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**Optimizing recipes in hybrid continuous - batch
manufacturing systems: application in the multi-layer
plywood industry**

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Optimizing recipes in hybrid continuous - batch manufacturing systems: application in the multi-layer plywood industry

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Abstract

Many companies in the upstream segments of value chains combine continuous or semi-continuous processes with batch manufacturing. These companies face problems such as an increasingly high variety of final products being demanded by markets, a high incidence of raw materials in the cost structure and an intensifying international competition. This paper deals with the rationalization of recipes and bills of materials, which is one of the key problems encountered by such companies. The work uses an optimization approach and proposes Mixed-Integer Linear Programming models for the case of multi-layer plywood and blockboard manufacturing, developed in cooperation with one of the major Italian manufacturers. The preliminary results achieved to date are broadly aligned with the cost structure and recipes currently being used by the firm, but introduce substantial elements of improvement, especially in the reduction of the number of recipes.

Keywords: bill of materials, optimization, semi-continuous batch manufacturing.

1. Introduction

Students of operations management usually classify production systems according to Hayes and Wheelwright's well-known product / process matrix (Hayes and Wheelwright 1979(a), 1979(b)) which distinguishes between job shops, batch manufacturing systems, production lines and continuous flow manufacturing plants. Each of these production systems is usually viewed as distinct with respect to the others and is associated to a peculiar set of priorities, problems, tradeoffs and managerial approaches. Due to these significant differences, most authors dealing with manufacturing strategy tend to highlight the difficulties of managing a production system that crosses these boundaries. This is in accordance to the idea that Skinner (1969, 1974) pioneered more than 35 years ago, i.e. that factories should be "focused", and that companies should keep production operations exhibiting different properties separate from each another. Despite this common thought, evidence tells us that many firms do not have "focused factories" at all, because the obvious benefits deriving from "focusing" can be offset by technological and/or business reasons requiring the opposite choice (Ketokivi and Jokinen 2006). In the case of "unfocused factories", manufacturing systems are a hybrid between Hayes and Wheelwright's categories and lead to managerial problems that are not easy to decompose according to standard classifications.

"Unfocused" factories are quite commonly found in the upstream segments of value chains, where continuous or semi-continuous processes are vertically integrated with batch manufacturing processes. In

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such cases, the first process phases are generally continuous and are responsible for the preparation of intermediate components (generally deriving them from a low number of raw materials). The subsequent process phases are then dedicated to forming or assembling these intermediate components into a large variety of final products. For instance, in the cardboard industry the first phase deals with the preparation of boxes of standard sizes, while the second will lead to hot printing customer-specific designs on them. In plywood manufacturing, the first phase consists in peeling logs in thin veneers, while the second consists in assembling panels of varying thickness, structure and finishing. The economics of these two phases are markedly different. The former generally is capital intensive and has the aim of minimizing inefficiencies in the use of raw materials and production equipment. The latter is labour intensive and the major problems are connected to ensuring acceptable service levels to customers, despite high product variety, and without using high levels of inventory.

Among the major problems found in these companies, it is possible to mention an increasingly high variety of final products being demanded by markets, the high incidence of raw materials in the cost structure (Knopf *et al.* 1982) and an intensifying international competition that forces firms to reduce prices, design integrated production-distribution networks (Vila *et al.* 2006) and commit to high levels of customer service. These three simultaneous factors discourage the idea of “focusing” and, consequentially, separating the two phases. Such an approach would in fact forfeit the gains in efficiency and effectiveness that can potentially come from a closer integration of decision-making.

The rationalization of recipes and bills of materials (BOMs) is one of the aspects that most can benefit from this kind of integration, since it can help firms balance the tradeoffs that are typical of the two process phases. In fact, an optimized definition of bills of materials can at the same time increase efficiency in the upstream preparation of components and simplify downstream assembly. This kind of rationalization is generally highly needed, because intermediate components and end items are generally introduced and added over the years according to market opportunities, and companies hardly ever attempt to revise the entire set of their bills of materials. Such revision can be beneficial for optimizing direct production cost with respect to the many technical and economic tradeoffs that come in play. Moreover, it can reduce excessive variety in the bills of materials and the resulting inefficiencies in managing manufacturing operations.

Rationalization of BOMs can be performed at many different levels, depending on the impact on the system and the degrees of freedom that one wishes to deal with (see Table 1) . At the uppermost level, it is possible to have a complete revision (Type 1) ranging from the types of raw materials and going all the way down to the selection of profitable end items to be manufactured. This kind of optimization is

extremely large-scale, would have a very broad impact on the company and would require an impressive amount of data from upstream suppliers and from marketing. Type 1 optimization can therefore be thought to be of limited practical relevance. Slightly less ambitious approaches would consist in taking either raw materials or end items as givens, and optimizing all the rest (respectively Type 2 and 3 optimization). This would somewhat limit the amount of data required, but would still have a significant impact on either purchasing or marketing functions, something that firms not always are willing to accept. It is therefore possible to envisage more limited approaches, which limit their impact to the manufacturing function.

(Table 1)

In Type 4 optimization, raw materials and end items are taken as givens and both intermediate components and bills of materials are optimized. In Type 5 optimization, components are kept constant and optimization deals with bills of materials only.

