An order release approach to improve material usage efficiency in MTO contexts

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Abstract: In recent decades, global market pressures have increasingly led companies in gaining competitive advantages leveraging new solutions to improve the customer service level while trying to limit the non – value added activities (NVA). Among these latter, the focus is on the ones characterized by a massive production of material industrial wastes, which have a great impact on the sustainability and profitability of companies. In this context, Lean Production represents a fundamental approach to identify, categorize, and reduce industrial waste while maximizing operational performance of manufacturing systems. This provides a methodology to enhance the exploitation of available resources, by solving a bin packing problem, to make full use of the available raw material resources. A four – phase methodology was developed, and, validated by means of a case study application. The output of the methodology is an optimal order aggregation on resources along with order sequencing which is based on priority rules. Overall, the case study application permitted us to reduce of order delays, material waste and costs, while delivering an improved customer satisfaction.

Keywords: Bin packing, Scheduling, Multi-Objective Optimization Problem, Genetic Algorithm, Lean Production

1. Introduction

The constantly increasing need for companies to gain competitive advantages in a globalized environment, results in the pursuit of improved business performances. In this context, Lean Production found wide application in different organizations with the common objective of reducing waste and improving plant efficiency. The idea of Lean Manufacturing or Lean Production identified a series of management methodologies aimed at reducing and eliminating waste of unused resources to generate value for the customer satisfaction (Gupta & Jain, 2013). Specifically, (Ohno & Bodek, 2019) identified seven types of waste within manufacturing processes. Material waste optimization is indeed a key element in the field of industrial production. The introduction of green economy and circular economy policies has led companies to focus more and more on reducing and reusing materials waste, recycling resources, and reintroducing them into production processes. The impact of these policies affects both the internal profits of companies, which manage to obtain a higher number of finished products, and the entire supply chain, generating the need to implement environmental control policies such as LCA (Life Cycle Assessment), widely used to achieve more sustainable and green supply chains (Genovese et al., 2017). It is in this context that the need arises to modify Planning and Production Control policies with a greener approach to achieve increasingly streamlined processes in terms of consumption and production waste (Sutherland et al., 2020). Among these latter, a particular attention has been placed on material waste, in fact, the problem of optimizing the resources resulted to be a core concept when dealing with Bin Packing and Scheduling problems. A Bin Packing (BP) problem typically represents a linear one-dimensional problem whose main objective is to allocate production orders on a specific resource to optimize packing and cutting (Christensen et al., 2017). However, in recent years the increasing demand and industrial necessities have led to an increasing complexity of BP problems, addressing new optimization challenges. As a matter of fact, a new frontier of BP problems has been investigated by (Lodi et al., 2002) leading to two-dimension BP (2BP). In these problems, the combination of cutting type and elements orientation plays a fundamental role to the optimization process. The evolution of this problem considers rectangles elements with prespecified sets of height, width and different orientations with the goal of minimizing the number of bins used to pack the orders without any overlapping (Ao et al., 2023). Moreover, as mentioned above, the type of cutting has led to new classifications of 2BP investigated by (Ma & Zhou, 2017). Furthermore, the combination with scheduling problem solution characterized by dispatching rules makes the solution even more challenging. In this operative context, a study which combines a two-dimensional packing and sequencing techniques was found in literature in order to obtain a proper exploitation of available resources, in a make-to-order context (M'Hallah & Bouziri, 2016). Among others addressing a combination of BP and scheduling (Ciscal-Terry et al., 2015) investigated a BP with precedence constraints as well as (Pereira, 2016). Similarly, (Arbib et al., 2021) studied a two-dimensional orthogonal undirected bin packing problem, whose items are characterized by due dates. (Polyakovskiy & M'Hallah, 2021) considered on-time guillotine cutting small rectangular items and in order to solve this two-dimensional just-in-time bin packing problem (JITBP), two discrete optimization problems were combined together. (Liu et al., 2020) studied the problem of packing containers of different sizes with the aim of packing all the items sequencing containers with the lowest cost. For this reason, the aim of this work is to develop a decision support framework which leverages an order packing model to ensure a proper management of production resources while considering customers' requirements also in terms of order due dates. In fact, the proposed four step methodology is conceived as a tool to make the most of production resources, reduce material waste and guarantee order delivery dates. The reminder of this work is structured as follows. Section 2 provides an overview of the work related associated to the Bin Packing problem combined to scheduling problems, while Section 3 presents the proposed four-step methodology, Section 4 provides the context of the case-study application along with the parameter values used. Afterwards, in Section 5 the results of the presented work are provided and finally, conclusions and future works are outlined in Section 6.

