

A Mixed Integer Linear Program for Operational Planning in a Meat Packing Plant

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Abstract: This paper reports a mixed integer linear programming model to support the planning at an operational level in a meat packing plant. The deterministic formulation considers multi-products (yielded from different cutting patterns applied to the carcasses), multi-periods, a batch quality distribution on carcasses and perishability. The perishability of the product is modeled by the inclusion of disaggregated inventory decision variables that take into account a given maximum number of days for fresh product. The main contribution of the present work is to develop an optimization model in a real tactical planning problem. Also we develop a sensitivity analysis on the quality of the carcasses, subject to large variability. We present here two different scenarios, comparing them to assess their economical impact.

1 INTRODUCTION

Pork is the most produced and consumed meat worldwide. In 2012, with a global production of approximately 109 millions of tonnes, pork continues to be the most important protein source for humans (FAO, 2014). In recent years it has been observed that most pork production is starting to be produced under larger productive structures called Pork Supply Chains. Inside these structures several complex problems are faced by the chain manager, who needs to integrate the stakeholder operations in order to coordinate the flow of product through the chain. One of the most challenging problems is that related to the planning and scheduling of operations for processing the carcass (body of the animal gutted and bloodless) into pork and by-products, taking into account vertical integration links.

Operations Research is one of the most important disciplines that deal with advanced analytical methods for decision making. It is applied to a wide range of problems arising in different areas and their fields of application involve the operations management of the agriculture and food industry. There are several works related to these topics, see (Ahumada and Villalobos, 2009) for a review of agricultural supply chains; see (Bjørndal et al., 2012) for a review of

operations research applications in agriculture, fisheries, forestry and mining; see (Higgins et al., 2010) for an application of agricultural value chains using network analysis, agent-based modeling and dynamical systems modeling; In (Pl et al., 2014) the authors draw insights for new opportunities regarding OR for the agricultural industries; (Rodríguez et al., 2014) presents a key description of the pork supply chain and points out the existing gaps in this topic.

In particular, there are numerous references that consider models and strategies using methodologies such as linear optimization models, see e.g. (Rodríguez et al., 2012); integer programming, see e.g. (Jena and Poggi, 2013); nonlinear, see e.g. (Henseler et al., 2009) multiobjective, see e.g. (Annetts and Audsley, 2002); dynamic programming, see e.g. (Gigler et al., 2002); stochastic programs, see e.g. (Ahumada et al., 2012); robust, fuzzy, see e.g. (Biswas and Pal, 2005); optimum control models, see e.g. (Dong et al., 2013); decision theory models, see e.g. (Zangeneh et al., 2002). For more details about the listed previous methodologies see e.g. (Pardalos and Resende, 2002).

In this paper, we present a mathematical optimization model to support the decision making process that focuses on the processing phase of the pork production process, taking into account a supply chain

context. Regarding agricultural supply chains (ASC), authors in (Ahumada and Villalobos, 2009) identified four main functional areas: production, harvest, storage and distribution. In this work, we want to handle the production and storage first, leaving distribution for future work. For "harvest" models specifically applied to pork supply chains, see (Rodríguez et al., 2009), regarding sow farms. In particular, we formulate a linear mixed integer program (MILP) that addresses decisions at the operative level of the processing phase in a meat packing plant. In Section 2, we outline some background information on the pork industry through a literature review to frame and motivate our work. In Section 3 we describe the details of the problem. Section 4 describes the mixed integer linear programming formulation that, indicates how often a cutting pattern is applied and on which type of carcass, in order to keep a certain level of inventory, meeting demand requirements and other storage capacities. Section 5 summarizes the computational results and finishes with a sensitivity analysis on some stochastic parameters. Section 6 summarizes the main conclusions and discusses future work.

2 LITERATURE REVIEW

The planning in a meat packing plant has been studied by several authors. Although most of the existing literature targets beef production, these contributions can also be applied to pork production as we will show later. To the best of our knowledge, the first contribution was done by (Whitaker and Cammel, 1990), who presented a linear programming formulation of a partitioned cutting stock problem applied in a meat industry. The main feature of their formulation is the partitioning of cutting patterns among carcass sections that vastly reduces the number of cutting patterns in the formulation. However, such model was devoted to market planning purposes, and consequently lacks elements that support the production planning, such as inventory and time horizon, among others.