This paper discusses Type 4 and 5 optimization problems with reference to the case of multi-layer plywood and blockwood manufacturing. Although this is a relatively easy problem type, we are not aware of other papers dealing with this type of problem neither in general, nor in the industry being considered. In fact, literature generally deals with “focused factories” and with the problem of process flexibility and end-item assortment. When focusing on process flexibility, bills of materials are usually kept fixed and used as constraints in the process (Hua *et al.* 2007). In other instances they are made flexible allowing for the substitution of items for one another while ensuring the smallest possible deviation from the default BOMs (Bala Ram *et al.* 2006) or having the selection of specific components dependent on external process or market data (Verwater-Lukzso and Keesman 1995). When the end-item assortment is considered, instead, the research is generally directed on modelling and managing modular or generative BOMs (van Ven and Wortmann 1992).

Our research has been developed in cooperation with one of the major Italian plywood and blockboard manufacturers, and we believe that the model could be applicable beyond this case study and in other industries sharing similar problems. Being one of the first attempts to tackle this problem, and in order to ensure industrial applicability, the paper deals with the two simpler types of optimization problems defined above. At first, a Type 5 optimization model will be discussed for both plywood and blockwood, followed by a Type 4 optimization for the case of blockwood, in which the definition of the right “intermediate components” seemed to be more critical.

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Section 2 of the paper presents the plywood manufacturing process and the main problems associated to it. Math programming models for dealing with the two rationalization problems are then presented in Section 3, and computational results will be discussed in Section 4.

2. The plywood manufacturing process

Plywood [7] is an engineered wood that is widely used for a number of applications, from construction to furniture manufacturing, both for indoor and outdoor applications. Apart from allowing a more efficient use of raw material, plywood exhibits better behaviour than ordinary wood with respect to cracking, shrinkage, twisting/warping, and strength. Plywood (Figure 1, to the left) is a sandwich of thin sheets of wood (generally poplar or fir), called *plies* or *veneers*, glued together.

Plywood manufacturers often also produce blockboard panels (Figure 1, right hand side), in which part of the panel thickness is made up of softwood strips. Blockboard is a lower-cost product, and exhibits a slightly lower quality than plywood.

(Figure 1)

The production process for plywood and blockboard panel manufacturing is sketched in Figure 2. The first phase of plywood manufacturing deals with producing plies, or veneers. The logs are first prepared by cutting them to a specified length, stripping them from bark and conditioning them with steam in order to facilitate peeling. After that, they are peeled to the desired thickness (from about 1 to 4 mm). Modern plants usually perform this task by using highly automated lathes that take laser scans of the log profile, which is evidently far from being a perfect cylinder, and identify the rotation axis that optimizes the usage of material. In theory it would be possible to produce veneers of any desired thickness, but it is common practice to produce a discrete number of variants from which plywood panels will later be composed. The continuous veneer resulting from the peeling process is then cut to sheets of a standard length, which are dried in ovens, inspected and finally stocked according to their grade (or quality level).

In the second phase of the process, plies are collected from inventory according to the desired bill of materials, glued, assembled in sandwiches and hot pressed. The resulting product is then ground in order to bring it to the desired thickness and within tolerances, squared and trimmed, and placed in the finished goods inventory.

Blockboard manufacturing follows a similar process, but strips used as the core of the panel are either sourced from other companies or sawn from logs in another department of the same company. Again, it is possible to obtain strips of any thickness, but companies tend to define a discrete number of strip thicknesses on which to base their end-item BOMs.

(Figure 2)

2.1 *Optimizing bills of material for plywood manufacturing*

Plywood panels are produced in many variants according to thickness and quality, which is associated to the grade of the exterior veneers. Defining bills of materials for plywood therefore requires to determine the *number*, *thickness* and *grade* of the plies to be used to assemble each panel variant. This problem faces a number of technical constraints (that will be detailed in Section 3, when introducing the optimization models) and the following main tradeoffs.

- (1) Producing plies of many different thicknesses requires greater effort in the peeling phase, but makes it easier to assemble a sandwich that will be close to the final thickness. This allows to minimize the waste of material and the time associated to the grinding phase. On the opposite, using fewer ply variants increases efficiency in peeling but increases raw material waste.
- (2) Using many thin plies also helps getting close to the desired thickness, but these will take more time to be produced during the peeling phase and to be assembled. On the opposite, using a low number of thick plies significantly increases efficiency of the peeling and assembly phases, but leads to wasting material during finishing.
- (3) As mentioned, peeling produces plies of different grades (quality levels). Since the percentage of high-quality veneers is relatively low, the best plies should be used for the outer layers of the end items of corresponding quality, while the plies of inferior quality should be used for the inner part of the sandwich structure. Of course, it is possible to “downgrade” high-quality veneers and use them in the outer layers of low-quality panels or even for inner layers, but this would lead to a suboptimal use of raw material.
- (4) It would be advisable to make high-quality exterior veneers as thin as possible, in order to optimize the usage of this scarce input. However, this would increase the risk of grinding the entire thickness of exterior veneers away during the finishing phase, when the panel is brought to its nominal size. Therefore, exterior veneers cannot be thinner than the overall tolerance of the sandwich structure.

