Journal of Industrial Engineering and Management
JIEM, 2012 – 5(1):115-132 – Online ISSN: 2013-0953 – Print ISSN: 2013-8423
http://dx.doi.org/10.3926/jiem.374

Optimisation of cutting in primary wood transformation industries

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Received June 2011
Accepted February 2012

Abstract:

Purpose: The loss of raw materials in wood cutting industries has reached high proportions (30 to 36% of volume yield, Ngolle Ngolle, 2009). The purpose of this paper is to solve the problem of optimising the production on the basis of the commercial value of the cuts.

Design/methodology/approach: In order to tackle this problem, we started with the generalities on the exploitation and the primary conversion of wood in Cameroon. After that, we studied the various methods of cutting and the different products obtained. We then proceeded with the formulation of the log cutting optimisation problem based on a real shape model of the logs, objective of research works presented in (Danwé, Bindzi, Meva'a & Nola, 2011). We finally completed our work with the design and the presentation of a software package called cutting optimiser.

Findings: We start by having some knowledge on the geometry of the logs, cutting strategies and classification of cuts. This classification enables us to determine the quality and quantity of the production, and to estimate the commercial value of the log. The solution to this problem then led to the design of a software package.

Research limitations/implications: In this paper, the optimisation problem concerns problems where the objective function is non-explicit, the variables discreet, and the constraints non-explicit.

Practical implications: The solution to this problem then led to the design of a software package to be used as a cutting optimiser. The automation of the cutting operation leads to an accelerated work and an increase in the volume of the cuts produced daily.

Originality/value: This research is among the few to solve discrete optimization problems with constraints. Some constraints concerning the mechanical characteristics of the logs are taken into account. The constraints can equally be non-explicit. Moreover the market standards impose technological constraints which render the problem of optimisation even more complex.

Keywords: geometric model, cutting, simulation, optimisation

1 Introduction

The Cameroon forest covers about 20 millions of hectares, representing 44% of the national territory. At the sub-regional level, Cameroon possesses one of the most developed primary conversion wood industry. According to the Cameroonian Minister of Forestry and Wildlife, wood is the second export product after oil (Ngolle Ngolle, 2009). The wood production is currently estimated at 2.45 million m^3/year. Today, 300 species are marketable, and five species (designed in Cameroon as Ayous, Sapelli, Azobe, Iroko, Fraké) represent close to 70% of the total production. The industrial exploitation of timber in Cameroon is governed by the law N° 94/01 (Cameroon Law N° 94/01, 20th January 1994), (Duhesme & Ngatchou, 2006) which actually stipulates up to date that the export of timber is forbidden and the totality of the national production must be transformed by the local industry. Following this law, close to 50 new factories have been constructed for a conversion capacity of about 1.5 million m^3/year.

The restriction of timber exportation is an industrialisation policy in the wood sector since it incites industries to invest in local wood conversion. Today, Cameroon counts about 87 factories of primary wood conversion, which are preferably situated in free industrial areas or close to the Douala seaport. The commercialisation of wood in Cameroon is well structured as far as the export market is concerned, but remains unorganised at the local level despite the reality of a progressing market. Exports are mainly for the European (that absorb 70% of timber and 90% of the sawing) and Asian markets. The local market consumes essentially 2nd choice sawing and plywood. A good part of the internal demand of wood is satisfied by cut wood from the artisanal sawyers.

Statistical analyses have shown that there exists a considerable difference between the volume of logs bought by primary conversion wood factories in Cameroon and the volume of the cuts leaving the industries. This low efficiency results in the waste of raw material, which is burnt as biomass.

Moreover, with the trend towards accelerated investment, it would be imperious to regulate and to orientate the development of the primary conversion wood factories in Cameroon so as to make it compatible with the long-term management and forest planning. The present work therefore proposes methods of optimisation in order to improve on the wood production capacity and quality, alongside avoiding a waste of the logs.