Years later (Stokes et al., 1998) presents a contribution for a Meat Packing Plant production plan, using a Mixed Integer Goal Programming formulation to pursue multiple objectives, however such a model does not take into account that in a given batch there may be different types of carcasses, and variations in some parameters. (Bixby et al., 2006) presents an integrated system of 45 linear programming models to schedule operations in a real case for Swift & Company, a beef meat packing plant. Several thesis dissertations have also been found in the literature. One

of these (Wikborg, 2008) develops online optimization techniques for determining which cutting pattern to use in each carcass according to both carcass attributes and demand. (Reynisdottir, 2012) presents a linear programming formulation to maximize the value of pork products. (Sánchez, 2011) develops a DEA study on some parameters and uses a planning model to determine the levels of pork production by product. (Sanabria, 2012) develops a planning production model for a beef meat packing plant but without including multi-periods.

Unlike the approaches existing in the literature, the proposed model takes into consideration a planning horizon, different type of products, raw material availability, and regards the quality and availability of carcasses from pigs supplied. Also, our approach considers the perishability issue through the modeling of a specific variable that manages the freshness of meat, and more importantly, we realize and consider the existence of different types of carcasses in a batch of pigs. On the other hand, biological and economical parameters in pork production systems are subject to large variations (like the weight of the animal or its fat content), but no previous study has assessed the economic impact of these variations. Hence, our approach aims to cover some of the gaps found in the literature related to the animal's yield and its importance.

3 PROBLEM DESCRIPTION

The pork supply chain involves several operations for producing pork and by-products from pigs. Usually in an integrated structure each chain echelon is specialized in one or two productive operations. The fattening farms are in charge of producing fattened pigs ready to be slaughtered. Slaughter and packing operations are usually developed in two facilities: the Slaughterhouse and the Meat Packing Plant (MPP). For our formulation let's assume that they are located close to one another and are both part of a MPP. Every day, a batch of fattened pigs arrive at the MPP facility by truck. The truck is unloaded and the pigs are kept in a pen waiting for the slaughtering time. Slaughtering operations are straightforward; slaughter the entire batch of pigs because inventory of pigs is not possible. Once the entire batch of pigs is slaughtered, the carcasses (carcass means body of the slaughtered animal with the head, limbs, blood and entrails removed) are sent to a freezing storing room where the carcasses are kept for a period of time in order to decrease carcass temperature. The carcasses are processed forward to obtain several pork products and

sub-products.

Pork production planning at operative levels involves determining the production levels of each product and its level of inventory. These decisions depend on how to cut up the carcasses in order to satisfy consumer demand. Several cutting patterns exist in the market; each cutting pattern entails its corresponding set of products, specific rewards and operating costs. It can be possible that different cutting patterns share a common product, that means a specific product can be obtained through different cutting patterns, but the yield per product obtained is related to the cutting pattern used. However, the yield per product depends not only on the cutting pattern applied on the carcass but also on the quality of the carcass (raw material). Hence, it is important to select the right cutting pattern for each type of carcass. This problem in an isolated way could be tackled through data analysis, but in practical implementation, its interaction with the demand makes it much more complex to solve. In the production planning at the operative level the chain manager must consider not only the yield of products, and carcass availability, but also the demand behavior. Demand behavior is not constant through time, and moreover it is not homogeneous among all pork products, each product has its own level of demand. Such issues are particularly relevant in a disassemble problem like the production of pork. There exists a set of pork products (from the entire carcass) with a large demand while other products have small or no market at all. Hence, the major difficulty is to balance the benefits between demand and production, while managing inventories of perishable products. The main concern here is to determine the number of times each cutting pattern is applied to the available carcasses, and the levels of production obtained for the entire list of products.

Large variability, uncertainty, perishability, large scale of operations and large lead times are some issues that most pork supply chain managers must face at the operational level.