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6 Moreover, thin exterior veneers must be placed on a sandwich that gets very close to the final
7 thickness. In turn, this means that the sandwich must be composed by using a high number of thinner
8 plies, which adds to its cost.
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13 In the current circumstances, BOMs used by the firm have been composed over the years based on
14 experience and practical considerations, without attempts to perform an overall optimization that may
15 lead to a more efficient use of materials and production resources. These aspects are generally taken into
16 account implicitly and “on the fly”, since each end item is associated to a number of alternative BOMs.
17 The materials planner then chooses the BOM to be used at the moment, depending on the current
18 availability of materials and on the saturation level of the production equipment. This way, besides using
19 a potentially suboptimal set of BOMs, the company is forced to continuously depend on the experience
20 and know-how of an individual, and is hindered from using computer-based scheduling tools for
21 managing operations on a short-term basis.
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25 Optimizing BOMs means finding a reduced set of recipes (if only one is impossible) for each end
26 item, given the available components in terms of types of plies and strips and the end items that have to
27 be produced. In this context, a recipe defines the structure of the plywood in terms of number of
28 component plies and the thickness of each. These sets of recipes should be the “best” in order to reduce
29 material and inventory costs while satisfying market demand, and the problem to find them is a Type 5
30 problem, i.e., a *basic manufacturing-level revision*.
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40 **2.2 Revising the bill of materials for blockboard panels**

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42 The case of blockboard panel bill of materials is quite similar to plywood, though with the difference that
43 the structure of each end item (i.e. the number of strip cores and of veneers) is specified up front. What
44 therefore remains to be determined and optimized is the thickness of each of these elements. Since
45 plywood and blockboard production share the same veneer manufacturing and assembly facilities, it is
46 quite straightforward that BOM optimization should be jointly performed for both product families. In
47 fact, this is the objective of the first model to be presented in the following Section 3.
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51 As already mentioned, the company uses a standardized set of strip thicknesses. Because of this, the
52 degrees of freedom in composing each blockboard BOM will be relatively limited. In a panel of given
53 thickness and structure the choice of the core strips to be used will be somewhat forced, and the final size
54 will be achieved by more or less easily combining veneers of different thicknesses and grades. This
55 argument has raised the suspicion that this pre-defined set of strip thicknesses could worsen the quality of
56 the solution and should therefore be reassessed. So, it has been decided to formulate a second
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optimization problem in which strip thickness is not be to selected from a predefined set, but is a decision variable in its own right. This is a Type 4 problem, i.e., a *complete manufacturing-level revision*, in which the optimization of BOMs is carried out together with the intermediate components (strips thickness, in this case) optimization.

3. Mathematical formulation of the problem

In this section we present a MILP formulation of the problems described in Section 2.1 and 2.2. MILP formulations are quite often used in medium-long term optimization problems, especially in production planning, even in complex environments (for example Kanyalkar and Adil (2005), Omar and Teo (2007)). The relatively limited time pressure that characterizes such problems (unlike the case of short term or real time problems) allows for an optimization approach that naturally requires significant computational effort. An alternative to optimization could be the development of a constructive heuristic. However, this would be very difficult because of the complexity of the problem, which is characterized by many elements and tradeoffs between costs, volume and production yields. Developing a rule-based heuristics capturing the knowledge of the skilled engineer that currently performs this task has also been attempted, but has proved impractical. By the way, though it is not difficult to generate feasible solutions to the problem, these are often far from optimal and lead to excess inventory and shortage costs (as will be explained in Section 4.1).

At first, we present the problem of optimizing the recipes on the basis of the available components. Afterwards, the objective has been to rationalize the number and the type of components themselves (though this has been limited to softwood strips used in blockboard panels). In practice, these two steps will have to be performed iteratively, i.e., once the number and thickness of components have been rationalized, it is possible to optimize recipes again, on the basis of these new components. We start by presenting the model for recipe optimization, and then we show how to modify it in order to deal with the second problem. Before entering into details of the model, we define the sets, parameters and the variables used.

Sets:

- i : types of veneers;
- z : types of softwood strips;
- j : types of multi-layer plywood;
- l : types of blockboard panels;

- k : combined quality levels of end products (plywood and panels).

Each multi-layer plywood or blockboard panel has two external sheets, which must have the same thickness but can have different quality. Combined quality levels summarize with a single attribute the quality of both the external sheets. In our case study, for example, external sheets can have 4 different qualities (e.g., 1, 2, 3, 4) that results in 10 combined quality levels (e/g., 1/1, 1/2, 1/3, 1/4, 2/2, 2/3, 2/4, 3/3, 3/4, 4/4).

Parameters:

- p_i : thickness of veneer i . Note that thickness is what mainly characterizes veneers. In practice, veneer i is the one with thickness p_i , and the same will holds for multi-layer plywood and strips. Thickness is measured in mm.
- s_j : thickness of multi-layer plywood j (in mm).
- α_j : security tolerance due to the finishing phase of multi-layer plywood j . This is necessary because the assembled plywood panel will be ground to the final thickness.
- CP_i : production cost of veneer i . It is given in Euro/m².
- VP_{jk} : annual demand for multi-layer plywood j of quality k . This parameter is measured in m² since thickness is an attribute of the plywood itself, as already discussed. The index k is linked to the quality of the external veneers.

When a log is stripped, and peeled to veneers, these will have different qualities that can make them suitable for external layers, for internal layers to be glued, and for internal layers not to be glued. Moreover, sheets to be used externally are further differentiated in quality levels. Since the percentage of each quality level is a characteristic of veneer production, we have:

- β^F_k : percentage of veneer usable for external layers of quality k ;
- β^I : percentage of veneer usable for internal glued layers;
- β^A : percentage of veneer usable for internal non-glued layers.