During the last decades, the introduction of computerisation and data processing have revolutionised methods of design and manufacturing in the domain of wood production; firstly in the industries, with the introduction of numeric positioning machines and later on those with numeric command, to carry out machine works of increasing complexity. Several research teams have developed simulation and optimising computer software systems (Pinto, 2004; Chiorescu & Grönlund, 2000). Nowadays the use of data is common, either by implementing all the required manufacturing dimensions directly into the machine, or by an interface that enables the entry of data with CAD software: cross-sections, lengths, choice of tools, etc… (Perré & Badel, 2003). These changes are imposed by the supply cost of the logs and the cutting cost, which all together counts for a continuously increasing portion of the selling price of processed woods. The raw material and the production capacity of sawmills should therefore be efficiently used in order to extract from every log the optimal quantity (Danwé, Bindzi, Meva'a & Mbagnia, 2009). In this work we studied the optimisation of wood production in industries of primary conversion. Primary wood conversion embodies the set of operations performed on trees hence they are cut and transported out of the forest. It comprises the activities of sawing and wood planning, unrolling and trenching, drying, and finally wood impregnation. This survey applies to the situation of Cameroon. We started our work with the generalities on the exploitation and the primary conversion of wood in Cameroon, after which we studied the various methods of cutting and the different products obtained. We then proceeded with the formulation of the log cutting optimisation problem based on a real shape model of the logs, objective of research works presented in (Danwé, Bindzi, Meva'a & Nola, 2011). We finally completed our work with the design and the presentation of a software package called cutting optimiser.

2 Geometric modelling and cutting up

The achievement of a better profit in sawing industries depends mainly on the mathematical representation of the logs of wood during cutting up. Geometric modelling of logs serves as a preliminary stage in the automation of operations in a sawmill (Pinto, Pereira & Usenius, 2002). The automation also requires real time simulations. Time required for the analysis of data related to logs should then be reduced. This additional constraint imposes a compromise between the accuracy of the model and the quantity of data to be processed.

2.1 The geometric model used

The geometric model used here is derived from the analytic equations representing logs, of which the data describing the external shape are consistent with those generated by multiple axes sensors (Longuetaud, Saint André & Leban, 2005). The hypotheses of regular cross-sections are abandoned. The cross-section is rather represented as an intersection of two half - conics in order to account for the flat parts or the oval of the section as well as its real eccentricity, which is the case when the geometric centre of the section is not a centre of symmetry.

The log is represented by a set of surfaces of a circular or elliptical shape having straight generatrix. The logs are then subdivided into smaller logs which can be approximated by these (primitive) surfaces. Therefore for a straight log of wood, a unique primitive is sufficient whereas for a curved log, many primitives will be needed. In this case the discretisation could be controlled by the variation of the slope of a log's generatrix. Any log of wood can be represented by a stack of primitives without necessarily considering paraboloides or neloides.

To best approach the real shape of the logs, it is necessary to represent the cross-sections by an adequate analytic function. The use of a unique function (circle or cylinder) does not permit the representation of an arbitrary log. An error in representation can have a drastic influence over the qualitative evaluation of the sawing resulting from the log. The shape of the cross-section presented could be due to the eccentricity of the medulla of a trunk for a given straight log, or could simply represent the best approximation of an irregular surface. Also, in situations where the log is curved, the various primitives are inclined to the “vertical” by a certain angle, and the cross- sections (perpendicular to the vertical direction) are then the intersection of these primitives with the horizontal plan. Such ovoid surfaces should not be represented by regular ellipses (symmetrical), but by two half - ellipses.

It is quite relevant to mention that in modelling the external shape of the log, swellings (which generally characterise the roughness of logs), should not be taken in account in the perspective of optimising the volume output of logs being cut up. Indeed they are generally outgrowth of buds and must be modelled as such; here we have only modelled smooth logs.