4 MATHEMATICAL FORMULATION

This section provides a detailed description of the mathematical formulation designed to solve the described problem and also to support the decision making at an operative level. Major decisions of this model include the number of times each cutting pattern must be applied on the available carcasses in each period of time, the total yield per product and its corresponding levels of inventory. It is assumed

that the company is willing to allow unsatisfied demand, and it is this unsatisfied demand which measures the level of demand to be covered by other stakeholders (meaning the company must buy those products from its competitors). The model addresses these decisions using an objective function that seeks to maximize the revenue of the producer, taking into consideration different constraints to represent demand requirements, inventory balance, cutting pattern yields, shelf life of fresh products, balance between the section of the animal, warehouse capacities and labor availability in the production process. The proposed model considers the following notation:

Sets and indexes:

- $t \in T$: Planning horizon (days).
- $j \in J_k$: Set of cutting patterns per sections.
- $j \in J$: Set of the whole cutting patterns.
- $i \in P$: Set of Products.
- $k \in K$: Set of sections per carcass.
- $l \in L$: Shelf life for fresh products.
- p_i^f : Selling price per fresh product i .
- p_i^e : Selling price per frozen product i .
- c_j : Operational cost of pattern j .
- c_j^e : Operational cost of pattern j in overtime.
- u^e : Freezing cost per kilogram.
- CM_i^f : Holding cost of fresh product.
- CM_i^e : Holding cost of frozen product.
- CME : Holding cost by outsourcing.
- s_i^f : Penalization for unsatisfied-demand of fresh product
- s_i^e : Penalization for unsatisfied-demand of frozen product
- CT_t : Freezing tunnel capacity at period t .
- D_{it}^f : Demand of fresh product i in period t .
- D_{it}^e : Demand of frozen product i in period t .
- CI^f : Warehouse capacity for fresh products.
- CI^e : Warehouse capacity for frozen products.
- t_j : Cutting-operation time for pattern j .
- T_w : Available work hours.
- T_wE : Available overtime hours.
- r_{ij} : Yield of product i in cutting pattern j .
- τ : Minimum period of time that a product must stay in the warehouse before sale.
- H_t : Carcasses available to process in each period.

Decision Variables:

- z_{jt} : Number of times to perform the cutting pattern j in period t in normal work hours.
- z_{jt}^e : Number of times to perform the cutting pattern j in period t , in overtime.
- $x_{it(t+l)}^f$: Quantity of fresh product i to process in period t to be sold at $t+l$

- x_{it}^c : Quantity of frozen product i to process in t .
 v_{it}^f : Quantity of fresh product i to be sold in t .
 v_{it}^c : Quantity of frozen product i to be
 I_{it}^c : Quantity of frozen product i to hold in t .
 O_t : Frozen capacity to outsource in period t .
 x_{it} : Total quantity of product i to be processed in period t .
 d_{it}^f : Unsatisfied-demand of fresh product i in t .
 d_{it}^c : Unsatisfied-demand of frozen product i in t .

The objective of the mixed integer linear programming presented here is oriented to maximize the net profit. The net profit is obtained by calculating the difference between the incomes from selling the products yielded by the cutting patterns, minus the operational costs incurred. These operational costs involve inventory, freezing costs, unsatisfied-demand penalties and labor costs to perform the cutting-patterns. Final output includes fresh and frozen products.

$$\begin{aligned} \max \quad & \sum_{it} (p_i^f v_{it}^f + p_i^c v_{it}^c - u^c x_{it}^c - CM^c I_{it}^c) - \\ & \sum_{it} (s_i^f d_{it}^f + s_i^c d_{it}^c) - \sum_{ij} (c_j z_{jt} + c_j^e z_{jt}^e) - \\ & \sum_{it} (CM_t^f x_{it(t+1)}^f) - \sum_t CME c_t^e \end{aligned} \quad (1)$$

The optimal solution of the model satisfies a different set of constraints described next.

Carcass Availability. Cutting patterns are partitioned into sections in order to reduce the number of different patterns, as explained by (Whitaker and Cammel, 1990). Thereby, the carcass can be cut in different sections, and for each section a different cutting pattern can be applied. These constraints ensure a balance between cutting patterns and the number of carcasses. Equality is forced because of the infeasibility of leaving unprocessed raw material, due to perishability issues.

$$H_t = \sum_{j \in J_k} (z_{jt} + z_{jt}^e) \quad \forall t \in T, \forall k \in K, \quad (2)$$

Cutting Patterns Yield. In the pork industry, different cutting patterns can be applied on the carcass to make different products. A cutting pattern is therefore defined by a combination of a set of products and their respective yields. It is assumed that a specific product can be obtained from different cutting patterns, but not from different sections. In reality, this might not be the case in some specific products, such as skin,

bones, and trimming. The following constraint calculates the total number of products, retrieved from all the cutting patterns applied in each period.

