CC and CW.

Beside the previously defined constraints (2) - (4)

$$\sum_{i=1}^{m} x_{ij} r_i + LOl_j = l_j \quad j = 1, 2, \ldots, n$$

$$YL_j \geq \frac{LOlj}{l_j} \quad j = 1, 2, \ldots, n$$

$$\sum_{j=1}^{n} x_{ij} = 1 \quad i = 1, 2, \ldots, m$$

and (6) - (7)

$$\begin{aligned} LOl_j - WL_j \leq M \cdot YR_j \qquad & j = 1, 2, \ldots, n \\ W - LOl_j \leq M \cdot (1 - YR_j) \qquad & j = 1, 2, \ldots, n. \end{aligned}$$

We need to introduce the following new constraint:

$$YU_j \geq \frac{\sum_{i=1}^{m} x_{ij}}{M_2} \quad j = 1, 2, \ldots, n. \tag{9}$$

where M_2 is a constant that is large enough to scale $\sum_{i=1}^{n} x_{ij}$ into the interval $[0, 1]$. $M_2 = m$ could be a suitable choice. Thus, constraint (9) sets a strictly positive lower bound for the binary variable YU_j, if there is an order assigned to it.

3. Implementation and limitations

In order to investigate the limitations of our model, we implemented it in Python using Pyomo universal framework[14] and Gurobi solver.[15]

Our goal was to describe the connection between the size of the model and the required runtime. Thus, we generated inputs for simulation in three category of stock number of bars in stock $\{B_1, \ldots, B_n\}$:

- Low stock, when $n \leq 80$. (Symbol: ○)
- Moderate stock, when $80 < n \leq 100$. (Symbol: □)
- High stock, when $100 < n$. (Symbol: ▽)

Figure 1. shows the relation between the number of orders (horizontzal axis) and the runtime in seconds (vertical axis) for random generated data grouped by stock category. Figure shows that, depending on stock category, sooner or later there is an exponential increase in runtime.

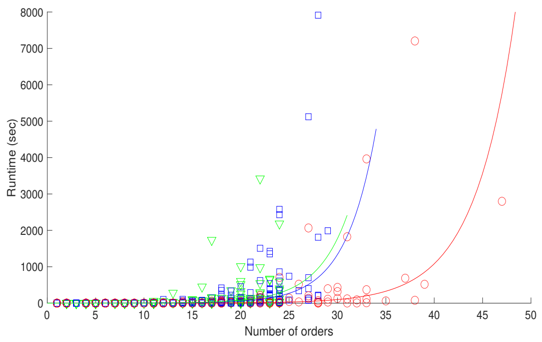

Figure 1. Runtimes

We used exponentional least square fitting to find the parameters a and b of $f(x) = a * e^{b*x}$ function most closest to the points in the different categories. Fig. 1. also shows the fitted functions that are:

$$f(x) = \begin{cases} 0.2388 * e^{-2.5669*x} & \text{if } n \leq 80 \\ 0.3190 * e^{-2.3725*x} & \text{if } 80 < n \leq 100 \\ 0.3079 * e^{-1.7568*x} & \text{if } 100 < n \end{cases}$$

4. Commercial softwares for 1D cutting

We used Search Engine Optimization (SEO) tools[16,17] in order to find out which are the most popular software on the market for optimizing one-dimensional cutting tasks. These SEO tools are using the google ranking statistics on a particular keyword and give an overview of top ranked sites. The examined keyword was "1D cutting optimizer". According to them and the current result of google search rank on that keyword these are the top listed sites in this topic:

- OptiCutter from Devtica s.r.o.
  www.opticutter.com/linear-cut-list-calculator
- 1D Solutions and 1D solver
  These two are the same. The company changed the domain name after the 4th version of the software, but kept the older version.
  www.1d-solutions.com and 1d-solver.co
- Optimalon
  www.optimalon.com

4.1. OptiCutter

OptiCutter[18] is an online cutting optimization tool developed by the Slovak Devtica s.r.o. company. It has 4 version from the free trial version to the Enterprise API in price range up to 99 EUR / month. Extended versions can be used not only for 1-dimensional but also for 2-dimensional tasks. It also offers visualization of the cutting plans in a userfriendly interface. It supports reading data from properly prepeared excel spreadsheets (.csv and .xlsx). It provides two option, minimization of waste or the number of cuts.