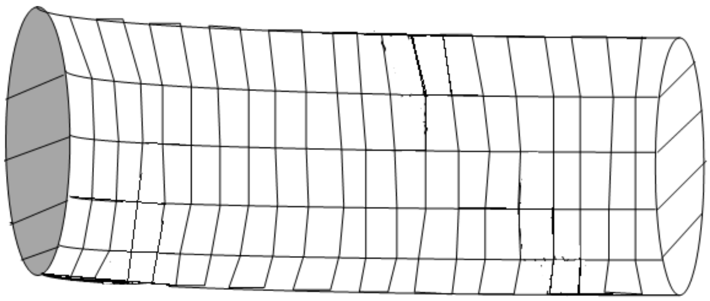


Figure1. Discrete geometric model of the log

2.2 Cutting up

From the geometric model of the logs, cutting consists of extracting the produce from the analysis of the intersection at various orientations of a cutting plane (modelling the saw blade) and the terminal surface of the log. The mode of cutting depends on the characteristics of the log and the equipments of the company.

In order to optimise cutting decisions, an automated real-time (i.e. at production speed) evaluation of material dimensions and quality is required. Many modern sawmills now use scanners to collect data concerning the log geometry. This set of data is next processed by sophisticated software tools which help optimise the cutting process. It seems that the most important decision the sawyer usually makes is the rotational and lateral positioning of the log on the carriage for the first cut. The first cut of a log consists of cutting through one or more faces of the log. The first cut is a very important stage in log processing since all the other stages depend on it. Once a first cut is made, all other subsequent cuts are either parallel or perpendicular to it. Some of the requirements listed in (Williston, 1985) for a first cut to lead to a maximum value yield of a log are a knowledge of the log geometry (length, diameters, eccentricity, sweep...), the log quality, the determination of the best orientation and position of the log at the first cut, and the use of a cutting system that enables to obtain plane surfaces during log cutting.

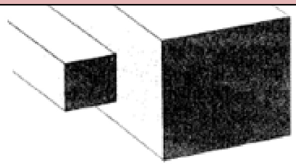
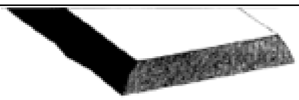
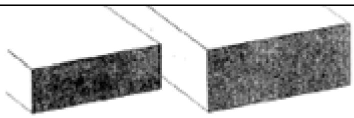
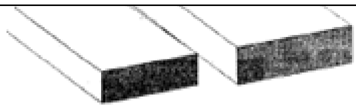
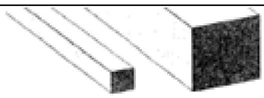
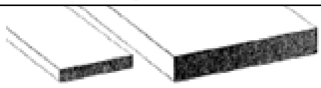
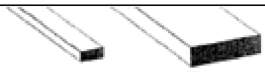
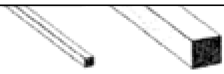
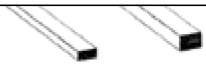
Sketch of cut	Name	Characteristics
	Square piece Or Beam	Square cross-sections from 100 X 100 mm to 400 X400 mm
	Plateau	Minimal dimensions : Thickness of 60mm Width of 225 mm
	Beam	Dimensions from 75 X 205 mm to 105 X 225 mm
	Bastaing (french)	Dimensions from 55 X 155 mm to 65 X 185 mm
	Rafter	Square cross-sections from 40 X 40 mm to 120 X 120 mm
	Plank	Rectangular pieces of thickness between 27 and 54 mm and width at least equal to four times the thickness
	Batten	Rectangular pieces of thickness between 7 and 20 mm and width at least equal to four times the thickness
	Joist	Dimensions from 26 X 65 mm to 45 X 105 mm
	Frieze	Dimensions from 40 X 40 mm to 35 X 120 mm
	Carrelet (french)	Dimensions from 15 X 15 mm to 50 X 50 mm
	Liteau (french)	Dimensions from 18 X 35 mm to 30 X 40 mm
	Lath	Dimensions from 5 X 26 mm to 12 X 55 mm

Table 1. products from the first stages of primary conversion of wood

The prominent Best Opening Face (BOF) system (Lewis, 1985) serves in many sawmills as a means to help determine the first cut. The BOF uses the principle that the first cut is the key of the sawing strategy for a given sawing pattern, in order to maximise the yield of the saw log. Unfortunately this method is based on an oversimplification of the saw log as a truncated cone. Furthermore, BOF only considers the volume-yield of the saw log, leaving out the effect of internal characteristics.