2. Related work

2.1 Bin packing and scheduling problems

Bin packing problems emerge as fundamental in manufacturing context for solving problems aimed at reducing material waste. These allow maximum surface area utilization through geometric optimization of items by achieving proper placement of these items in larger elements. Many of the cutting and packing problems are NP-hard (Chou, 2016) complexity problems, and over the years many solutions have been provided for them. In the literature, there are few examples of implementations that address both the bin packing and scheduling problem. Specifically, (Arbib et al., 2021) address an orthogonal undirected bin packing problem where each item is associated with due dates. The authors consider two objectives: firstly, the minimization of the number of bins and secondly, the minimization of maximum lateness of the items, proposing a sequential value correction (SVC) heuristic algorithm. (Polyakovskiy & M'Hallah, 2021) consider on-time guillotine cutting of small rectangular objects from large containers of the same shape. The items assigned to a container define its processing time. Any deviation of the completion time of an item from its due date causes penalty. For this Bin Packing Just-in-Time (JITBP) problem, two discrete optimization problems are combined: bin packing and single machine scheduling. The authors model the problem by considering two sets of constraints: the first set focuses on the feasibility of bin packing, while the second is the result of a linear program that schedules full bins on a single machine. Similarly, (Liu et al., 2020) study the problem of packing containers of different sizes, where items are characterized by multiple volumes. The aim of the authors is to sequence the containers minimizing the costs in order to pack all the items. They first formulate the problem as an integer programming model proposing subsequently three heuristic algorithms for the solution. (Aloui & Hadj-Hamou, 2021), solve a real case problem of nesting and scheduling modelled with mixed linear programming and uses a heuristic that can provide better solutions in reasonable time. (Zeng & Zhang, 2022) study a single batch processing machine scheduling problem (SBPMSP) with 2-D rectangular bin-packing constraints. The problem, formulated as a MILP, aims to minimize the number of bins and the total priority weighted waiting time through the use of an adaptive large neighbourhood search (ALNS) algorithm which allows to obtain efficient results. (Zhang et al., 2023) propose the solution of a two-dimensional bin packing problem (2DBP) aimed to optimize the makespan. They divide the problem in three sub-problems combining the 2DBP with job assignment, job placement, and job sequence. A genetic algorithm is performed to obtain an initial population for random generated instances. The efficiency of the algorithm is assessed through the comparison of various heuristic algorithms with the MILP model. By employing fuzzy logic and pattern-based predictions of the distribution of item sizes in online bin packing, (Lin et al., 2024) introduces a novel algorithm capable of effectively addressing uncertainty in scheduling and planning problems with evolving distributions, making it a promising solution for real-world applications where the item sizes may change over time. As can be seen in Tab.1, based on the previous research, no work has proposed an approach that aggregates two-dimensional techniques and sequencing techniques, aimed at the proper utilization of available resources, minimizing material waste in manufacturing industries. Indeed, no previous work has addressed the simultaneous satisfaction of both company and customer requirements in terms of cost reduction, waste reduction, resource utilization, and delay minimization. Therefore, a new methodology was developed and implemented to overcome the gap in this field.