4.2. 1D Solutions

The company of the same name promises that 1D Solutions[19] is a very simple and productive software to generate cutting plans with minimal waste. The Chilean company offers fast and accurate response with maximum efficiency of optimization. It uses a mixture of mathematical algorithms and heuristics, that could make the response time much more quick. The company offers more license version from 200 EUR single license to 790 EUR Enterprise license.

4.3. Optimalon

Optimalon[20] has three different solution for cutting optimization and all of them is available freely to download and try for a certain period. 1DCutX is an add-in for Microsoft Excel and it promises to give the best cutting plan in order to minimize the waste and cutting cost within the same Excel workbook. Company offers a free online tool for 2D cuts and a complex software for both linear and sheet cutting optimization (CutGLib). Prices of 1DCutX license depends on the number users. The Canadian company offers the product from 97 USD (one user) to 997 USD (unlimied users).

5. Comparison

5.1. Cost and functionality

Let us first overview a financial and input type comparison of the three commercial software in Table 2.

Table 2. Software overview

	OptiCutter	1D Solutions	Optimalon
Platform	**ONLINE**/API	**PC**	ONLINE/PC/**add-in**
Free DEMO	✓	✓	✓
DEMO limit	limited stock and orders	30 days	15 days
Excel input	✓	✓	✓
Unlimited license	19 EUR / month	199 EUR (single user)	97 USD (single user)
Visual output	✓	✓	✓

Since cutting problems in real world have very different parameters and cost components, a software can be widely used if it provides the decision maker with customisation options. Table 3 shows if these tools allow the user to set the parameters, that we considered important and inserted into our solution.

- Cut Cost, i.e. the cost of conducting a cut.
- Waste limit, i.e. the minimum reusability length.
- Waste cost, i.e. loss from unusable parts.

Table 3. User settings

	OptiCutter	1D Solutions	Optimalon
Cut Cost	✗	✗	✗
Waste limit	✗	✓	✓[a]
Waste cost	✗	✗	✗

[a]Orders below this limit are not allowed.

5.2. Numerical example

In this section we would like to present the three commercial software and our solution throughout a simple example and compare the obtained results.

Let us suppose our company has the following bars in stock:

- B_1, B_2, B_3: Length: 200 cm ($l_1 = l_2 = l_3 = 200$)
- B_4, B_5, B_6: Length: 150 cm ($l_4 = l_5 = l_6 = 150$)

Moreover, we have to serve the following orders:

- O_1: Length: 100 cm ($r_1 = 100$)
- O_2: Length: 80 cm ($r_2 = 80$)
- O_3, O_4, O_5: Length: 70 cm ($r_3 = r_4 = r_5 = 70$)
- O_6, O_7: Length: 60 cm ($r_6 = r_7 = 60$)
- O_8, O_9: Length: 50 cm ($r_8 = r_9 = 50$)

The following cost parameters were set where allowed:

- Bars under 45 cm considered waste. ($W = 45$)
- Each unit of waste means 100$ loss. ($CW = 100$)
- Each cut costs 400$. ($CC = 400$)

5.2.1. Solution by MACROPT-1D

Our own model suggests a solution, where 6 cuts are required, that costs 2400$, 4 bars are used ($B_2, B_3, B_4, B_5$) and there is no waste, i.e. no leftover under the waste limit ($W = 45$).

Table 4. Cutting plan by MACROPT-1D in matrix form

	O_1	O_2	O_3	O_4	O_5	O_6	O_7	O_8	O_9
B_1									
B_2							✓	✓	
B_3			✓		✓	✓			
B_4	✓								✓
B_5		✓		✓					
B_6									

Fig. 2. shows a visualization of the obtained cutting plan with the leftovers.

