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Title:

Ergonomics as basis for a Decision Support System in the Printing Industry

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Ergonomics as basis for a Decision Support System in the Printing Industry

ABSTRACT

The newspapers must be printed each night in a very short time, in order to deliver them next morning. A printing plant must perfectly design the production, in which some manual operations as the supplement insertion are critical. The main concerns about this manufacturing step are to determine ergonomically the maximum capacity to setup and feed the line by the workers and improve the knowledge on the input conditions of each supplement. A decision support system to determine the number of hired workers needed for the manual insertion (setup and feeding) was developed for a printing plant. It takes into account the supplement characteristics, ergonomic issues and the production rates. A linear program has been defined and some variants have been studied. The new system led to a 13% increase in productivity, a reduction in cost overruns and an important reduction in labor costs. The system may be used for a short-term staff planning.

KEYWORDS

Ergonomics, manufacturing, decision support system, staff planning

1. INTRODUCTION

The night before we buy the newspaper, a printing plant has to print it. A newspaper company decided some years to create a specific company for the printing. Therefore, this new company needs to reach the maximum profit. This study shows the improvement on the management in a printing plant where five different newspapers are printed every night. In fact, what we purchase often consists not only of the newspaper itself, but also of additional supplements, such as advertisement brochures, special offers, gift items… This work is based on the insertion of these supplements in the newspaper.

In the past, the printing company had difficulties to determine the number of necessary workers for the insertion of supplements each night. The objective of this study is determine this amount depending on the specific conditions, i.e. type of supplements included in the newspaper, of a day. It also depends on the cycle time and the printing rate. In order to solve it, the printing plant has developed a decision-making support system, based on linear programming.

The main stages in the production process are: Printing, Insertion and Delivery. In Printing, the pages of the newspapers are printed, assembled, folded and prepared for the following stages. Insertion is the operation of inserting the supplements into the received printed newspapers. Delivery consists in the packaging of the newspapers and the movement to the docks, before the vans pick them up and deliver them. Printing and Insertion must be done in a very short period of time. As each van follows a route, a scheduled time with the client –the newspaper company- is previously agreed to have them at the dock.

The printing company must pay a penalty to the newspaper company for each newspaper arrived later than the forecasted times for the delivery. As the payment for penalties increased each day, the company decided to study the manufacturing flow. The first evidence was that Insertion generated many stoppages in the production line and became a bottleneck. At the same time, Insertion is the stage with the highest labor costs. Particularly, manual insertion is the most costly in terms of personnel, as this is hired from an outside company to carry it out.

The core of the study seeks determining a number of daily hired people in order to avoid the penalties due to delivery delays and, at the same time, reach as low as possible costs. They work in the simplest and repetitive tasks related to the insertion of supplements into the newspapers, but the supplements are different one day from the previous one. In this case, ergonomics plays an important role to know the minimum feasible cost. Production processes must be perfectly defined so as to be coherent with Occupational Safety and Health.

The study focuses on the two manual operations in Insertion: Setup and Feeding. It will be necessary to define these two tasks, their duration and, above all, the optimal number of units of supplements handled by the worker.

Section 2 gives an overall look on applied ergonomics in the task design. To understand the ergonomic key, in Section 3, the supplement insertion and the study to determine daily the number of workers for the setup and for the feeding operations are described. Section 4 develops the model based on linear programming and in Section 5 how it has been applied. Finally, Section 6 gives some results on production once the changes were applied and Section 7 underlines the conclusions taken from this case.

2. APPLIED ERGONOMICS IN MANUFACTURING MANAGEMENT

Ergonomics is primarily concerned with improving human well-being and overall man-machine system performance. Obviously, manufacturing activities and process are not limited only in machinery, but also involve the manual works by the human resources, which in some activities and process are more utilized than machinery due to its flexibility, low-cost, facility, etc. Despite the advantages of manual material handling (MMH) activities, such as flexibility and facility, it is widely accepted that MMH is a high risk activity that can lead to musculoskeletal disorders (MSD) in workers.

According the estimations of the International Labor Organization (EU-OSHA 2019), the economic cost of work related injuries and illnesses is approximately 2680 billion € globally and 476 billion € in the European Union (EU). Furthermore, the second cost in the EU is due to MSD (EU-OSHA 2019). In terms of years of life lost or years lived with disability (DALY) because of MSD, estimates accounts for 15% of both globally and in the EU (EU-OSHA 2019).

Ergonomic awareness towards MMH activities amongst the workers was explored by Deros et al (2015). They concluded that managers should take full responsibility to increase the awareness of workers to a higher level. On the other hand, at small and medium enterprises (SME), the so called reactive ergonomic approach, that is, to search the solution after problems occur, is common. The main reason is the lack of ergonomics expertise, especially in the case of MSD (O'Sullivan and Gallwey 2006).

The use of computational simulation ergonomic tools allows for testing processes before implemented, so they are consequently proactive, and at the same they improve current processes (Santos et al. 2007). Polášek et al. (2015), comparing digital tools for ergonomics, pointed several advantages they bring, such as the elimination of the cost of reworking and particularly the short time in their implementation.

Though many companies have improved worker health and system performance through ergonomic interventions, the literature does not suggest that these interventions have resulted in financial savings for the companies. Beevis and Slade (2003) provide some examples where applying ergonomic principles have resulted in production cost reductions; on the other hand, according to de Looze et al. (2010) there is no large body of well-documented cases that have applied ergonomic principles to their operations.