For blockboard panels we have parameters similar to the ones introduced above for multi-layer plywood:

- g_z : thickness of softwood strip z (in mm).

- r_l : thickness of blockboard panel l (in mm).
- η_l : security tolerance in the finishing phase of blockboard panel l .
- CQ_z : production cost of softwood strip z in Euro/m².
- VQ_{lk} : annual demand for blockboard panel l of quality k (in m²).

Blockboard panels of a given thickness have a predefined structure and the task is to determine the optimal thickness of each element, given the composition currently used by the firm. Moreover, there are constraints limiting the percentage of overall thickness that can be taken up by strips and by veneers. This information is captured by the following parameters:

- n_{lk} : number of softwood strips in blockboard panel l of quality k ;
- a_{lk} : number of internal non-glued veneers in blockboard panel l of quality k ;
- h_{lk} : number of internal glued veneers in blockboard panel l of quality k ;
- $\gamma_{min,l}$: minimum percentage of softwood strips in panel l ;
- $\gamma_{max,l}$: maximum percentage of softwood strips in panel l .

Variables:

- x_{ijk} : binary variable assuming value 1 if sheet i is used as external layer in plywood j of quality k .
- I_{ijk} : number of single glued veneers of type i used in multi-layer plywood j , quality k .
- A_{ijk} : number of single non-glued veneers of type i used in multi-layer plywood j , quality k .
- IC_{ijk} : number of pairs of glued veneers of type i used in multi-layer plywood j , quality k .
- AC_{ijk} : number of pairs of non-glued veneers of type i used in multi-layer plywood j , quality k .
- Y_i : availability of veneers i (in m²).
- YF_{ik} : availability of veneers i used for external layer of quality k (in m²).
- YI_i : availability of veneers i used for internal glued layer (in m²).
- YA_i : availability of veneers i used for internal non-glued layers (in m²).
- ZI_{ijk} : binary variable assuming value 1 if veneer i is used as internal glued layer in plywood j , quality k .
- ZA_{ijk} : binary variable assuming value 1 if veneer i is used as an internal non-glued layer in plywood j , quality k .
- y_{ilk} : binary variable assuming value 1 if veneer i is used as an external layer in panel l of quality k .
- D_{ilk} : number of single glued veneers of type i used in blockboard panel l , quality k .

- E_{ilk} : number of single non-glued veneers of type i used in blockboard panel l , quality k .
- DC_{ilk} : number of pairs of glued veneers of type i used in panel l , quality k .
- EC_{ilk} : number of pairs of non-glued veneers of type i used in panel l , quality k .
- N_{zlk} : number of single softwood strips of type z used in blockboard panel l , quality k .
- NC_{zlk} : number of pairs of softwood strips of type z used in panel l , quality k .
- ZD_{ilk} : binary variable assuming value 1 if veneer i is used as internal glued layer in panel l , quality k .
- ZE_{ilk} : binary variable assuming value 1 if veneer i is used as internal non-glued layer in panel l , quality k .

Model 1:

$$\min \sum_i CPY_i + \sum_z CQ_z \sum_{l,k} VQ_{lk} (N_{zlk} + 2NC_{zlk}) \quad (1)$$

s.t.

$$\sum_i (I_{ijk} + 2IC_{ijk}) - 1 = \sum_i (A_{ijk} + 2AC_{ijk}) \quad \forall j, k \quad (2)$$

$$\sum_i (I_{ijk} + A_{ijk}) = 1 \quad \forall j, k \quad (3)$$

$$I_{ijk} + IC_{ijk} \leq 10000ZI_{ijk} \quad \forall i, j, k \quad (4)$$

$$A_{ijk} + AC_{ijk} \leq 10000ZA_{ijk} \quad \forall i, j, k \quad (5)$$

$$\sum_i ZI_{ijk} = 1 \quad \forall j, k \quad (6)$$

$$\sum_i ZA_{ijk} \leq 2 \quad \forall j, k \quad (7)$$

$$\sum_i (2x_{ijk} + A_{ijk} + 2AC_{ijk} + I_{ijk} + 2IC_{ijk}) p_i \geq 1.05s_j \quad \forall j, k \quad (8)$$

$$\sum_i (2x_{ijk} + A_{ijk} + 2AC_{ijk} + I_{ijk} + 2IC_{ijk}) p_i \leq 1.14s_j \quad \forall j, k \quad (9)$$

$$\sum_i x_{ijk} = 1 \quad \forall j, k \quad (10)$$

$$\sum_i x_{ijk} p_i \geq 0.05s_j + \alpha_j \quad \forall k \quad (11)$$

$$YF_{ik} = \beta_k^F Y_i \quad \forall k \quad (12)$$

$$YI_i = \beta^I Y_i \quad \forall i \quad (13)$$

$$YA_i = \beta^A Y_i \quad \forall i \quad (14)$$

$$\sum_i (D_{ilk} + 2DC_{ilk}) = h_{lk} \quad \forall l, k \quad (15)$$

$$\sum_i (E_{ilk} + 2EC_{ilk}) = a_{lk} \quad \forall l, k \quad (16)$$

$$\sum_z (N_{zlk} + 2NC_{zlk}) = n_{lk} \quad \forall l, k \quad (17)$$

$$\sum_i (D_{ilk} + E_{ilk}) + \sum_z N_{zlk} = 1 \quad \forall l, k \quad (18)$$