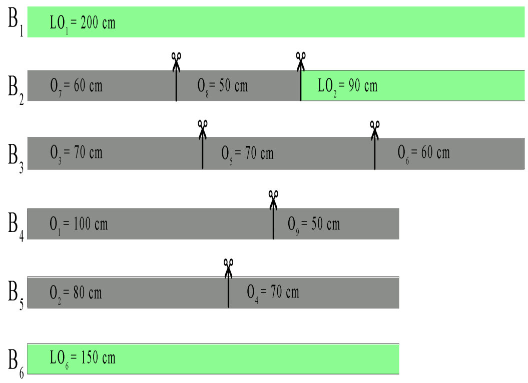

Figure 2. Visualization of the cutting plan

5.2.2. Solution by OptiCutter

After preparing the appropriate .csv input file, it was uploaded to the OptiCutter linear cutting list calculator webapplication. The input file contains the stock items with length and the order pieces with length. As Table 3. also shows OptiCutter does not offer the oportunity to set the waste limit or the cutting cost.

OptiCutter suggests a solution where 6 cuts are needed on 4 bars and there is a 40 cm waste on bar B_4. Table 5. shows the cutting plan in matrix form and the visualisation can be seen on Fig. 3.

Table 5. Solution by OptiCutter in matrix form

	O_1	O_2	O_3	O_4	O_5	O_6	O_7	O_8	O_9
B_1									
B_2									
B_3			✓		✓	✓			
B_4	✓								✓
B_5		✓		✓					
B_6							✓	✓	

On Fig. 3. we can see the visualization of the obtained cutting plan.

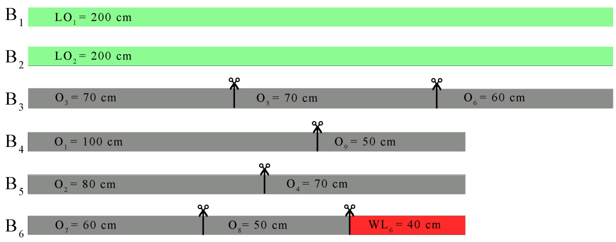

Figure 3. Visualization of OptiCutter's cutting plan

5.2.3. Solution by 1D Solutions

We used 1D Solutions desktop version to find the optimal cutting plan. Here we have the option to set the 45 cm waste limit. This software can load data from .csv file too. The file contains the stock and order details with length but waste limit should set manually. The obtained result shows a cutting plan consisting of 8 cuts, with a total of 40 cm of waste and 4 bars.

Table 6. Solution by 1D Solution in matrix form

	O_1	O_2	O_3	O_4	O_5	O_6	O_7	O_8	O_9
B_1									
B_2									
B_3			✓			✓		✓	
B_4				✓	✓				
B_5		✓					✓		
B_6	✓								✓

Table 6. shows the matrix form of the obtained cutting plan, and Fig. 4. presents the visualization of it.

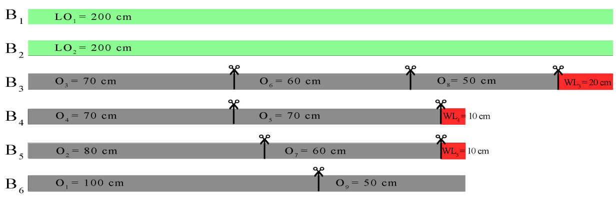

Figure 4. Cutting plan

5.2.4. Solution by Optimalon

We used Optimalon Excel add-in. After installing the extension, a new button willappear on the Excle toolbar. Here we have to select and mark the part of the workbook that contains the stock, the orders and their length. The waste limit can also be set manually. Optimalon gives a solution that requires 6 cuts, 4 bars are involved and there is no waste. Table 7. and Fig. 5 present the cutting plan.

Table 7. Solution by 1D Solution in matrix form

	O_1	O_2	O_3	O_4	O_5	O_6	O_7	O_8	O_9
B_1									
B_2		✓		✓				✓	
B_3			✓		✓	✓			
B_4	✓								✓
B_5							✓		
B_6									

5.2.5. Overview

Table 8. shows the comparison of obtained cutting plans. We can see that 40 cm of waste appears for software OptiCutter and 1D Solutions, while the other two tools found a cutting plan without waste. Despite the fact that 1D Solutions gives the oportunity to set the waste limit, it seems to ignore it moreover the number of cuts is also higher in its cutting plan.