As it is difficult to assess company improvements from ergonomic applications in terms of potential savings, improvements can be evaluated from the standpoint of productivity. An ergonomic intervention aims to improve worker comfort and safety, as well as productivity. In this sense, Leyshon et al. (2010) seek to determine the level and quality of evidence supporting ergonomic interventions to improve worker comfort, safety and productivity.

Some models, such as Methods Time Measurement (MTM), are useful for determining unitary time needed to perform a repetitive and short-cycle task. Nevertheless, these models do not sufficiently address certain ergonomic risk factors, such as posture and physical effort.

Several studies (Andersson 1992; Koningsveld et al. 2005; Oxenburgh et al. 2004; Riel and Imbeau 1996) examine the effectiveness of ergonomic interventions in improving worker task performance. However, they do not look extensively at the effects of these interventions on overall company productivity and performance. The applications of ergonomics principles in operation design methods are higher in recent years: Dempsey et al. (2010) study pace and temporal management of repetitive assembly and disassembly tasks; and Baraldi and Kaminski (2011) consider ergonomic interventions as a means of achieving competitive advantage.

This paper is based on applied ergonomics in the manufacturing management, thus reflecting an interdisciplinary collaboration. This integration has been treated, for instance, by Lodree et al. (2009), following upon the work of Dessouky et al. (1995). Both studies examined the impact of incorporating human characteristics into classical scheduling and manufacturing decisions. On the other hand, Finneran and O'Sullivan (2010) carried out an experiment on a repetitive task in which the relationship between worker force and productivity was measured.

3. DESCRIPTION OF THE PROBLEM: THE SUPPLEMENT INSERTION

3.1. The Insertion stage

The nominal printing capacity in 8 hours of the night shift is 700,000 copies of 112 page-newspapers. Although each press can print up to 85,000 copies per hour, supplement insertion is at a maximum rate of 45,000 units per hour. There are two options for inserting supplements:

- The **Automatic Supplement Insertion** is used when the supplements can be rolled on disks, due to the newspaper and the supplement share the same dimensions and kind of paper.
- The **Manual Supplement Insertion** is used for supplements that cannot be stored on disks. They are put in a secondary loading line which feeds them to the main line. One or more operators insert the supplements and must work at the pace set by the line.

Under these conditions, if a supplement gets stuck because it has not been properly prepared or the pace of insertion is not fast enough, the entire production line must halt until the problem is solved.

The supplements may vary according to the day or even to the newspapers' sales point. Thus, various final products could be produced under a single newspaper brand in a given day. Generally speaking, each day t the newspaper company requires tot_t copies to the printing plant with a number of manual-inserted supplements nms_t. If nms_t>0, manual insertion is required at a rate $r_t \leq 45{,}000$ units per hour and line.

Manual insertion, the bottleneck in the process, constitutes the highest personnel costs for the printing plant and is tightly controlled by the client –the newspaper company-. Two operations are manual:

- **Operation 1, Setup**. The protective wrapping of the supplements, which arrive in metal band-protected pallets or boxes, is taken off and the supplements are prepared for the later feeding. This activity depends on the characteristics of each supplement.
- **Operation 2, Line Feeding**. This consists of binding the prepared supplements and placing them correctly into the stream feeder, which is a loading line connected to the main line. In this way, they are inserted into the main product.

Fig 1 shows the layout of these two operations. At the top, we can see the main line. In this case, two loading lines are feeding respectively two different supplements (on the left and on the right of the Fig 1). The line feeding is done by worker in the closest position to the main line, in front of the stream feeder. Previously, the setup has been done in the farthest position, between the pallets and the stream feeder.

Fig 1. Manual operations (feeding and setup) in two feeding lines (for supplements 1 and 2).

The setup for the posterior feeding is expected to be done before starting the production. Table 1 describes the flow of a supplement in the plant. Suppose the newspapers start to be printed at midnight. The feeding should be done from the midnight (the same day D of the newspaper delivery), but the setup can be done before the midnight (the day D-1). At most the day D-2 the printing plant receives the supplements in strapping packages on the pallets. Then, the plant manager decides which number of people should be hired for the evening of day D-1 and the night of the day D.

Table 1. Actions related to the manual insertion of supplements, between days D-2 and D.

3.2. Workers in the operation 1, the Insertion Setup

In the past, there were many staff and production problems due to lack of planning. The company wanted to determine the required time to prepare the supplements previously to the line feeding. This is known as Setup (operation 1 in Section 3.1) and includes removing pallet protective coverings (retractable plastic, metal bands, protective wrapping, boxes, etc.) and preparing ergonomically optimal-sized packets. To determine the time, a study was carried out to identify the relation with these arriving conditions. These packets are the same later fed to the line (operation 2 or Line Feeding, studied in Section 3.3). The main difficulty here arises from the fact that each supplier sends supplements according to its own criteria and needs.

The collected data became the base for the designed decision support software for hired personnel in supplement setup. The considered work elements were divided into basic (subdivided in setup, handling and remove) and additional. The times for each element and their frequency are given in Table 2.

Table 2: Unit times and frequency of the work elements in the Setup.