$$D_{ilk} + DC_{ilk} \leq 100ZD_{ilk} \quad \forall i, l, k \quad (19)$$

$$E_{ilk} + EC_{ilk} \leq 100ZE_{ilk} \quad \forall i, l, k \quad (20)$$

$$\sum_i ZD_{ilk} \leq 2 \quad \forall l, k \quad (21)$$

$$\sum_i ZE_{ilk} \leq 2 \quad \forall l, k \quad (22)$$

$$\sum_i (2y_{ilk} + E_{ilk} + 2EC_{ilk} + D_{ilk} + 2DC_{ilk}) p_i + \sum_z (N_{zlk} + 2NC_{zlk}) g_z \geq 1.03r_l \quad \forall l, k \quad (23)$$

$$\sum_i (2y_{ilk} + E_{ilk} + 2EC_{ilk} + D_{ilk} + 2DC_{ilk}) p_i + \sum_z (N_{zlk} + 2NC_{zlk}) g_z \leq 1.10r_l \quad \forall l, k \quad (24)$$

$$\sum_i y_{ilk} = 1 \quad \forall l, k \quad (25)$$

$$\sum_i y_{ilk} p_i \geq 0.03r_l + \eta_l \quad \forall l, k \quad (26)$$

$$\sum_z (N_{zlk} + 2NC_{zlk}) g_z \geq \gamma_{\min, l} r_{lk} \quad \forall l, k \quad (27)$$

$$\sum_z (N_{zlk} + 2NC_{zlk}) g_z \leq \gamma_{\max, l} r_{lk} \quad \forall l, k \quad (28)$$

$$\sum_{j,k} (A_{ijk} + 2AC_{ijk}) VP_{jk} + \sum_{l,k} (E_{ilk} + 2EC_{ilk}) VQ_{lk} \leq YA_i \quad \forall i \quad (29)$$

$$\sum_{j,k} (I_{ijk} + 2IC_{ijk}) VP_{jk} + \sum_{l,k} (D_{ilk} + 2DC_{ilk}) VQ_{lk} \leq YI_i \quad \forall i \quad (30)$$

$$\sum_{j,k} 2x_{ijk} VP_{jk} + \sum_{l,k} 2y_{ilk} VQ_{lk} \leq YF_{ik} \quad \forall i, k \quad (31)$$

Equation (1) represents the objective function, i.e., the minimization of the overall cost of producing sheets and strips. For sheets we use aggregate variables Y_i which represent the square meters of sheets of type i produced, while for strips the square meters produced are computed by multiplying the volume of produced panels times the total number of strips z used. The number of strips and sheets is partitioned in “single elements” and “pairs”. This is due to the fact that, apart from the central element, all sheets and strips used in an end item must be symmetrical and with equal thicknesses. In multi-layer plywood, the

central elements can be a glued or a non-glued sheet, while in blockboard panels it can be also a strip; all the other elements will be paired. This technical aspect is assured by constraints (3) for plywood and (18) for panels. The same symmetry must hold for external sheets and this is guaranteed by constraints (10) and (26), that assure a single type of external sheet is chosen for each final product.

Since for multi-layer plywood no structure is pre-defined, for each plywood end item j we must determine both the number of sheets and their thickness. This is subject to the constraint that the number of non-glued sheets must be always one unit smaller than the number of glued veneers, as stated by equations (2).

Constraints from (4) to (7) are used to represent the technological need to have, in each multi-layer plywood, at most a single type of glued and at most two types of non-glued veneers. If this were not the case, the assembly process would be very complicated to perform and require more space for keeping many different types of veneers.

Equations from (19) to (22) model a similar need for blockboard panels, for which, however, it is possible to have at most two types of sheets both for glued and non-glued.

For multi-layer plywood, constraints (8) and (9) are used to define the final thickness as the sum of sheets thicknesses. Note that the assembled product must have a thickness bigger than the nominal s_j . Equation (11), instead, is used to guarantee that the first layer is at least as thick as the minimum difference between s_j and the real thickness plus the security tolerance for grinding. This is necessary to avoid that the finishing process eliminate the first layer completely. Equations (23), (24) and (25) are the analogous for blockboard panels.

Constraints from (12) to (14) define how many square meters of sheets of each quality level are available, given the total quantity produced Y_i . These variables are used in constraints (29), (30) and (31), which represent capacity constraints: for each type of sheets, it is not possible to use more than what is available.

Finally, equations (15), (16) and (17) give the panels structure in terms of glued and non-glued sheets and strips respectively. Constraints (27) and (28) assure the percentage of strips is in-between the given limits.

This model can be easily modified to represent the problem of rationalizing softwood strips for blockboard production. First of all, set z and parameters g_z , CQ_z , disappear, since the number of possible strip thicknesses is not fixed any longer. Moreover, since there must be symmetry also for strips in panels, and since their thickness is now a decision variable, we use parameters nc_{lk} representing the number of

pair of strips that must be present in panel l (combined quality k), while n_{lk} defines, differently from before, the number of single strips in panel l (combined quality k). To evaluate the cost of a strip, we use a parameter b , representing the unit cost per mm of thickness. Finally, binary variables N_{zlk} and NC_{zlk} are redefined as N_{lk} and NC_{lk} , continuous variables representing the thickness of single strips and pairs of strips, respectively, used in the structure of panel l (combined quality k). All the other variables, parameters and sets remain the same as in the model just discussed.