The table 1 presents some lumber types obtained after a primary conversion.

3 Production optimisation

The main factors that influence production in sawmills are the quality of raw material, the machines used, and the staff and work organisation.

The quality of the timber has an impact on the products obtained after cutting (Pinto, 2004). With respect to the small logs, loss of material can be observed due to the effects of the wood feature, the precision, the method used in cutting, and the thickness of the saw. The achievement of a better profit in sawing industries depends mainly on the mathematical model of logs during cutting. It then becomes clear that the commercial value of the cuttings defined as our objective function is non-explicit. There exist constraints concerning the mechanical characteristics of the logs. These constraints can equally be non-explicit. Moreover the market standards impose technological constraints which render the problem of optimisation even more complex.

3.1 The cutting process and classification

Classification is the determination of the quality and quantity of cuts produced at a given moment in a sawing industry. To each class Ci we associate the commercial value Pi; this will enable us to evaluate the commercial value of the entire log. The classification has a very important role in the process of log exploitation; this helps us maximise production profitability. For this, some knowledge on the classification is required at various stages of the production. In factory processes, the classification of logs begins with an evaluation of the raw material. Normally, the higher the value of an item, the more important and necessary it becomes to have quality norms. These norms can either be defined locally or standardised. Such a classification of raw materials has beneficial effects on the timber producer, be him independent (selling his own product) or dependent (controlled by industries). These effects will give each of the stakeholders additional details on the real value of the raw material.

There exist two major classification techniques: a machine classification and a visual classification. The machine classification is based on the use of mechanical stress with the help of a machine which permits us to have admissible stress values for flexion and the modulus of elasticity. The visual classification is based on external aspects of the cuts. The classes are defined according to the distribution of the nodes on the faces (position on the cuts), their size, and the number of nodes per face. For local sawing industries, we encounter three major classes. For the first class is made up of cuts presenting no defect (absence of nodes, dimensional conformity according to the functional condition of contract). The second class is made up of cuts having at most one node. For the third one, the number of nodes is greater than or equal to two and in addition, we can also find dimensional defects.

3.2 Formulation of the optimisation problem

Optimisation of the cutting consists of detecting and analysing the characteristics of a piece of wood in sight of running the cutting program in a way so to maximise the value of the products of each log to be transformed (Cummings & Culbertson, 1972). In the optimisation model, the system determines the optimal values of the exploitation parameters in a way as to maximise profit, subject to the constraints linked to the exploitation process. The optimisation model resorts to wide-spread techniques of linear programming or operational research (Schrijver, 2004).

Let us denote the design variables n^i_λ as the number of pieces of class *i* from cuts of type λ. The objective function

$$\mathbf{P_T} = \sum_{i=1}^{N} n^i_\lambda P_i \qquad (1)$$

Corresponds to the total cost of the cuts to be optimised, *Pi* being the price of class *i* cuts. The constraints *j (j=1 to m)* can be written in the form: $\mathbf{g}^{\mathbf{ij}}_\lambda(n^i_\lambda) \leq 0$

The optimisation problem can thus be written as:

$$\text{Maximise } \mathbf{P_T} = \sum_{i=1}^{N} n^i_\lambda P_i \text{ Subject to } \sum_{i=1}^{N} n^i_\lambda S_i - S_\lambda \leq 0 \text{ with } S_i = e^i_\lambda . l^i_\lambda \qquad (2)$$

n^i_λ is a positive integer for *i=1, .. , N*

S_λ denotes cross-section of the log

S_i the cross-section of the cuts of class *i*, From the expression of the constraints we can consider that the variable l^i_λ, denoting the length of the cuts in class i, does not appear in an explicit manner. In addition, the variation of the cross-section of the log S_λ can be controlled during cutting by the variable in l^i_λ the optimisation problem, we therefore have:

N^i_λ the number of nodes per face on a cut of class *i* and of type λ.
T^i_λ the size of each node on a slice of class *i*, type λ (the size of each node on a slice of class *i*, type λ (T^i_λ could be the distance between two extreme points taken on the contour of the node or the surface described by the cutting plane and the node envelope intersection curve).