According to the reception of the supplements from the providers, for a given manual supplement *ms* to be inserted in day *t*, there are the following parameters are necessary:

- The number of received pallets $p_{ms,t}$, in the printing plant, of manual supplement *ms* for day *t*
- The number of packages $pack_{ms,t}$ per pallet of manual supplement *ms* for day *t*
- The number of units $unit_{ms,t}$ in a package of manual supplement *ms* for day *t*
- The pallet protection of manual supplement *ms* for day *t* can be retractile or with metal brands. We define the Boolean variables $yret_{ms,t}$ and $ymet_{ms,t}$, respectively.

Therefore, the total time $setup\_time_1$ for a single worker in operation 1 dealing with the manual supplement *ms* inserted in day *t* (in TMU) can be calculated as:

$$Setup\_time_1 = 10539.7 \cdot p_{ms,t} + 472.4 \cdot p_{ms,t} \cdot pack_{ms,t} + 5657.2 \cdot p_{ms,t} \cdot yret_{ms,t} + (533.4 \cdot p_{ms,t} + 138.6 \cdot p_{ms,t} \cdot pack_{ms,t}) \cdot ymet_{ms,t} \qquad (1)$$

Generally, if $W_{1,ms,t}$ is any number of workers, the total time (in TMU) is calculated as:

$$Setup\_time_{\mathrm{w}} = 8828.3 \cdot p_{ms,t} + (2311.4 \cdot p_{ms,t} + 472.4 \cdot p_{ms,t} \cdot pack_{ms,t})/W_{1,ms,t} + 5657.2 \cdot p_{ms,t} \cdot yret_{ms,t} + (533.4 \cdot p_{ms,t} + 138.6 \cdot p_{ms,t} \cdot pack_{ms,t} / W_{1,ms,t}) \cdot ymet_{ms,t} \qquad (2)$$

Example 1

The following data correspond to a supplement, in order to show the decision on the hired workers:

- 65,000 newspapers have to be printed.
- 13 pallets of a single supplement are delivered to the plant.
- Each pallet contains 100 packages with each package containing 50 supplement units.
- The packages are strapped with metal bands.

Applying formula (1) with p=13, pack=100, yret=0, ymet=1, the time required if a single worker were assigned would be $Setup\_time_1$=9.38 hours. Given that the maximum allowed time to work are 8 hours, the insertion setup cannot be completed by a single worker. On the other hand, if two workers are hired, the required time using formula (2) is $Setup\_time_2$=5.26 hours, which is an accepted solution. Therefore, the number of necessary workers are 2 for the Setup.

Fig 2 shows how the manager introduces the input data on the left of the software, and on the right, the software gives the number of working hours if the hired personnel are one person, two people, and so on.

Fig 2: Example of the decision support system to determine the number of hired workers for the setup.

3.3. Workers in the operation 2, the Line Feeding

The Line Feeding becomes the bottleneck, because it should be done during the printing of the newspapers. The findings of the study, where the ergonomic limits play an important role, are described in the following subsections.

3.3.1. Determination of the number of workers for feeding

A cycle consists in the movement of a set of supplements by a worker. It is necessary to determine the number of copies of the supplement *ms* of the day *t* moved in a cycle of feeding by a worker [units/cycle_worker] what we will call $fn_{ms,t}$. Once known, the number of copies of a supplement *ms* for the feeding moved during an hour of the day *t* [units/hour_worker], known as $fh_{ms,t}$, can be calculated.

Similarly, the number of workers to be hired for operation *2* to feed the supplement *ms* in day *t* is defined as $W_{2,ms,t}$. Given a production rate in the line, the workers must supply the supplements in the feeding line faster than the flow r_t in the main line. Therefore:

$$W_{2,ms,t} = \left\lceil \frac{r_t}{fh_{ms,t}} \right\rceil \qquad \forall ms, \forall t \qquad (3)$$

Given a supplement *ms* of the day *t*, the number of copies $fn_{ms,t}$ per cycle is related to the safety and health conditions in the work and the characteristics of each supplement (Section 3.3.2). The worker's feeding rate $wr_{ms,t}$ for the supplement *ms* of day *t* depends on this number of copies $fn_{ms,t}$ and the considered cycle time *ctime*:

$$wr_{ms,t} = \left\lfloor \frac{fn_{ms,t}}{ctime} \right\rfloor \qquad \forall ms, \forall t \qquad (4)$$

3.3.2. Calculation of the standard cycle time for feeding

In order to ascertain the cycle time *ctime* required for the feeding, a time study was carried out. It was based on a set of direct observations made over a month, considering any number $fn_{ms,t}$ of units to be moved in a batch. The three considered operations were:

- Placing. Take with the two hands a batch of $fn_{ms,t}$ copies and place it on the shaking table.
- Handling. Take the $fn_{ms,t}$ copies with the two hands, position them properly (vertically, with the back-up and the cover in front), frame on the four sides and place them in the feeder.
- Removing. Eventually, if a unit is shrivelled, remove it from the batch and lay it aside.

For the usual number of units ($fn_{ms,t}$), the cycle time *ctime* is 835.9TMU and can be considered constant. The number of inserted units per hour with normal activity is at most 41,420 and could reach the 55,227 units in case of optimal activity.