Table 1: Summary of related work

Authors	Problem description	Algorithm	Objective
Liu et al., 2020	Two-dimensional	First Fit Decreasing	Number of Bins

	irregular bin packing problems (2DIRBPP) with limited rotations	(FFD) and Bottom-Left algorithm	Minimization
Aloui and Hadj-Hamou, 2021	Nesting Production Problem with technological constraints.	Mixed Linear Programming	Total delay minimization and use rate machines maximization
Polyakovskiy and M'Hallah, 2021	On-time Guillotine Cutting	Branch-and-check model	Bin Packing and Total Weighted Earliness Tardiness Single Machine Scheduling.
Arbib et al., 2021	Orthogonal non-oriented two-dimensional bin packing problem	Sequential Value Correction (SVC)	Number of Bins Minimization and Item Lateness Maximization.
Zeng and Zhang, 2022	Single-Machine Batch Processing Scheduling with 2-D Rectangular Bin-Packing Constraints	Adaptive Large Neighborhood Search	Total Weighted Waiting Time and Resource Utilization
Zhang et al., 2023	Parallel batch processing machine scheduling problem with 2-D rectangular packing constraints	Mixed Integer Linear Programming Model and Improved Biased Random Key Genetic Algorithm (OBRKGA)	Minimize Makespan
Lin et al., 2024	Online Bin Packing Problem.	Novel FuzzyPattern Pack (FPP)	Minimization of Number of Bins

3. Methodology

The improper order management generates an increase in wasted material and related operating costs. In fact, in order to ensure efficient use of available resources and effectively reduce waste, it is important for companies to implement a clear and precise methodology aimed to better manage production planning, simplifying activities and ensuring the reduction of wasted resources. Suppose to consider a make-to-order (MTO) company structured as a flow shop production system, where semi-finished products move from one production site to another through a standard, predetermined sequence. The proposed methodology is developed in four steps. Phase zero involves the collection of orders data and the construction of a database of the company's pre-shop pool. The i-th order, before being released into the production system, is initially collected in a pre-shop pool. Each order differs from the other by a specific delivery date d_i already defined by the customer. The First phase involves the application of a two-dimensional Sheet Packing Model (2DSPM), maximizing the utilization of the available material resources. In order to make the best use of the available two-dimensional resource of size W and H, the first objective of the methodology is to realize an optimal aggregation of orders, by positioning them with an appropriate rotation within the resource. The orders are characterized by two-dimensional sizes w_i and h_i. Through the use of the aforementioned aggregation, it will be possible to reduce material waste, but also to leverage production capacity by quickly emptying the pre-shop pool, processing multiple orders simultaneously, reducing lead time and minimizing production costs. Subsequently in the second phase of the methodology preliminary assessment is evaluated, which verifies the adequacy of resources to be scheduled in the production system, respecting lower limits based on the *Resource Utilization Index* which represents how much of the available area of the j-th resource configured was exploited. The *Resource Utilization Index*, U_j is calculated as follows:

$$U_j = \frac{\sum_{i \in j} v_i}{V_j} \qquad i = 1,2,\dots,n \quad j = 1,2,\dots,l \quad (1)$$

Where:

- n represents the number of orders in the pre-shop pool.
- l represents the number of configured resources.
- v_i represents the i-th resource area configured on j-th resource.
- V_j represents j-th resource area.

Finally, the third stage involves the implementation of sequencing based on due date dispatching rules that takes into account the prefixed delivery dates and the priority that the company associates with each customer. In the specific, the *Order Priority Index* P_i is calculated dividing the *i*-th client weight and the *i*-th order due date.

$$P_i = \frac{p_i}{d_i} \quad (2)$$

Subsequently, *Resource Priority Index* is calculated, as the sum of the priority indices of the orders belonging to the resource.

$$P_j = \sum_{i \in j} P_i \quad (3)$$

At this point, the sequencing of the configured resources is defined according to the aforementioned index.