The optimisation problem can now be written as:

Maximise $$\mathbf{P_T} = \sum_{i=1}^{N} n^i_\lambda P_i \qquad (3)$$

Subject to:

$$\sum_{i=1}^{N} n^i_\lambda S_i - S_\lambda \leq 0$$

$$l^i_\lambda = kl_i$$

$$N^i_\lambda \leq N_i$$

$$T^i_\lambda \leq T_i$$

Where:

S_λ Cross-section of the log

S_i Cross-section of the cuts of class *i* $S_i = e^i_\lambda \cdot l^i_\lambda$,

N^i_λ The acceptable number of nodes on a cut of class *i*

T^i_λ The acceptable size of a node in the class *i*

The above optimisation problem can be assimilated to a knapsack problem with non-bounded variables which can be formulated thus: We have *N* types of object (product from log cutting) in an infinite number for each type (Osario, Glover & Hammer, 2002).

An object of type k has a positive integer value C_k (its market price) and occupies a volume a_k (for a cut cross-section S_k). Let μ_κ be the number of type k objects in the bag. The problem is thus expressed as: *Finding the subset of objects of maximum value, whose volume does not exceed the capacity **b** of the bag.*

We can thus formulate the problem as:

$$\mathbf{M}ax \quad \sum_{k=1}^{N} C_k \mu_k \tag{4}$$

Subject to

$$\sum_{k=1}^{N} a_k \mu_k \leq b, \; \mu_k \geq 0 \text{ and integer values, for k = 1, 2,...,N}$$

This is an integer problem linear programming with constraints. The problem is solved as a problem of resource allocation (Hanafi & Wilbaut, 2006).

3.3 Resolution of the optimisation problem

Dynamic programming is a method of resolving exact sequential optimisation problems, thanks to (Kellerer, Pferschy & Pisinger, 2004). The formalism of dynamic programming leads to many possibilities and variants. As a general rule, it is a problem (P) whose goal is to optimise a series of decision making with respect to the cost it involves.

The knapsack problem denoted here as KP, is a problem of combinatorial optimisation (Bertsimas & Demir, 2002; Fréville, 2004). We use it to model the following situation:

- In portfolio management systems: to equilibrate selectivity and diversification in the perspective of finding a better connection between profitability and risk for a capital invested in financial assets (shares…)
- When loading ships or planes: all luggage have to be packed without overloading
- When cutting materials: to minimise scraps when cutting rods into iron bars.

The knapsack problem has the property of a *sub-optimal structure*, which is to say we can construct the optimal solution of the problem with *i* variables from a problem with *i-1* variables. This property allows us to solve this problem using the method of dynamic programming. We shall let KP *(i, c)* be the problem reduced to i variables and capacity *c*. From the works of (Garfinkel & Nemhauser, 1972) the idea is as follows:

Given a number of variables *i* and a capacity *c*, the optimal solutions of *KP (i, c)* may be:

- The optimal solution of the problem with *i-1* variables with the same capacity *c (KP(i-1, c))* to which we add $x_i=0$;

- The optimal solution of the problem with *i-1* variables with capacity $c - w_i$ *(KP(i-1, c-w_i))* to which we add $x_i=1$;

We have two kinds of problems: the binary knapsack problem, and fractional knapsack problem. It is to the last model that we assimilate our optimisation problem. Given a general problem, the specificity relies on the fact that we have the possibility of choosing more than one object of each type. Mathematically, it is all about finding $(u_1, u_2 \ldots u_n) \in \mathbb{N}^n$ such that

$$\text{Max} \sum_{i=1}^{n} u_i b_i \qquad (5)$$

Subject to

$$\sum_{i=1}^{n} u_i w_i \leq W$$

The algorithm put in place is the following (Kellerer, Pferschy & Pisinger, 2004):

```
Begin
        {fill table}
            For k=1 to N Do
                Find j/wj<=k
                    For each j
                        calculate z(k)=cj+z(k-wj)
                    Get and store j/ z(k) max(j(k))
        {Choice of objects}
                    Find k/ z(k) max
                    a ← k
                    while j(a) not zero Do
                    j(a)=a1, u(a1) ← u(a1)+1
                    a ← a-w(a1)
        End.
```

The implementation of this algorithm leads us to the log optimisation software package presented the section below.