$$x_{it} = \sum_{j \in J_k} r_{ij} (z_{jt} + z_{jt}^e) \quad \forall i \in P, \forall t \in T, \quad (3)$$

Available Daily Work Hours. These constraints ensure that the labor time does not exceed the viable working hours.

$$\sum_{j \in J_k} z_{jt} t_j \leq T_w \quad \forall t \in T \quad (4)$$

$$\sum_{j \in J_k} z_{jt}^e t_j \leq T_w^E \quad \forall t \in T \quad (5)$$

It is recognized that the pork industry works with perishable products subject to spoilage. In order to extend the life of the product, it undergoes a freezing process. Thereby, a product can be sold in two presentations, fresh and frozen. A product is considered fresh if it is sold within 4 days after elaboration. On the other hand, frozen products can be kept for almost 2 years. However, the profit of selling frozen products decays considerably.

Fresh and Frozen Balance: This constraint determines the amount of product to be frozen and the amount to keep fresh to be sold in the next period.

$$x_{it} = \sum_{l \in L} x_{it(t+l)}^f + x_{it}^c \quad \forall i \in P, \forall t \in T \quad (6)$$

Fresh Product to be Sold. As mentioned, fresh products are not allowed to be kept for more than 4 days. Constraint (7) calculates the total amount of fresh products that can be sold in a period t , but were produced in previous periods.

$$v_{it}^f = \sum_{l \in L} x_{i(t-l)t}^f \quad \forall i \in P, \forall t \in T \quad (7)$$

Frozen Product to be Sold. Fresh products need to stay at least 2 days in the freezing tunnel, to be considered frozen. The following constraint balance the inventory of frozen products for each period.

$$v_{it}^c = I_{i(t-1)}^c + x_{i(t-\tau)}^c - I_{it}^c \quad \forall i \in P, \forall t \in T \quad (8)$$

Demand of Frozen Products. Ensures that the requested level of each frozen product is addressed, allowing the existence of unsatisfied-demand if the raw materials are insufficient.

$$v_{it}^c + d_{it}^c = D_{it}^c \quad \forall i \in P, \forall t \in T \quad (9)$$

Demand of Fresh Products. Ensures that the requested level of each fresh product is addressed, allowing the existence of unsatisfied-demand if the

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$$v_{it}^f + d_{it}^f = D_{it}^f \quad \forall i \in P, \forall t \in T \quad (10)$$

Freezing Tunnel Capacity. Fresh products need to be processed in a freezing tunnel in order to become frozen. The following constraint ensures that the capacity of this tunnel is never exceeded.

$$\sum_{i \in P} (x_{i(t-1)}^c + x_{it}^c) \leq CT_t \quad \forall t \in T \quad (11)$$

Fresh Products Warehouse Capacity. Ensures that the capacity for holding fresh products is never exceeded.

$$\left(\sum_{l=1}^L \sum_{l'+1 \leq L} x_{i(t-l)(t+l)}^f + \sum_{i \in P} \sum_{l=1}^L x_{it(t+l)}^f \right) \leq CI^f \quad \forall t \in T \quad (12)$$

Frozen Products Warehouse Capacity. Ensures that the capacity for holding frozen products is never exceeded.

$$\sum_{i \in P} I_{it}^c \leq O_t + CI^c \quad \forall t \in T \quad (13)$$

Decision Variables Nature. $z_{jt} \geq 0$ and $z_{jt}^e \geq 0$ are integer variables. The rest of the decision variables are all continuous and non-negative i.e. $x_{it(t+l)}^f \geq 0$, $x_{it}^c \geq 0$, $v_{it}^f \geq 0$, $v_{it}^c \geq 0$, $I_{it}^c \geq 0$, $c_t^e \geq 0$, $x_{it} \geq 0$, $d_{it}^f \geq 0$, $d_{it}^c \geq 0$.

We now explore the proposed model described by developing experiments, in order to gain knowledge about its sensitivity when changing some parameters.