We must apply an allowance coefficient (Niebel and Freivalds, 2002). For this case, the coefficient is in the range between 11% and 16% (depending on the element considered). Some factors were considered: Effort (weight of the handled materials, frequency of physical effort and a part of the body affected); Work posture (normally standing, moving from one place to another bearing or not bearing loads); Short cycle (highly repetitive work in the finger, hand, and arm muscles); concentration (attention for placing supplements in the feeder); Monotony (the same repetitive task); and Noise (constant noise).

3.3.3. Setting the ergonomic limits for the process

This part of the study entails setting the limits for manual insertion in terms of quantity per cycle, i.e. hand height (in centimeters) and maximum weight.

Hand height: This refers to the distance between the first articulation of the thumb and the second articulation of the index finger, with the fingers applying sufficient pressure to the supplement packet to be able to handle it effectively. This process can be carried out by either men or women, but as specified in UNE-EN ISO 15537:2004, we need to center on the measurements corresponding to the hand of a small woman. The distance is measured between the base of the palm to the tip of the thumb. On the basis of this distance (approximately 10.7 cm), it is possible to calculate the ergonomic optimal number of supplement copies to be handled per cycle.

Maximum weight: In order to prevent possible health risks to the workers, a maximum weight per cycle has also been set. This process can also be executed by either a man or a woman. According to the NIOSH Lifting Guidelines (Hidalgo et al. 1997), the objective is to compute the Variable Lifting Index (VLI). Given the rest of parameters, the idea is to evaluate several values for the load per cycle. The one associated to the limit of VLI=1 is the maximum accepted weight (a greater value for VLI would imply a risk for the worker). The following parameters were introduced for this evaluation purpose:

- Cycle time: 15 seconds. Equivalently, 4 lifting per minute.
- Loading Height: 90 cm.
- Unloading Height: 90 cm.
- Process duration: usually, 240 minutes.
- Distance covered carrying load: 35 cm.
- Corporal angular deviation during cycle: 0º.
- Number of hands in action: 2.

The weight of 4.1 kg (9 lb) leads to a VLI=0.59 for a man and a VLI=0.99 for a woman. If the work is done by a man (VLI<0.85), no additional prevention actions should be carried out. On the other hand, if it is done by a woman (0.85≤VLI≤1), they should be informed that a greater weight could be risky.

Given the rest of parameters, it is possible to handle a load of up to 4.1kg per cycle with no physical risk to the worker (male of female). But the limit of 10.7cm height for the batch of supplement units will be usually the active constraint. Now, it is time to determine the number of supplement units each worker can handle without passing these two ergonomic limits.

3.3.4. Classification of the supplements

Two main features for supplements were associated to the hand height and the maximum weight to move: pagination and grammage of the paper. The aim of following study is to ascertain, on the basis of supplier information regarding grammage and pagination, the real supplement thickness and weight.

There are two main difficulties in determining $fn_{ms,t}$, the number of copies to be moved in a cycle:

- The suppliers only provide grammage as technical information. No database informed previously about the thickness of a supplement sheet based on its grammage. The thickness is necessary to determine the total height of a batch. As this was fundamental, an analysis of the sheet thickness in the laboratory was carried out for all the kinds of supplements received during a year.

- There was considerable doubt regarding the validity of grammage information provided by the suppliers.

The study was based on 69 different supplements, classified into 12 groups based on their theoretical grammage. The theoretical grammage could vary between 45 and 250 g/cm^2. Table 3 presents the results to determine the mean thickness per sheet (in µ) and the real grammage of a sheet (in g/cm^2).

For the manual supplement *ms* in day *t*, the theoretical grammage $gram_{ms,t}$ and the number of pages $page_{ms,t}$ (columns 1 to 3) were given by the suppliers. The thickness for each supplement was measured and each supplement was weighed, in the laboratory. Columns 4 (mean thickness) and 5 (mean weight per sheet) show the results. For manual supplement *ms* in day *t*, the values will be $thick_{ms,t}$ for the thickness and $weight_{ms,t}$ for the weight per sheet. Finally, column 6 shows the mean values for the real grammage, which can be compared with the theoretical informed by the suppliers.

Table 3: Mean results for supplements' thickness and real grammage according to the groups based on the theoretical grammage.

From the results in Table 3, the mean values for each of the 12 groups are used for a lineal regression to provide the real sheet thickness and grammage. The correlation between theoretical or supplier grammage and real grammage $gram'_{ms,t}$, as measured in the company, has a coefficient of $R^2= 0.90$. This validates the hypothesis that the ink, among other factors, affects the supplement weight.

Using lineal regression, the average weight of a supplement page according to its theoretical grammage ($weight'_{ms,t}=5.85+0.822\cdot gram_{ms,t}$) has a correlation coefficient of $R^2=0.86$. This provides a more accurate weight for a supplement sheet based on the supplier grammage.

Similarly, the mean sheet thickness according to theoretical grammage ($thick'_{ms,t}=13.04+0.312\cdot gram_{ms,t}$) was found with a correlation coefficient of $R^2=0.80$. This set the maximum number of supplement units to be handled by each worker according to hand grabbing limits.

Using extrapolation, the initial database of 12 groups was divided into 35 groups of supplements with different grammage, and the two most frequent formats (DINA4 and DINA5) are considered in the system to simplify the number of cases.

3.3.5. Determination of the need for personnel

The algorithm starts determining the maximum number of supplement units to be handled by personnel according to ergonomic limits (10.7 cm and 4.1 kg). Then, the number of cyclic repetitive movements is obtained dividing the number of daily newspaper copies by that maximum number of supplement units. The printing speed is determined to reach the production goal. On the basis of these values, the number of workers is then ascertained by this decision support tool.