Model 2:

$$\min \sum_i CPY_i + b \sum_{l,k} VQ_{lk} (n_{lk} N_{lk} + 2nc_{lk} NC_{lk}) \quad (1 - \text{bis})$$

$$s.t. \quad (2) - (16), (19) - (22), (25), (26), (29) - (31)$$

$$\sum_i (D_{ilk} + E_{ilk}) + n_{lk} = 1 \quad \forall l, k \quad (18 - \text{bis})$$

$$\sum_i (2y_{ilk} + E_{ilk} + 2EC_{ilk} + D_{ilk} + 2DC_{ilk}) p_i + n_{lk} N_{lk} + 2nc_{lk} NC_{lk} \geq 1.03r_l \quad \forall l, k \quad (23 - \text{bis})$$

$$\sum_i (2y_{ilk} + E_{ilk} + 2EC_{ilk} + D_{ilk} + 2DC_{ilk}) p_i + n_{lk} N_{lk} + 2nc_{lk} NC_{lk} \leq 1.10r_l \quad \forall l, k \quad (24 - \text{bis})$$

$$n_{lk} N_{lk} + 2nc_{lk} NC_{lk} \geq \gamma_{\min, l} r_{lk} \quad \forall l, k \quad (27 - \text{bis})$$

$$n_{lk} N_{lk} + 2nc_{lk} NC_{lk} \leq \gamma_{\max, l} r_{lk} \quad \forall l, k \quad (28 - \text{bis})$$

In practice, while in the previous model we selected strips from a predefined set z , we now decide the thickness of each strip needed in the composition of a given blockboard panel. Note that this model will select a unique thickness for all pairs of strips and a, possibly different, unique thickness for every single strip on a panel. For single strips this is not a problem, since in each panel, for symmetry reasons, there is at most a single strip. In case of pairs, instead, our modelling choice prevents using different thickness for pairs in the same panel. If on the one hand this might seem a strong restriction, on the other, and in first approximation, it could be used to try and rationalize recipes even further while we rationalize softwood strips.

4. Computational results

4.1 Recipes optimization

We have applied the MILP model for recipe optimization to the industrial case study that included the entire production portfolio of the participating company. The model was characterized by about 55000

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variables (54000 of which integer or binary) and 17000 constraints, has been developed using OPL Studio 3.5 and solved with CPLEX 10.0 on a Pentium (R)4 (RAM: 2 GB, Clock: 3.0 GHz).

In about 200 seconds we were able to find a feasible solution with optimality gap (computed by CPLEX as $100 \times (\text{Best solution} - \text{Lower bound}) / (\text{Best solution})$) of 0.05%. However, we were not able to close the gap further in 3600 seconds.

The value of the minimum production cost is aligned with the current manufacturing cost estimated by the firm (actual values cannot be disclosed because of confidentiality issues). In relative terms, the optimized production cost is 92% of the costs recorded by the firm's accounting system. Of course, the comparison is not perfect since the accounting system is likely to record costs in a more sophisticated way than in the model. The substantial elements of improvement our model introduces are mainly due to the reduction in the number of different recipes used for assembling a given final product, and in a better use of intermediate sheets. This is due to the fact that optimization aligns bills of materials to actual demand and to the different quality levels produced in the peeling process. As a matter of fact, the un-optimized bills of materials being currently used have historically led the company to produce veneers in a somewhat unbalanced way, with shortage of some sheets and excess inventory of other ones. Shortages and excess inventory can have a huge impact on costs. In fact, wood cannot be kept for too much time in inventory (veneers can bend due to humidity), while shortages lead to ordering the production of unavailable sheets, thus postponing order satisfaction. Since these costs are not usually accounted for, we suppose that these improvements will in the end lead to a substantial improvement in the operational performance of the firm, something that is being confirmed by the usage of the model in the company.

Table 2 reports part of the solution for the recipes used in multi-layer plywood, while in Table 3 we present part of the recipes found for the 3-layers, 1-strip blockboard panels (we cannot report the complete solution for plywood and panels because this would require too much space, adding nothing to the content of the paper).

(Table 2)

In Table 2, column *nth*, *rth* and *layers* contain respectively the nominal thickness (in mm) of the plywood, the real thickness (in mm) due to the assembling of the various layers, and the number of layers used to assemble the plywood. The other columns contain the number of used veneers and their type (*e* refers to external sheets, *g* for internal glued veneers and *ng* internal non-glued veneers) for each of the

available type in terms of thickness (remember, in fact, that the feasible thickness of sheets and strips are given). It is possible to note how a same plywood end item can be assembled by using several recipes for assembly, in order to better match the capacity constraints on the available material (constraints (29), (30) and (31) in the formulation). For example, the 3-layer plywood of nominal thickness 4.0 mm can be assembled using 2 external sheets of 1 mm and 1 internal glued veneer of 2.2 mm, or 2 external and 1 internal glued sheets all with thickness of 1.4 mm, or 2 external sheets of 1.7 mm and 1 internal glued veneer of 1 mm. The first two recipes lead to a real thickness of 4.2 mm and the last recipe to a real thickness of 4.4 mm.