5 COMPUTATIONAL RESULTS

In this section a case study is presented in order to illustrate the suitability and advantages of the proposed optimization model. Instances solved consider 17 different types of pattern, 10 planning periods and a total of 40 products. This results in a model with 4351 variables, 340 of them integer and 2550 constraints. All instances of this case were solved using a PC with Windows 7, i5-3210M CPU @ 2.5GHz and 8Gb RAM. The modeling software used was IBM ILOG CPLEX Optimization Studio 12.2 with an academic license.

Basic parameters were created using market information gathered from different pork producers, such as prices, costs and capacities. Most countries use different patterns producing various products according to their history and gastronomic culture. In this case,

we opted to use the patterns used by a given Mexican pork firm. Pork carcasses were split up into 5 sections, and for each section a set of cutting patterns was assigned. In total, the company operates with 17 cutting patterns, and manages 40 pork products without taking into account the products derived from the skin, head, trotters, tongue and viscera.

The first instance represents a batch of 300 fattened pigs arriving everyday to the meat packing plant during a horizon period of 10 days. The labor capacity is considered as 8 hours per day. Moreover, it is also assumed that the demand is given, and the available amount of carcasses is fixed and known. One of the most important and relevant aspects of the model is that it gives the option to operate with different types of carcasses. It is assumed that the company operates with a batch of homogeneous carcasses with average yield and average fat content. Table 1 considers 5 different types of carcasses, where instance C corresponds to the most common type of carcass, and the rest are modifications of the previous with a greater or lower fat content. Each case has a different group of possible cutting patterns, according to their quality, and different sets of possible products.

Table 1: Instance composition.

Cases	Description	Fat Content
A	Excellent meat	1.44%
B	Exc-Average meat	3.78%
C	Average meat	6.05%
D	Ave-low yield meat	8.264%
E	Low meat	10.44%

In the current work we will focus on the possible variations of the carcasses. Different types of carcasses can be defined by a combination of quality (fat content) and total yield. Table 2 lists the results of the instances defined above; the first column shows the optimal value achieved, the second column represents the percentage of demand met. The third column represents the percentage of utilization of the warehouses for frozen and fresh products. And the fourth represents the labor usage of work hours. The results show that the rewards increase as the quality of the carcass increases, as we expected, but also the facilities and labor capacity have better usage. In Europe and the USA, fattened pig producers receive a bonus for better quality of carcasses, but there are some Latin American countries that don't even evaluate their raw material quality. This study suggests that pork producers can have a bigger benefit if they process high quality carcasses. The difference between the objective value of instance A and the objective value of instance E is around 10%, thus showing a great financial increase

by having carcasses with better yields. These results suggest that the model responds to changes in the quality. Processing higher quality carcasses not only increases the meat yield, but also gives the producer the chance to sell high quality lean products, making them more competitive in the market and giving them access to different markets. The increments in the objective functions are explained because higher quality carcasses give more revenue to the producer as he spends less time cutting to produce more quantity of meat, and thus he can fulfill demand requirements more efficiently. It is shown that better quality can give differences up to 10% more profit. Labor is equal to employment but the use of facilities is reduced by 10%. Table 3 lists the results for the number of times the cutting patterns are applied, in each case. In the low quality cases, E and D, some patterns tend to disappear completely, 4 and 5 respectively, while other patterns reach their peak of usage, for example pattern number 11. This clearly shows that some patterns are better fitted to a certain type of carcasses than another.

Table 2: Results.

Instance	Opt.Value	Demand	Facilities	Labor
A	+2.5%	+3.6%	-9%	+0%
B	+2.5%	+1.2%	-4%	+0.1%
C	5,875,821	83%	91%	91%
D	-3%	-1%	+2%	+0%
E	-7%	-3%	+2%	+0%

Table 3: Applied number of patterns for the first instance.

Pattern	A	B	C	D	E
1	654	536	492	502	517
2	1012	1133	1250	1250	1239
3	834	831	758	748	744
4	45	21	12	0	0
5	807	851	884	930	994
6	1648	1628	1604	1570	1506
7	65	66	68	62	55
8	753	758	768	468	451
9	171	143	159	177	197
10	1511	1533	1505	1793	1797
11	2435	2458	2500	2451	2500
12	65	42	0	49	0
13	1856	1852	1844	1830	1813
14	644	648	656	670	687
15	1266	1266	1266	1317	1400
16	2683	2682	2682	2617	2151
17	1006	1006	1005	1006	1005