3.1 Two-dimensional Sheet Packing Model

Assuming a flow shop production line of *m* machines, characterized by the presence of a bottleneck on the first machine, which has the longest processing time t_p, the problem is simplified to a single-machine sequencing problem. A further objective of the methodology is to obtain the proper sequencing of resources, on which orders have been previously aggregated. To best introduce the presented model, in Tab.2 the sets, parameters and variables considered in this problem are given.

Table 2: Two-dimensional Sheet Packing variables and parameters.

Name	Description
I	Set of *2n*, where even-index orders represent odd-index orders rotated by 90°.
x_i	Continuous variable denoting the minimum coordinate of *i*-th order on x-axis.
y_i	Continuous variable denoting the minimum coordinate of *i*-th order on y-axis.
z_i	Binary variable equal to 1 if *i*-th order is assigned to the resource, 0 otherwise.
ow_{ik}	Binary variable equal to 1 if the *i*-th order interferes with the *k*-th order on the *x*-axis, 0 otherwise.
oh_{ik}	Binary variable equal to 1 if *i*-th order interferes with *k*-th order on the *y*-axis, 0 otherwise.
$M \in \mathbb{R}^+$	Sufficiently large number.
$W \in \mathbb{R}^+$	Width of the resource.
$H \in \mathbb{R}^+$	Height of the resource.
$w_i \in \mathbb{R}^+$	Width of the *i*-th order.
$h_i \in \mathbb{R}^+$	Height of the *i*-th order.
$v_i \in \mathbb{R}^+$	Value of the *i*-th order, equal to the area occupied by the order.

3.1.1 Model assumptions

The assumptions considered in the formulation of the Sheet Packing Model, implemented in the first phase of the methodology, are the following: 1) To reduce the computational complexity of the model, the use of only one resource at a time was considered. The model will be subsequently iterated for each type of resource considered. 2) To reduce complexity, a static approximation of a dynamic environment is considered by iterating the model in fixed time intervals. At each time interval Δt, in fact, the pre-shop pool, is updated. The orders for the composition of the resource, will be chosen from all available orders at fixed time intervals. 3) The x_i and y_i coordinates of the orders are assumed to be integers with rectangular dimensions of each order. 4) It is assumed that the rotation allowed for each order can be either 90° or zero.

3.1.2 Objective functions and constraints

Given set I of orders and a single rectangular resource, assuming that $w_i < W$ and $h_i < H$ $\forall i$, so that the areas of the n orders do not exceed the dimensions of the resource in width and height, respectively, the goal of the Sheet Packing Model is to place the orders on the resource in order to maximize the useful area of the latter.

$$Max \sum_{i=1}^{n} v_i z_i \quad (4)$$

s.t

$$z_i + z_{i+1} \leq 1 \qquad \forall i \in \{1, 3, 5, ..\} \qquad (5)$$

$$x_i + w_i z_i \leq W \qquad \forall i \qquad (6)$$

$$y_i + h_i z_i \leq H \qquad \forall i \qquad (7)$$

$$Moh_{ki} \geq h_i - (y_k - y_i) - M(1 - z_k) - M(1 - z_i) \qquad \forall i, \forall k \in I \mid i \neq k \qquad (8)$$

$$Mow_{ki} \geq w_i - (x_k - x_i) - M(1 - z_k) - M(1 - z_i) \qquad \forall i, \forall k \in I \mid i \neq k \qquad (9)$$

$$oh_{ki} + ow_{ki} + oh_{ik} + ow_{ik} \leq 3 \qquad \forall i, \forall k \in I \mid i \neq k \qquad (10)$$

$$x_i \leq W z_i \qquad \forall i \qquad (11)$$

$$y_i \leq H z_i \qquad \forall i \qquad (12)$$

$$x_i, y_i, w_i, h_i, W, H, M \geq 0 \qquad \forall i \qquad (13)$$

$$z_i, ow_{ik}, oh_{ik,}, ow_{ki}, oh_{ki} \in \{0,1\} \qquad \forall i, \forall k \in I \mid i \neq k \qquad (14)$$