(Table 3)

Similar indications are contained in Table 3. In this case, since blockboard panels have a predefined structure, we already know how many strips, glued and non-glued sheets are used for assembling. For this reason, we just need to report the thickness found in the solution. In case of 3-layers, 1-strip panels, it is known that there will be an internal strip and two external non-glued layers. This is why the *glued veneers* column is empty, and no number, except the thickness value, is reported in columns *strip* and *non-glued* column. Columns *nth* and *rth* again contain the nominal and the real thickness of the panel. To give an example, 3-layers, 1-strip panel of nominal thickness 15.0 mm can be assembled by using a strip of 10.5 mm and two non-glued sheets of 2.6 mm, or using a strip of 12.0 mm and two non-glued sheets of 2.2 mm. The real thicknesses are different (15.7 mm in the first case, 16.4 in the second), but both respect the requested tolerance (constraints (23) and (24) in the model).

4.2 Robustness issues

Since demand values are not deterministically known at the planning time, but they are just a forecast, it is important to determine the behaviour of the solution found by our approach, both in terms of objective function value robustness and in terms of “optimal recipes” robustness.

The first issue (i.e., objective function value robustness) represents the cost increase incurred if the demand changes, but the recipes used are the ones found on the basis of demand forecasts. The second issue, instead, measures how many recipes we should change, in order to achieve a newly optimal solution, if demand changes with respect to forecasts.

Since we are dealing with a MILP, and the classical sensitivity analysis used for LP cannot be performed, and the typical way to evaluate sensitivity therefore is to perturb some parameters (in our case

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demands, since costs are well assessed elements in the firm) and see their impact on performance. In our case, on cost increase and number of changed recipes.

In order to investigate the robustness of our model, we altered the annual demand data in order to generate 40 different scenarios. The scenarios are generated by drawing demands from a uniform distribution $U(A, B)$, where A and B are respectively $0.8*VP$ and $1.2*VP$, in case of multi-layer plywood, and $0.8*VQ$ and $1.2*VQ$, in case of blockboard panels.

We solved each scenario with the model presented in Section 3, terminating the solution process after 20 minutes of CPU time. The results over the 40 scenarios are reported in Table 4. Column *Optimality gap* and *Recipes change* show the changes resulting from the optimization run under perturbed demand with respect to the solution coming from the base demand scenario. They respectively provide information on the way with which changes in demand affect the quality of the solution when this is stopped after 20 minutes of CPU time (average, maximum and minimum optimality gap) and the technological solutions (average, maximum and minimum percentage of recipes changed). Finally, column *Cost increase* reports the average, maximum and minimum percentage cost increase if we keep on using the solution found in Section 4.1 (which is optimal under the base demand scenario) with the perturbed demands. In this case the recipes are kept the same, the usage of veneers and softwood strips of each type follows the new demand and the resulting total cost is of course greater than the optimized one.

(Table 4)

The values in Table 4 show that the solution found by the model is quite robust both in terms of objective function value and in terms of recipes, at least when changes in demand remain within $\pm 20\%$. The optimality gap is quite low (as it was in the base scenario) and, despite the percentage of recipes that should change is 12.2% (and 18.3% at the maximum), if one chooses not to change them at all, the cost increase is negligible (0.06% on average and never goes above 0.11%).

We also experimented other demand scenarios, whose results are reported in tables 5 and 6. The experiments are of the same type presented in Table 4, but with A and B respectively equal to $0.5*VP$ and $1.5*VP$ (and $0.5*VQ$ and $1.5*VQ$) for Table 5 (i.e., demand perturbations within $\pm 50\%$) and $0.2*VP$ and $1.8*VP$ (and $0.2*VQ$ and $1.8*VQ$) for Table 6 (i.e., demand perturbations within $\pm 80\%$).

(Table 5)

(Table 6)

From the results reported in tables 5 and 6 it is possible to notice that values of optimality gap (for a 20 minute CPU solution) are aligned to those of Table 4, which tells us that for a wide range of demand scenarios the model does not change its properties with respect to computational tractability. However, the solution of the unperturbed model becomes much weaker in terms of cost increase and recipe change robustness. If demands are allowed to vary up to 50% of the forecasted values, the average cost increase is 3.40% (with a maximum of 5.71%), while the percentage of recipes that should change in order to reach optimality is 39.7% on average (52.4% in the worst case). If the range of variation reaches 80%, the cost increase becomes 8.52% on average (maximum of 14.30%), while the average percentage of recipe changes is 70.4% (maximum of 91.1%). These results are expectable and support the validity of the proposed approach since they show that recipes should not be developed only with respect to technological terms but also according to demand. At the same time, solutions developed by taking technological constraints and demand data are quite robust under small variations of demand (up to $\pm 20\%$).

The values in tables 5 and 6 are also useful to understand that the key factor in recipe creation is the matching among market demand and process yields, especially in terms of quality. The model solutions suggest that the best way to cut sheets is to maximize the matching with given demand, i.e., reducing the total amount of wood being cut and hence veneers and strips in unused inventory. When demand is very different from those used in the base scenario, the available components will not match demand any longer, leading either to a huge increase in costs or requiring an high number of changes. It is clear that if there were no quality and yield problems, it would be possible to cut veneers of any thickness and compose any end product without caring about the most appropriate matching.

4.3 Strips thickness optimization

By using the modified version of the model, we dealt with the problem of determining the optimal thickness of strips used in the assembly of blockboard panels. As explained in Section 2.2, the firm was interested in knowing if using different strip thickness could lead to a better use of the sheets, that are the common components among plywood and blockboard panels.

The results are quite interesting. The number of different thicknesses generated by the model was 35% greater than the number currently used in the firm. This is reasonable, since the model leads to generate a “best” thickness for each panel without any penalty attached to the increase of variety. However, if we look at the thickness values, we can notice that many of them are very close to each other, and this can be used for reducing their number to a smaller set of values.