4 Optimisation software package for log cutting

This software package aims at determining the number of cuts of type k that we can extract from a log of wood in a way so as to optimise the material output (minimise loss) and maximise its commercial value. The interface for data entry of the optimisation software is shown below:

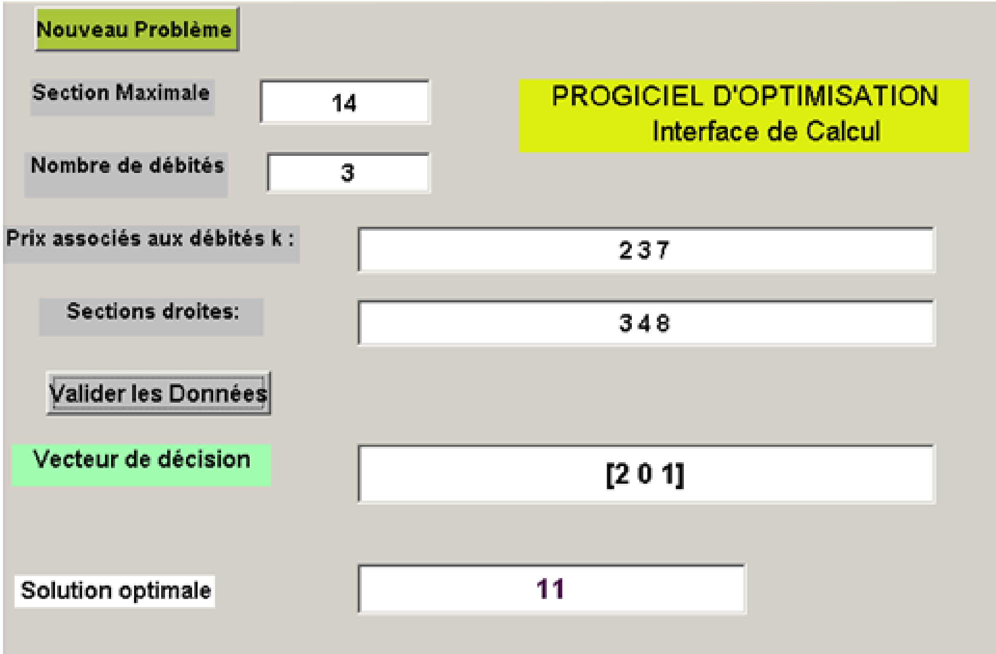


Figure 2. Optimisation software Interface

The fields located before the tab "***valider les données***" (validate data) are used by the user to enter the data of the cutting problem. In the field "***section maximale***" (maximal cross-section), the user enters the optimal section calculated at the cutting interface of the software. The fields: "***nombre de débités***" (number of cuts), "***prix associés aux débités k***" (prices associated to cuts of type k) and ***"sections droites"*** (cross-sections) are related to the command. The user fills the form according to the enterprise's decisions, the number of cuts for a particular type that he wishes to obtain and also the prices and the cross-sections associated to each type of cut. Once the data is introduced, the result obtained gives the **"Vecteur de décision"** (decision vector) which defines the quantity for each type that has to be cut in order to optimise the material output.

One simple applied example given for commands of three types: chevron, backing strip, and beam. The optimal cross-section of the log is 14, the associated prices are (2, 3, 7) and the cross-sections of the cuts are 3, 4, 8 respectively.