Example 1

We want to determine the number of hired workers to feed the first ($ms=1$) of the supplements of a day t. It has 52 pages and its theoretical grammage is 70. From Table 2, we know that the mean real weight per sheet is 1.66 g and the mean thickness per sheet is 41.35µ. The weight is 86.32 g and the thickness is 2.15 mm. Taking into account the ergonomic limits of 4.1 kg and 10.7 cm, the maximum number of copies must consider the maximum handled weight (4100/86.32=47.5 units) and the maximum height to be taken by the hand (107/1.07=99.52 units). As this must be integer and respect both limits, $fn_{1,t}=47$.

Applying the formula (4) and given ct=835.9TMU, the number of units per hour are $fh_{1,t}=5593$. If there are 6 hours to produce the 65.000 newspapers, the rate is $r_t=10833$ *units/hour* and the number of necessary workers in feeding are $W_{2,1,t}=2$ using formula (3).

4. MODEL FOR THE DECISION SUPPORT SYSTEM

As the company wanted to easily decide the number of workers required to insert supplements (manual operations of Setup and Line Feeding) in a given day, the result is a decision support system based on the following data and mathematical model.

4.1. Model 1 (optimization of worker hiring costs)

Parameters

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h: number of days to consider for the determination of hired workers
t: index for days ($t=1, 2, \ldots, h$)
op: number of operations to be manually by workers
j: index for manual operations ($j=1, \ldots, op$)
nms_t: number of manual supplements provided in the newspaper of the day t ($\forall t$)
ms: index for manual supplements in the newspaper of the day t ($ms=1,2, \ldots, nms_t$)
tot_t: total number of newspaper copies to be printed in day t ($\forall t$) [units]

$time_{j,t}$: maximum time for the manual operation j of a worker in day t ($\forall j, \forall t$) [h]

$mach_{j,t}$: number of machines available for operation j in the newspaper printing of day t ($\forall j, \forall t$)

$p_{ms,t}$: number of received pallets, in the printing plant, of manual supplement *ms* for day t ($\forall ms, \forall t$)

$pack_{ms,t}$: number of packages per pallet of manual supplement ms for day t ($\forall ms, \forall t$)

$unit_{ms,t}$: number of units in a package of manual supplement ms for day t ($\forall ms, \forall t$)

$yret_{ms,t} \in \{0,1\}$: Boolean variable that equals to 1 if pallet protection of manual supplement *ms* for day t is retractile *($\forall ms, \forall t$)*

$ymet_{ms,t} \in \{0,1\}$: Boolean variable that equals to 1 if pallet protection of manual supplement *ms* for day *t* are metal brands *($\forall ms, \forall t$)*

$page_{ms,t}$: number of pages in the manual supplement *ms* in day t ($\forall ms, \forall t$)

$gram_{ms,t}$: theoretical grammage for manual supplement *ms* in day t ($\forall ms, \forall t$)

r_t: production rate established for day t ($\forall t$) [units/hour]

allow1: allowance coefficient for operation 1, i.e. setup

avtime1: available time of a worker in an hour, for the operation 1 [TMU/h]

ctime2: cycle time of operation 2, i.e. feeding [s/cycle]

wc_j: daily worker's cost if a worker is hired for operation j ($\forall j, \forall t$) [u.m./worker_day]

Variables

$W_{j,ms,t}$: number of workers to be hired for operation j of the supplement *ms* to be inserted in the newspaper printed the day t ($\forall j, \forall ms, \forall t$)

$fn_{ms,t}$: number of copies of the supplement *km* of the day t moved in a cycle of feeding by a worker ($\forall ms, \forall t$) [units/cycle_worker]

$wrate_{ms,t}$: worker's feeding rate of a supplement k during an hour of the day t ($\forall ms, \forall t$) [units/hour_worker]

Some relations between the defined variables are:

1. The total number of workers W_t to be hired for the night of day t is:

$$W_t = \sum_{ms=1}^{nms_t} \sum_{j=1}^{op} W_{j,ms,t} \qquad \forall t \tag{5}$$

2. The pallets can have retractile or metal bands; therefore:

$$yret_{ms,t} + ymet_{ms,t} = 1 \qquad \forall ms, \forall t \tag{6}$$

3. For the available time for the operation *1, avtime1*, the TMUs in an hour are decreased according to the allowance coefficient *allow1* (in this case, between 0.11 and 0.16)

$$avtime1 = 100000/(1+allow1) \tag{7}$$

Some initial considerations in this case study are:

- The number of operations *op* is 2: $j=1$ for the Setup and $j=2$ for the Line Feeding.

- There are 4 proliners (2 proliners per line and 2 lines); therefore, $mach_{2,t}$=4 and a maximum number of 6 positions leads to $W_{2,ms,t} \leq 24$. The maximum of Setup workers is not relevant.