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In Figure 3, we plot the annual demand per each of the strip thickness values found by the model. This can be used to aggregate thickness values that are close to each other, by substituting the less requested thickness values with the closest value with high demand.

We noticed that the values found by the model have smaller values than the thicknesses used by the firm; in fact the model suggests strip thickness ranging from 8 mm to 22.7 mm, while the strips currently used are in the range (10 mm, 27.6 mm).

The aggregation of values and the re-iteration of the recipe optimization model with these new strip thickness values is an on-going work being carried out in cooperation with the firm, and for this reason no further results are available at the moment we are writing.

5. Conclusion

In this paper we presented a structured approach for dealing with a typical problem of hybrid continuous-batch manufacturing systems in which the continuous production of components is integrated with a discrete assembly of end items. Specifically, we studied the case of multi-layer plywood and blockwood manufacturing in cooperation with one of the major Italian manufacturers, and we tackled the problem of recipe optimization and bill of material rationalization. The problem was modelled with a mathematical programming formulation and solved with a commercially available solver.

(Figure 3)

Our results, although not yet complete from an industrial viewpoint, are encouraging since are both in line with the current performance and behaviour of the firm, but introduce important elements such as the possibility to reduce the number of used recipes and the variety of some components.

Moreover, our model turned out to be also robust both in terms of objective function value and of selected recipes. This is an important result, since annual demand is only forecasted but – of course – cannot be known with certainty.

Other developments are possible and currently being investigated, thanks to the flexibility of the proposed models, that are quite easily adaptable and applicable beyond this case study. Specifically, it is possible to envisage both adaptations to other industries sharing similar problems, as well as extensions of the mathematical programming models to more complex problems (specifically, of Type 2 and Type 3) that can typically be found in “unfocused” factories.

As mentioned above, the key contribution of the model is to match demand for end items with the yields of the primary peeling (component manufacturing) process. This problem can be found in other industries beyond woodworking, wherever a primary process is subject to varying yields and the resulting components have to be “assembled” and processed in order to lead to final products. For instance, in the food processing industry vegetables come in different qualities associated to shape, size and color. Depending on their quality, these can be sold as such, they can be ground or cut in smaller or larger bits and, finally, they can be cooked alone or in combination with other vegetables and then packaged, canned or frozen.

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Table 1. Summary of potential optimization problems in “unfocused” manufacturing systems.

Type of problem	Raw materials	Intermediate components	Recipes and Bills of materials	End items
Type 1 - Complete revision	O	O	O	O
Type 2 - Near-complete revision reaching market level	G	O	O	O
Type 3 - Near-complete revision reaching purchasing	O	O	O	G
Type 4 – Complete manufacturing-level revision	G	O	O	G
Type 5 - Basic manufacturing-level revision	G	G	O	G

O = Optimized, G= Given

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Table 2. Multi-layer plywood recipes.

PLYWOOD			VENEERS					
nth	rth	layers	1.0 mm	1.4 mm	1.7mm	2.2 mm	2.6 mm	3.6 mm
3.0	3.4	3	2e	1g				
4.0	4.2	3	2e			1g		
	4.2	3		2e + 1g				
	4.4	3	1g		2e			
5.0	5.4	3	1g			2e		
6.0	6.6	3		1g			2e	
7.0	7.4	3				1g	2e	
	7.8	3					2e + 1g	
9.0	9.8	3					1g	2e
12.0	12.6	5		2g			1ng	2e
	12.8	5	2g					2e + 1ng

Table 3. Blockboard panels recipes.

3-layers 1-strip PANELS		STRIPS	non- glued VENEERS	glued VENEERS
nth	rth	thickness	thickness	thickness
13.0	13.4	10.0	1.7	
14.0	14.5	11.1	1.7	
	15.2	10.0	2.6	
15.0	15.7	10.5	2.6	
	16.4	12.0	2.2	
16.0	17.2	10.0	3.6	
	17.2	12.0	2.6	
17.0	17.7	10.5	3.6	
	18.2	13.8	2.2	
	18.3	11.1	3.6	
18.0	19.2	12.0	3.6	
	19.8	12.6	3.6	

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Table 4. Results over 40 demand scenarios with perturbations within 20%.

	Optimality gap	Cost increase	Recipes change
average	0.08%	0.06%	12.2%
maximum	0.21%	0.11%	18.3%
minimum	0.00%	0.0001%	5.2%

Table 5. Results over 40 demand scenarios with perturbations within 50%.

	Optimality gap	Cost increase	Recipes change
average	0.06%	3.40%	39.7%
maximum	0.25%	5.71%	52.4%
minimum	0.01%	0.19%	12.5%

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Table 6. Results over 40 demand scenarios with perturbations within 80%.

	Optimality gap	Cost increase	Recipes change
average	0.08%	8.52%	70.4%
maximum	0.23%	14.30%	91.1%
minimum	0.03%	2.77%	28.6%

FIGURES' CAPTION

Figure 1: Structure of plywood (left) and blockboard (right) panels

Figure 2: Process flow for plywood and blockboard manufacturing

Figure 3: Annual demand of optimized strip thicknesses

For Peer Review Only

142x34mm (600 x 600 DPI)

Peer Review Only

139x44mm (600 x 600 DPI)

142x88mm (600 x 600 DPI)