The optimisation problem is presented in the following manner:

$$\text{Max} \quad 2u_1 + 3u_2 + 7u_3$$

$$\text{Subject to } 3u_1 + 4u_2 + 8u_3 \leq 14$$

Where u_1, u_2, u_3 are integers

The computation of the program suggests that we have to cut out 2 chevrons and 1 beam to optimise the material output and the commercial value. For each log, the decision vector specifies which products have to be cut for a maximum material output and commercial value. Figure 3 gives an implementation example for a command list of 8 pieces.

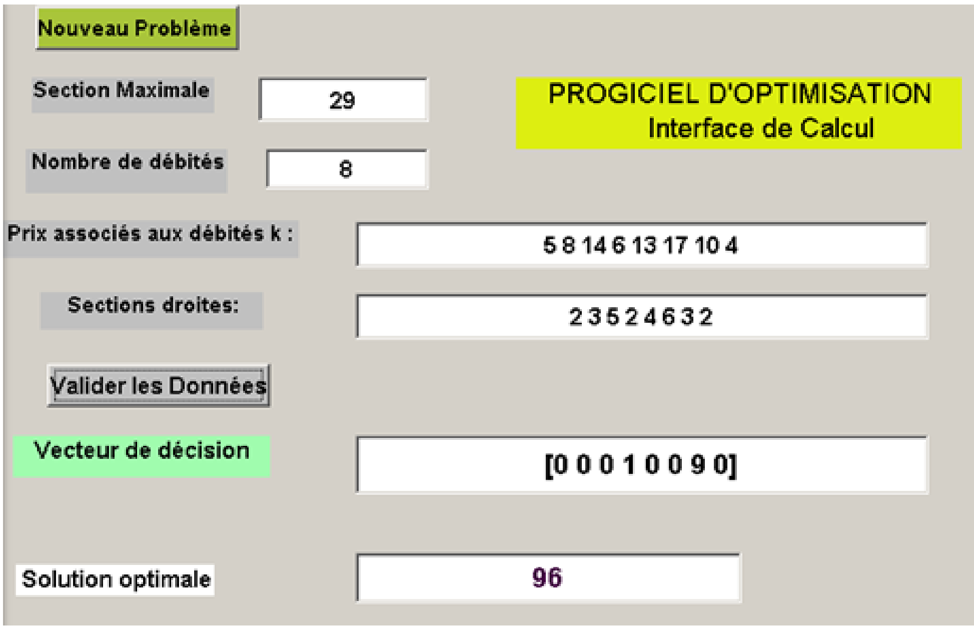


Figure 3. Implementation for a list of orders

We realise here that for a log with cross-section 29, the optimal solution is to have nine cuts of type 7 and one cut of type 4.

4.1 The cutting optimiser

In traditional sawmills the log carriage is driven by operators, who have the responsibility of orientating the log and to make a first open up (Best Opening Face) that later results to a first saleable product and equally to a cutting method on the whole log which in one way or the other optimises the final result. The work complexity of the log carriage relative to the operators and the high risk of material waste bring about a drop in production rate and a low efficiency in these companies.

Semi-modern sawmills are characterised by an automation of the movements of the log carriages. For these sawmills, adding to the automatic control of the carriage, they equally make use of a software tool for automation and cutting optimisation. This software integrated in a command system made up of a screen and a keyboard, works in the following way:

The optimisation program provides a cutting schedule. This program calculates the first position and the next positions depending on the memorised log dimensions and the thickness of the blade. The operator can call at any moment a program earlier installed or store the program in the memory. For example, to extract pieces of thickness 27 mm, the figure 4 below displays on the screen after programming the operations:

The automation of the cutting operation leads to an accelerated work and an increase in the volume of the cuts produced daily. The wasted ratio is equally reduced and the rejected cuts are usually due to programming errors or defects in the log. More than 70% of sawmills found in Cameroon are semi-modern. The optimisation software used by these sawmills present some deficiencies which are implicitly at the roots of our problem statement given above. These deficiencies are due to the following facts:

- The material output is not significant (30 to 35%),
- Ordering requires the intervention of an operator in decision making
- The software does not take into consideration the ordering list of the enterprise and the market prices in optimising of the cutting process.