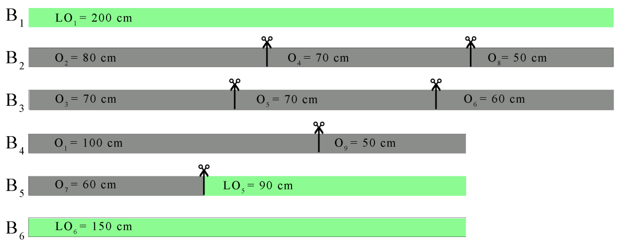

Figure 5. Cutting plan

Table 8. User input comparison

	OptiCutter	1D Solutions	Optimalon	MACROPT-1D
Cuts:	6	8	6	6
Waste:	40 cm	40 cm	-	-
Waste cost:	4000$	4000$	0$	0$
Total cost:	6400 $	7200$	2400$	2400$
Used qty:	4	4	4	4

6. Computational tests

In order to better investigate the issues raised in the numerical example, simulations were carried out. The key questions of the experiment are:

(1) What is the ranking of plans given by the different software when considering only the number of cuts and when considering cuts and the amount of waste together?
(2) Does 1D Solutions always ignore the waste limit?
(3) Optimalon and our implementation seem equally effective in the example. Are there cases where they give different results?

For testing, we generated 20 random inputs and applied the same waste limit ($W = 45$), cut and waste costs ($CW = 100$, $CC = 400$) as in the numerical example. Optimalon offered a very short trial period, so only 10 test cases were solved. The full data set can be found in Table A1. in the Appendix.

Table 9 shows the ranking based on the number of cuts. There is not much difference in the number of cuts. There are only a few cases where there is a difference between the obtained plans, here the best one is highlighted in green.

Table 9. Ranking based on no. cuts

	MACROPT-1D	OptiCutter	1D solutions	Optimalon
T1	6	6	7	6
T2	8	8	8	8
T3	7	7	7	7
T4	5	5	5	5
T5	5	5	5	5
T6	6	8	8	8
T7	7	7	7	7
T8	5	5	5	5
T9	5	5	5	5
T10	5	5	5	5

Table 10. Ranking based on total cost

	MACROPT-1D	OptiCutter	1D Solutions	Optimalon
T1	2400 \$	2900 \$	9400 \$	2400 \$
T2	5600 \$	8900 \$	8900 \$	8900 \$
T3	2800 \$	10900 \$	6900 \$	2800 \$
T4	2000 \$	5800 \$	5800 \$	2000 \$
T5	3000 \$	3100 \$	3100 \$	3100 \$
T6	2400 \$	4800 \$	4800 \$	3200 \$
T7	4600 \$	7600 \$	7600 \$	7600 \$
T8	2000 \$	7700 \$	7700 \$	2000 \$
T9	3600 \$	3600 \$	3600 \$	3600 \$
T10	4000 \$	4500 \$	4500 \$	4500 \$

Next table (Table 10.) shows the ranking when considering the total cost of cuts and waste loss together, using $CC = 400$ \$ and $CW = 100$ \$ just as in the numerical example.

Of course the total cost depends on waste fee (CW) and so the differences in Table 10. show one particular case, when the waste cost is 400 \$. That is why we extend the the above table the total amount of waste accured, i.e. the sum of the leftover pieces under 45 cm. Figure 6. represents the efficiency of the methods in terms of recycling or waste management.

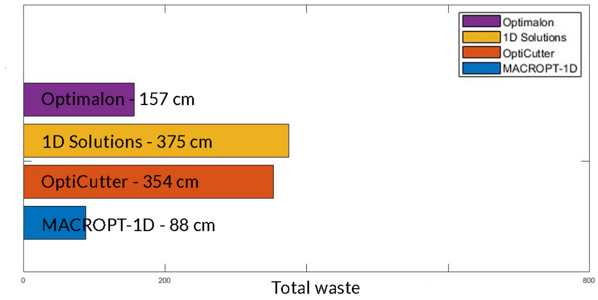

Figure 6. Total amount of waste

Concerning the question (2), tests show that in 10 out of 10 cases, 1D Solution gave a plan with waste, even if a feasible waste-free cutting plan exists. Even though you can set the minimum length below which leftovers are considered scrap, this value does not seem to affect the solution. In those cases where a waste-free solution exists (e.g. T1, T3, T4, etc) we set several waste limits, but in all cases we got the same plan.