Equation (4) represents the objective function, aimed at maximizing the total value of the orders selected for the resource, thereby maximizing the area occupied by the latter. Constraint (5) ensure that an order cannot be placed on the resource simultaneously in two different directions. Constraints (6) and (7) ensure that an order does not exceed the maximum size of the resource. Constraints (8) and (9) make the overlap variables and order coordinates consistent in height and width, respectively. Constraint (10) ensure the non-overlap of two orders. Constraints (11) and (12) avoid symmetric solutions. Constraint (13) defines integer variables, while constraint (14) defines binary variables.

4. Case study application

4.1 Phase 0: Data Collection and Analysis

Phase zero involves collection and analysis of data. Specifically, the data retrieved are company data of customers' orders; actual disposition of orders on resources in the AS-IS scenario; analysis of resources costs; information on completion times of machines in the production system; company data of weight associated to each customer. A classification of orders requiring the same resource is made. The orders belonging to a specific group are arranged by increasing due dates d_i, in order to give priority to those closest to the deadline. Information about processing times of the machines (Tab.3), thicknesses and respective dimensions in width and height of each order (Tab.4) are obtained.

Table 3: Machine characteristics

Machine	Processing Time (t_p) [min]
M1	40
M2	40
M3	8
M4	10
M5	6
M6	6

Table 4: Orders characteristics

Thickness	Width *W* [cm]	Height *H* [cm]
1,14	203	127
1,70	203	127
2,54	203	127
2,84	203	127
1,14 NX	152	107

4.2 Phase 1: Packing Model application

Once collected, classified, and sorted the data, the first phase of the methodology is implemented, with a two-dimensional bin packing model, named Sheet Packing Model. Performances in terms of maximum occupied area are then evaluated. Finally, the realized waste values are compared with the AS-IS scenario to identify the improvement made with the application of the aforementioned model. Tab.5 shows the values of the parameters used in the proposed model.

Table 5: Value of parameters used in the proposed model.

Parameter	Value
N	Variable
M	10000
W_j	203
H_j	127
$W_{1.14HD}$	152
$H_{1.14HD}$	107

The model returned for each iteration which order belonging to the pre-shop pool was inserted into the resource, along with its position, and its orientation. At each optimal solution, the orders inserted in the sheet were extracted, proceeding the iteration for the remaining orders. The iterations stopped when the fixed time interval ended, updating the pool, incorporating the newly acquired orders. As an illustrative example, Fig.1 shows one of the different configurations of orders positioned on the resource obtained by the optimization model.

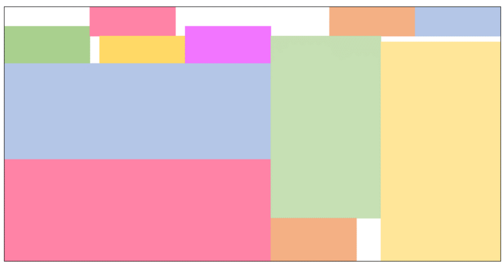

Figure 1: An illustrative example of the association of order to a generic resource.

4.3 Phase 2: Preliminary Evaluation

The output of the first phase consists of a set of configured resources. Before releasing in the production, an evaluation of these resources must be carried out. The second phase aims to verify the adequacy of these outputs by comparing the value of the *Resource Utilization Index* with a lower limit and subsequently evaluating order urgency. Lower bounds U_{LB} used are reported in Tab.6. It appears to be inconvenient for the company in terms of profit to have a resource utilization ratio above the lower bound reported.

Table 6: Lower bound values.