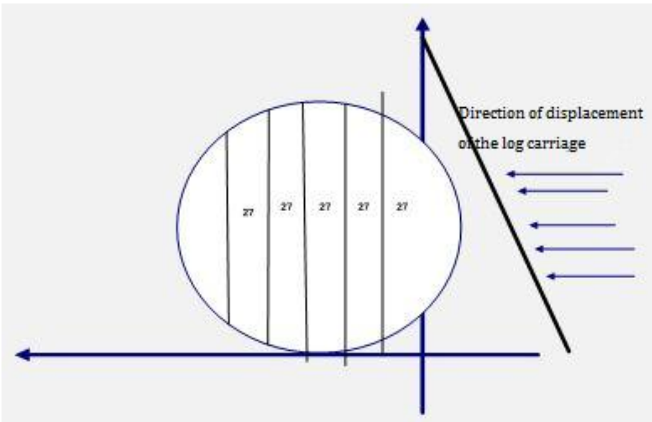


Figure 4. Cutting Optimisation

- Cutting is done uniquely with one of the cutting methods, whatever the operator's order.

- The software neither takes into consideration the real shape of the log, nor does it take into consideration the defects (nodes, rots …) on it. It deals only with the principal cross-section of the log. We run the risk of having much scrap.

The cutting optimiser system implemented in this work permits us not only to optimise the material output, but also fill the gaps indicated above subject to the constraints associated to the exploitation.

4.2 The command principle of the cutting optimiser

The optimisation system determines the optimal value of the exploitation parameters in a way so as to maximise the commercial value of the cuts. The command principle of the optimiser is presented in the diagram below:

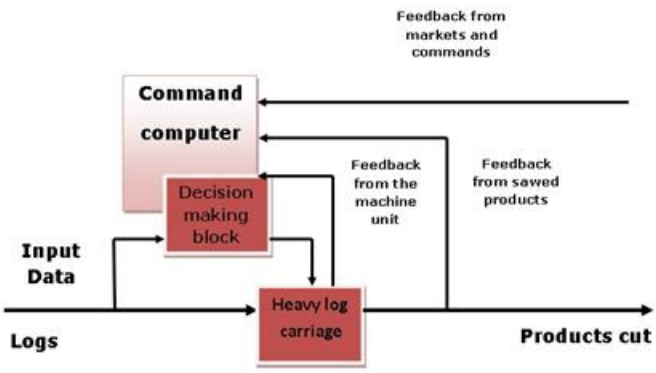


Figure 5. The command principle of the optimiser

At the input of the system (Figure 5), we have the log already shaped into standard shapes of particular lengths defined by the cutter. The length of each log varies depending on the order. At the output of our system (Figure 5), we obtain the cuts. The optimisation system for the log carriage has in addition devices of the semi-modern software (piloting and optimisation devices), a decision making block which receives data from the input (characteristic dimensions of each log), analyses them together with the data from the command computer and then takes a decision on the cutting method to be implemented. This decision is transmitted to the automaton that commands the rotational and translational movements of the carriage. The command computer receives at its input a feedback from the market (database on the prices of the cuts) and the commands received by the enterprise.

The form of the log of wood is generated by the geometric model described above. The precision and reliability of operations will enable us to increase the material output, productivity and the quality of the cuts produced independent of the wood type and the production type.

5 Conclusion

The purpose for this work was to develop a production optimising tool in primary conversion wood industries of Cameroon. This technological procedure enables enterprises to improve on the material output of the transformed wood and also on their profitability. It has been observed from this study that since the implementation of article 71(1) of the Law n°94/01 of 20 January 1994, prohibiting the exportation of timber, the primary conversion of wood is done locally and the cutting is mainly traditional (manual log carriages) and semi-modern (automated log wagons). The modelling of the real shape of the log enabled us to identify the input parameters to generate the log in real shape. The formulation of the optimisation problem assimilated to a knapsack problem was solved using the method of dynamic programming. That enabled us to set up an algorithm for optimum cutting of the log, alongside a cutting optimiser. This work has led to a possible solution for increasing material output, productivity, and quality of cuts, regardless the type of wood.

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