Model 1

$$[MIN]z = \sum_{\forall j,t}[wc_j \cdot \sum_{\forall ms}(W_{j,ms,t})] \quad (8)$$

Subject to

$$time_{1,t} \cdot avtime1 \cdot \sum_{\forall k}[\delta_k \cdot w1t_{k,ms,t}] - (8828.3 \cdot p_{ms,t} + 5657.2 \cdot p_{ms,t} \cdot yret_{ms,t} + 533.4 \cdot p_{ms,t} \cdot ymet_{ms,t}) \cdot W_{1,ms,t} \geq 2311.4 \cdot p_{ms,t} + 472.4 \cdot p_{ms,t} \cdot pack_{ms,t} + 138.6 \cdot p_{ms,t} \cdot pack_{ms,t} \cdot ymet_{ms,t} \quad \forall ms,\ \forall t \quad (9)$$

$$\sum_{\forall k}[w1t_{k,ms,t}] = W_{1,ms,t} \quad \forall ms,\ \forall t \quad (10)$$

$$w1t_{k,ms,t} \leq 1 \quad \forall ms,\ \forall t,\ \forall k \quad (11)$$

$$w1t_{k+1,ms,t} \leq w1t_{k,ms,t} \quad \forall ms,\ \forall t,\ \forall k \quad (12)$$

$$W_{2,ms,t} \leq 24 \quad \forall ms,\ \forall t \quad (13)$$

$$(13.04+0.312 \cdot gram_{ms,t}) \cdot 0{,}5 \cdot page_{ms,t} \cdot fn_{ms,t} \leq 107000 \quad \forall ms,\ \forall t \quad (14)$$

$$(5.85+0.822 \cdot gram_{ms,t}) \cdot fn_{ms,t} \leq 4100 \quad \forall ms,\ \forall t \quad (15)$$

$$wrate_{ms,t} = fn_{ms,t} \cdot 3600/ctime2 \quad \forall ms,\ \forall t \quad (16)$$

$$wrate_{ms,t} \geq r_t \quad \forall ms,\ \forall t \quad (17)$$

$$time_{2,t} \cdot W_{2,ms,t} \cdot wrate_{ms,t} \geq tot_t \quad \forall ms,\ \forall t \quad (18)$$

$$W_{j,ms,t} \geq 0 \quad \forall j, \forall ms,\ \forall t\ ;\ w1t_{k,ms,t} \geq 0 \quad \forall j, \forall ms,\ \forall t\ ;\ fn_{ms,t}, wrate_{ms,t} \geq 0 \quad \forall ms,\ \forall t \quad (19)$$

Equation (8) presents the objective function. The aim is to minimize the costs associated to the hired workers; later the possible penalty for arriving late will be added. Equation (9) determines the minimum number of hired workers in operation 1 according to the available time $time_{1,t}$, *avtime1* (see relation 3) and the number of workers $W_{1,ms,t}$. For this reason, as a quadratic term appears in the first term, equations (10), (11) and (12) are necessary for the linearization; $w1t_{k,ms,t}$ indicates if the *k-th* worker is necessary and δ_k is its parameter. Equation (13) limits the number of workers per manual supplement according to the space constraints (see the second consideration before the model). Equations (14) and (15) use the ergonomic criteria defined in Section 3.3.3. Equation (16) obtains the worker rate for feeding, which must be greater than the flow rate of newspaper in the main line, as shows equation (17). Finally, equation (18) is used to determine the number of hired workers in operation 2 according to the available time $time_2$, the number of workers and the personal capacity. Constraint (19) imposes that the variables are non-negative.

As constraint (18) is nonlinear, it must be linearized. The new parameters and variables associated to the linearized model are:

Additional Parameters

NR: Length of the vector limiting possible values for wr_t.

NW: Length of the vector limiting possible vales for $W_{2,ms,t}$.

vr_i: Discretized value for wr_t, i=(1,...,NR), and $vr_1 = 1$, $vr_{NR} = 40000$.

$vw_{i'}$: Discretized value for w_{2t}, i'=(1,...,NW), and $vw_1 = 1$, $vw_{NW} = 10$.

γ_{NR}, γ_{UW}: Sets of values that parameters vr_i and $vw_{i'}$ can adopt respectively.

Additional Variables

$yrw_{ii't} \in \{0,1\}$	Boolean variable that equals 1 in the case variables $yr_{it} = 1$ and $yw_{i't}$=1.
$yr_{it} \in \{0,1\}$	Boolean variable that equals 1 in the case $wr_t = vr_i$.
$yw_{i't} \in \{0,1\}$	Boolean variable that equals 1 in the case $w_{2t} = vw_{i'}$.

And finally the new constraints to replace the constraint (18) are:

$$time_2 \cdot \sum_{i=1}^{NR} \sum_{i'=1}^{NW} vr_i \cdot vw_{i'} \cdot yrw_{ii't} \geq tot_t \qquad \forall t \qquad (20)$$

$$\sum_{i=1}^{NR} yr_{it} = 1 \qquad \forall\, t \qquad (21)$$

$$wr_t = \sum_{i=1}^{NR} vr_i \cdot yr_{it} \qquad \forall\, t \qquad (22)$$

$$\sum_{i'=1}^{NW} yw_{i't} = 1 \qquad \forall\, t \qquad (23)$$

$$W_{2,ms.t} = \sum_{i'=1}^{NW} vw_{i'} \cdot yw_{i't} \qquad \forall\, t \qquad (24)$$

$$2 \cdot yrw_{ii't} \leq yr_{it} + yw_{i't} \leq 1 + yrw_{ii't} \qquad \forall t; \forall i \epsilon \gamma_{NR}; \forall i' \epsilon \gamma_{NW} \qquad (25)$$

Therefore the model is composed of the objective function (8) and the constraints (9)-(17), (20)-(25) and (19).