Thickness	Lower Bound (U_{LB})
1.14	0,78
1.14 HD	0,85
1.70	0,81
2.54	0,73
2.84	0,82

In order not to generate delays the Sheet Packing Model (SPM) is not allowed to reiterate indefinitely. The necessary condition for the model to reiterate is to meet the due dates of each order. The presence of urgent orders will result in immediate processing of the resource. The urgency of each order is assessed comparing the total processing time of the resource and the relative due dates. These latter were assumed to be equal to the shorter of the due dates of the n orders loaded:

$$d_j = \min\,(d_1, d_2, \dots, d_n)$$

4.4 Phase 3: Sequencing

The objective of third phase is to indicate the appropriate sequence of resources in the plant so as to avoid delays in the delivery to customers. Taking as input company data regarding customers and the respective weight associated to each of them, the *Order Priority Index* P_i and the *Resource Priority Index* were calculated. A discrete scale of values [0: low, 2,5: medium-low, 5: medium, 7,5: medium-high, 10: high] is identified for the weight of each customer. At this point, the sequencing of the configured resources is defined according to the aforementioned index. The resource characterized by the highest priority index will be scheduled first.

5. Results Analysis

The procedure described so far was applied for each resource of the company in three weeks of data collection. The time-period considered for the analysis is based on the availability of data coming from the case study application. Furthermore, it is necessary to note that the total amount of resources considered for the analysis is 107 sheets. For each resource, the size and coordinates of the orders, the saving in cm^2 and in euro were highlighted. The results obtained from the implementation of the SPM, in terms of material and economic savings, related to the minimization waste of the resource, are reported in Tab.7.

Table 7: Thickness saving values.

Thickness	Saving (cm^2)	Saving (€)
1.14	301182	5274,97
1.70	17739	310,72
2.84	49783	896,94
2.54	5563	100,23
1.14 HD	17198	340,9

It can be clearly seen that over a period of three weeks, through the use of the SPM, substantial savings have been achieved generating environmental improvement, optimized production with an increase of profit. Waste reduction is closely linked to cost reduction, which can be attributed to the purchase, processing and disposal of resources which do not generate profit for the company. Having implemented the second phase for all resource types, it was not necessary to repeat the model since all resources showed adequate results in terms of resource utilization when orders were passed into production. From this result, it can be noted that the SPM achieved excellent order packing, meeting the imposed acceptability limits. Due to the implementation of the third phase, optimal sequencing of the bottleneck resource was achieved leading to zero delays with respect to the due dates indicated leading to higher customer satisfaction. Furthermore, it was possible to observe that through SPM it was possible to complete a major number of orders in less time achieving a reduction in company workday.

6. Conclusion

Material waste has been widely recognized as a serious problem in industry, affecting environment and business profitability. Waste occurs when companies make unnecessary use of resources to provide products or services to customers. Today, it is critical to manage business resources efficiently and optimize the use of available material resources. To address the aforementioned issues, this study developed a four-step methodology that optimizes the utilization of material resources and ensures their correct sequencing in the production area. Through its implementation in the company, the results showed a promising reduction in material waste and related costs as well as an improvement in the reduction of delayed delivery of finished products, ensuring improved customer satisfaction. The generality and extensibility of the methodology make it predisposed for use in any industrial sector characterized by inefficient management of available material resources, representing a very useful tool to reduce material waste and ensuring no delay in delivery. This contribution is significant as it advances research by providing a novel approach to resource optimization, addressing both efficiency and sustainability in material usage. However, there are certain limitations to the model. Firstly, it assumes a static environment with a fixed iteration interval, limiting model ability to account for real – time demand forecasting and order acquisition variability. Furthermore, the 2DBP approach utilised in this model challenges in accommodating real – world constraints, such as item fragility and handling requirements, and is inefficient with irregularly shaped items. Future research will focus on adapting the model to dynamic environments by incorporating real-time data and predictive analytics, and exploring heuristic methods for faster, near-optimal solutions. Additionally, investigating advanced bin packing techniques, including three-dimensional and irregular bin packing with material waste management, and integrating machine learning for demand forecasting could enhance model applicability and efficiency.

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