Regarding question (3): Optimalon proved to be an efficient tool on these test files. In every case where our solution has given a waste-free plan, it has returned with the same cutting plan. Difference were observed in cases where waste-free solutions exist (e.g. T2, T5, T7, T9). Here, the cutting plans provided by our implementation have less waste than those given by Optimalon.

7. Conclusion

We presented our MILP model MACROPT1D and it's implementation for optimizing cutting plans, where users have the possibility to customize the cost coefficiencies of waste and cuts. Furthermore, the reusable length limit can be set by users.

Cut management in the different indusrties may contain very different cost coefficients. While non-recyclable waste is a minor cost in some areas, it can be a significant cost in others. However, waste generation has a major environmental impact in all areas. Therefore, it would be important that the optimizers used for the cutting design also take into account the minimization of waste, as this would not imply any additional cutting costs for the company. Of course, adding an extra objective increases the complexity of the optimization model and in some cases may increase the response time of the algorithm.

Our goal was to reveal the importance of customizability in cutting plan optimization. For this we used our own developed MILP model and compared the results on generated test cases with the most popular 1D cut optimization software on the market. For the commercial software compared, Optimalon's solutions resulted the least waste, although in some cases solutions with less waste were not found. It is unfortunate, however, that other software either does not allow you to set a waste/reusable limit or, even if you can, the solutions fall far short of plans where the amount of waste is truly minimal.

The acceptable response time of our MILP model is strongly influenced by the number of orders. Another interesting area of research could be to investigate how much the optimal search process is complicated by the inclusion of an additional objective, the minimization of the non-reusable waste.

Acknowledgments

None.

Funding

None.

Conflict of interest

The author declare that they have no conflict of interest regarding the publication of this article.

Author contributions

This is a single-authored article.

Availability of data

Not applicable.

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Anett Rácz *graduated from the University of Debrecen, then she recieved her Ph.D. in Informatics from University of Debrecen. Since 2012 she has been an assistant professor at the Department of Applied Mathematics and Probability Theory of Faculty of Informatics, University of Debrecen. Her main fields of expertise are linear programming, computational optimization and multicriteria decision making. Anett Rácz is the author of 13 scientific papers cited by 47 articles, has 11 co-authors and wrote many other poceedings papers, lecture notes and teaching materials.*

https://orcid.org/0000-0002-6373-3194

Appendix

Table A1. Computational test

	MACROPT1D				OptiCutter				1D solutions				Optimalon			
	Cuts	Bars	Waste	Total cost	Cuts	Bars	Waste	Total cost	Cuts	Bars	Waste	Total cost	Cuts	Bars	Waste	Total cost
T1	6	5	-	2400 $	6	5	5 cm	2900 $	7	5	66 cm	9400 $	6	5	-	2400 $
T2	8	6	24 cm	5600 $	8	5	57 cm	8900 $	8	5	57 cm	8900 $	8	5	57 cm	8900 $
T3	7	6	-	2800 $	7	5	81 cm	10900 $	7	5	41 cm	6900 $	7	6	-	2800 $
T4	5	4	-	2000 $	5	4	38 cm	5800 $	5	4	38 cm	5800 $	5	4	-	2000 $
T5	5	4	10 cm	3000 $	5	3	11 cm	3100 $	5	3	11 cm	3100 $	5	3	11 cm	3100 $
T6	6	8	-	2400 $	8	4	16 cm	4800 $	8	4	16 cm	4800 $	8	6	-	3200 $
T7	7	4	18 cm	4600 $	7	4	48 cm	7600 $	7	4	48 cm	7600 $	7	4	48 cm	7600 $
T8	5	5	-	2000 $	5	3	57 cm	7700 $	5	3	57 cm	7700 $	5	5	-	2000 $
T9	5	5	16 cm	3600 $	5	5	16 cm	3600 $	5	5	16 cm	3600 $	5	5	16 cm	3600 $
T10	5	3	20 cm	4000 $	5	3	25 cm	4500 $	5	3	25 cm	4500 $	5	3	25 cm	4500 $