4.2. Model 2 (optimization of worker hiring costs and tardiness penalty)

It is possible to add in the objective function a penalty for arriving late, to study possible deviations from the theoretical a priori values. The new parameter in the objective function and the new variables, to be added to those from Model 1, are:

New Parameter for Model 2

tardp: tardiness penalty for each minute late comparing the expected finishing time with the required maximum time [u.m./min]

New Variables for Model 2

$extra_t$: number of extra minutes to the available time for feeding ($\forall t$) [min/ worker]

$exttot_t$: number of newspapers printed after the limit time of the day *t* ($\forall t$) [units]

Model 2

The new objective function includes a second term and substitutes equation (9) in Model 1:

$$[MIN]z = \sum_{\forall j,t} wc_j \cdot \sum_{\forall ms}(W_{j,ms,t}) + \sum_{\forall t} tardp \cdot \mathrm{extra_t} \tag{26}$$

The constraint (20) in Model 1 is reformulated as:

$$time_2 \cdot \sum_{i=1}^{NR} \sum_{i'=1}^{NW} vr_i \cdot vw_{i'} \cdot yrw_{ii't} \geq tot_t - exttot_t \qquad \forall t \tag{27}$$

And it is necessary to add a new constraint:

$$extra_t \cdot wrate_{ms,t} = 60 \cdot exttot_t \qquad \forall ms,\ \forall t \tag{28}$$

But once again, the constraint (28) is nonlinear and it must be linearized. The definitive Model 2 will have the following new parameters and variables associated to the linearized model, in order to determine the extra time minutes $extra_t$:

Additional Parameters for Model 2

$NMIN$: Length of the vector limiting possible values for wm_t.

$vm_{i"}$: Discretized value for $extra_t$, i"=(1,...,NMIN), and $vm_1 = 1$, $vw_{NMIN} = 120$.

γ_{NMIN}: Set of values that parameter $vm_{i"}$ can adopt.

Additional Variables for Model 2

$yrm_{ii"t} \in \{0,1\}$ Boolean variable that equals 1 in the case variables $yr_{it} = 1$ and $ym_{i"t}$=1.

$ym_{i"t} \in \{0,1\}$ Boolean variable that equals 1 in the case $extra_t = vm_{i"}$.

The new constraints to replace the constraint (28) are:

$$\sum_{i=1}^{NR} \sum_{i"=1}^{NMIN} vr_i \cdot vm_{i"} \cdot yrm_{ii"t} \geq 60 \cdot exttot_t \qquad \forall t \tag{29}$$

$$\sum_{i''=1}^{NMIN} ym_{i''t} = 1 \qquad \forall\, t \qquad (30)$$

$$extra_t = \sum_{i''=1}^{NMIN} vm_{i''} \cdot ym_{i''t} \qquad \forall\, t \qquad (31)$$

$$2 \cdot yrm_{ii''t} \leq yr_{it} + ym_{i''t} \leq 1 + yrm_{ii''t} \qquad \forall t; \forall i \epsilon \gamma_{NR}; \forall i'' \epsilon \gamma_{NMIN} \qquad (32)$$

The value 60 in the right hand side of equation (29) is due to the time unit conversion, as the rates are measured in units per hour and the extra time, in minutes. Therefore the model is composed of the objective function (26) and the constraints (9)-(17), (21)-(25), (27), (29)-(32) and (19).

5. EXPERIMENTAL RESULTS OF THE MODEL TESTS

This Section is divided in several parts:

1. The first will test the model with data similar to the company for which it was developed. They have been slightly modified for confidential treatment. A daily newspaper has between 0 and 3 manual supplements per day. Usually this number increases when the weekend arrives; therefore, the maximum number is on Sundays, followed by Saturdays and Fridays. The rest of the days, from Monday to Thursday, this number is variable according to the seasonality.
2. The second test will analyse the model performance on a set of instances, created with the most common characteristics of the manual supplements. There are a set of 14 days considering single manual supplement per day, another set of 14 days with two manual supplements per day and a set of 14 days with three manual supplements per day.
3. In the third and last part, the relation between the two parts of the objective function (worker's cost and penalty due to tardiness) is analysed in order to show how the Model 2 performs in case of extra time.

5.1. Experiment 1 with data of the printed newspaper

A week is considered (t=7), and each day has a minimum of a single manual supplement. The number of newspapers and manual supplements per day are given in Table 4. Table 5 indicates the minimum, the maximum and the mean values of the different characteristics in the 13 manual supplements considered, 7 of which were provided with retractile protection (54%) and 6, with metal bands (46%). In this experiment the daily worker's cost is lower than the penalty of each late minute ($wc_j < tardp$); for this reason, although Model 2 is applied, the extra time will be null.

Table 4: Number of newspaper copies to be printed and number of manual supplements per day in Experiment 1.

Table 5: Minimum, maximum and mean values for the different characteristics of the manual supplements in Experiment 1.

The number of necessary workers for each operation and each day are shown in Table 6. We must keep in mind that the number of manual supplements is not constant for all the days. The worker's feeding rates of a supplement vary between 6,854 and 11,457 units/hour_worker.

Table 6: Number of necessary workers per operation and day in Experiment 1.