Next, a second set of experiments is developed. In reality the batch of pigs arriving at the meat packing plant facilities is not composed of homogeneous

pigs. This is so, because the fattening process of a pig is very variable, pigs don't grow at the same rate and they have different feed conversion rates. Physically, these issues are reflected by the presence of heterogeneous pigs in the fattening batch, those pigs have different weight and carcass compositions. Although homogeneity is a highly demanded aspect by the chain manager for better control production, most producers just rely on the weight of the animals as a reference to calculate their profits, though the heterogeneity in the quality of carcasses in the batch can not be denied. Carcass composition is only known after slaughter, and even if pigs do have similar weights they may present different carcass composition. The meat yield per product depends on the carcass composition. Hence, it is important to study the impact of different distributions of carcass composition and which cutting pattern is more worthwhile for each type of carcass. One of the most important and relevant aspects of the model is that it gives the option of operating with different types of carcasses. Working with different types of carcasses at the same time seems to add complexity to the model, as the resolution time for these cases rises up to a max of 10 seconds in average.

Table 4: Composition of pattern yield for the 2nd instance.

Instance	Description
F	50% A and 50% C
G	50% E and 50% C
H	33% A 34% C 33% E
I	20%A 20%B 20%C 20%D 20%E

Table 4 lists a set of instances based on different distribution of carcasses, while table 5 lists the set of corresponding results. The results for these instances are similar to the first set; the instances with better quality of carcasses always have the highest values for the objective function, and better operational indicators, showing that in fact the quality of carcasses is very important to the revenue of these types of producers.

Table 5: Results for the 2nd instance.

Instance	Obj.Value	Demand	Facilities	Labor
F	5.917.113	82%	86%	61%
G	5.589.634	81%	87%	60%
H	5.746.693	81%	85%	43%
I	5.909.373	81%	95%	28%

Finally, we develop some sensitivity analysis on critical parameters, such as the number of processed animals, in order to observe the economic and technical impact of having the flexibility to choose the

number of raw materials to process. To study this, we changed the fixed number of carcasses in each period to a decision variable, so the model could choose the optimal number of raw materials for each time period. This analysis is raised regarding the parameter H_t . Model (1) - (13) assumes that H_t is given and known for every period. Now, we consider H_t as a decision variable and we add a new constraint imposing that the sum of this variable does not exceed the original amount of available carcasses throughout the time horizon.

Table 6: Value of H in each period of time.

Horizon	H_t
1	461
2	309
3	262
4	398
5	374
6	360
7	188
8	272
9	73
10	169

Results in table 6 show that variable H_t is mainly influenced by the demand, and only orders the number of pigs that are really needed. The optimal value of this instance increases the economic reward by 10% with respect to the most common case (Instance C). Also, the inventory level of ready to sell products decreases by 12%, due to a better usage of the different warehouses capacities, because here the producer is not forced to use all the material coming to the slaughter house, so the model can make a better fit of the demand and sales.

6 CONCLUSIONS AND FUTURE RESEARCH

In this paper we proposed and validated a mixed integer model for production planning in the meat industry. The objective of this paper, besides developing a model that incorporates aspects that were not present in the current literature, was to extrapolate some operational policies and advices for producers and farm growers. We accomplish this through the interpretation of the results obtained from the presented instances.

The results explained in the previous sections show that the formulated model is highly applicable due to low resolution times (it can be solved using commercial software) and the easy valuable information an employee can extract from it, making the pro-

duction planning more efficient. However, for larger instances of the model, ones with more periods, products and patterns, we can't assure yet that it will be solvable, because of the exponential growth of the integer variables. Although the instances tested here were developed to fit the reality of the industry, larger cases can exist in reality, due to the variable size of the patterns available across different countries.

According to the results obtained from the experiments with different quality carcasses, our suggestion is that producers and farmers should develop a quality system to guarantee the yields (more than the weight) of the raw material that they sell/work with, to ensure satisfying levels of revenue for both. The difference between the objective function and the other operational indicators are significant enough to make efforts towards this area, obtaining better usage of their machinery, man-labor, time available and demand fulfillment.

Future research in this area should go towards the development of a stochastic model that takes into account probabilities for different types of arriving batches, to make the production planning more robust. Also, efforts should be made to test the complexity of the model as available cutting patterns grow.

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