5.2. Experiment 2 with different number of manual supplements

This experiment will consist in testing data for 2 weeks, i.e. 14 days. The number of manual supplements per day is between 1 and 3. The number of newspapers varies between 100,000 and 270,000. Table 7 gives the minimum and the maximum values of the characteristics in the manual supplements; these values correspond to the most frequent cases. Approximately, 50% of the supplements are provided with retractile protection and the rest, with metal bands. Again, the daily worker's cost is lower than the penalty of each late minute ($wc_j < tardp$).

Table 7: Minimum and maximum values for the different characteristics of the manual supplements in Experiment 2.

Table 8 shows the results. Each row is for a different number of manual supplements (1, 2 or 3). In columns, there are the minimum, maximum and mean values for the workers necessary in both operations (1, for setup; 2, for feeding) and for the worker's feeding rate of a supplement.

Table 8: Minimum, maximum and mean numbers of necessary workers per operation and feeding rates in Experiment 2.

5.3. Experiment 3 related to costs in the objective function

This last experiment is focused on the objective function. Here we will test the Model 2 when $wc_j \geq tardp$ (wc_j is the same for any operation j) and demonstrate the sensitivity of the extra time depending on the demand, maintaining constant the rest of parameters. The reference situation is the one presented in

Example 1 in Section 3: 65,000 newspapers have to be printed and a supplement with 52 pages and a theoretical grammage of 70, which is delivered in 13 pallets, 100 packages per pallet, 50 supplement units per package and the packages are strapped with metal bands.

The initial solution proposes 2 workers for the second operation. If we check the capacity of both workers, they could feed up to 72,000 supplements in a day. For this reason, the reference demand is 72,000. Then, we want to know what happens if the demand is increased in a 1% (demand of 72,720 copies), and similarly with 2%, 3%, 4% and 5% (i.e. demand reaches 75,600 copies in this last case).

Table 9 shows the results of Experiment 3. In row, the relation between both costs starts when $wc_j = tardp$ ($wc_j / tardp=1$) and later goes from 10 to 50, increasing 10 each time. In columns, there is the excess of demand from 1% to 5% over 72,000 copies. When the relation of costs is still low, it does not matter to hire a third worker. But when this relation is higher than a certain point, it is more interesting to maintain the two workers with an extra time. When no extra time is required, there is no parenthesis next to the number of workers (3 in this case); otherwise, when the solution is two workers the number of minutes working extra time is shown in the parenthesis.

Table 9: Number of workers to be hired to feed this supplement and in parenthesis minutes of extra time in Experiment 3.

6. RESULTS ON PRODUCTIVITY AND OTHER QUANTITATIVE MEASURES

Mainly the decision support system, combined with other improvements, had significant and immediate positive effects on production. In the below list we explain some of them:

- Increase in the insertion productivity. The improvement, due to receiving well prepared supplements and having the appropriate number of personnel, is reflected in a higher number of newspapers handled per hour. Considering the data of the first 6 months since the decision support system is used, a linear regression gives a result of $y=42,694+13.26 \cdot t$, where y is the insertion productivity rate (in terms of newspapers/hour) and t is the number of days of use. In 181 days the mean number of more treated newspapers increases in 2,400. And the consequence, considering a standard production of 400,000 daily copies, is a reduction of half an hour in the feeding process, what implies also a reduction in the energy consumption.

- Reduction in paper waste due to mechanical breakdowns and jams. The improved supplement setup and feeding has reduced the machine malfunctioning, which in turn has improved productivity. In this case, since the decision support system is used, the linear regression has a trend of $-10.46 \cdot t$, being t is the number of days of system use. This supposes that the mean number of waste newspapers per day is reduced in more than 10 units. It must be considered that in a long term this value will be lower. As this is related with flow rates, we recommend to develop the model considering this parameter as a new variable.

- Reduction in the number of hired personnel. Worker hours during rush periods was reduced by an average of 6% in the first six months, even a new newspaper has started to be printed.

- Reduction in production stoppages. The new software permits a better planning in the feeding task, which in turn translates into fewer production delays or stoppages. Once again, the stoppages and flow rates follow an approximately linear trend. Therefore, this parameter converted in a new variable is also valuable.

7. CONCLUSIONS

This study was carried out at a printing plant of a company, whose production is expected to grow substantially in the coming years. The flows and processes required to make operational changes to ensure quality and increase the capacity. The most significant weakness was the manual supplement insertion, which was an important bottleneck for the entire plant.

The main work consisted in the analysis of the ergonomic conditions for personnel in the insertion task. To deal with this problem, some solutions were provided:

- Development of a decision support system based on the production parameters to determine the plant needs for temporary personnel.
- Reorganization of supplement setup process.

Ergonomic and time studies of supplement insertion, setup and feeding, allowed the company to hire the number of temporary personnel in accordance with supplement volume, format and production rates. The determination of that number, together with other measures, has had various positive consequences:

- A savings of 58,300€ per year in expenditures for materials (paper, packaging, pallets).
- A 13% increase in productivity equivalent to 1,585,560€ per year.
- A reduction in cost overruns of 52,500€ per year as a result of lower setup time.
- A reduction in temporary labor costs.

For the future work on the proposed model, the objective is to study the best flow rates in order to arrive on time but avoid stoppages and consider some deviations in the behavior of the workers: give a confidence interval to the cycle time and study a possible relation between the worker productivity and some extra salary.

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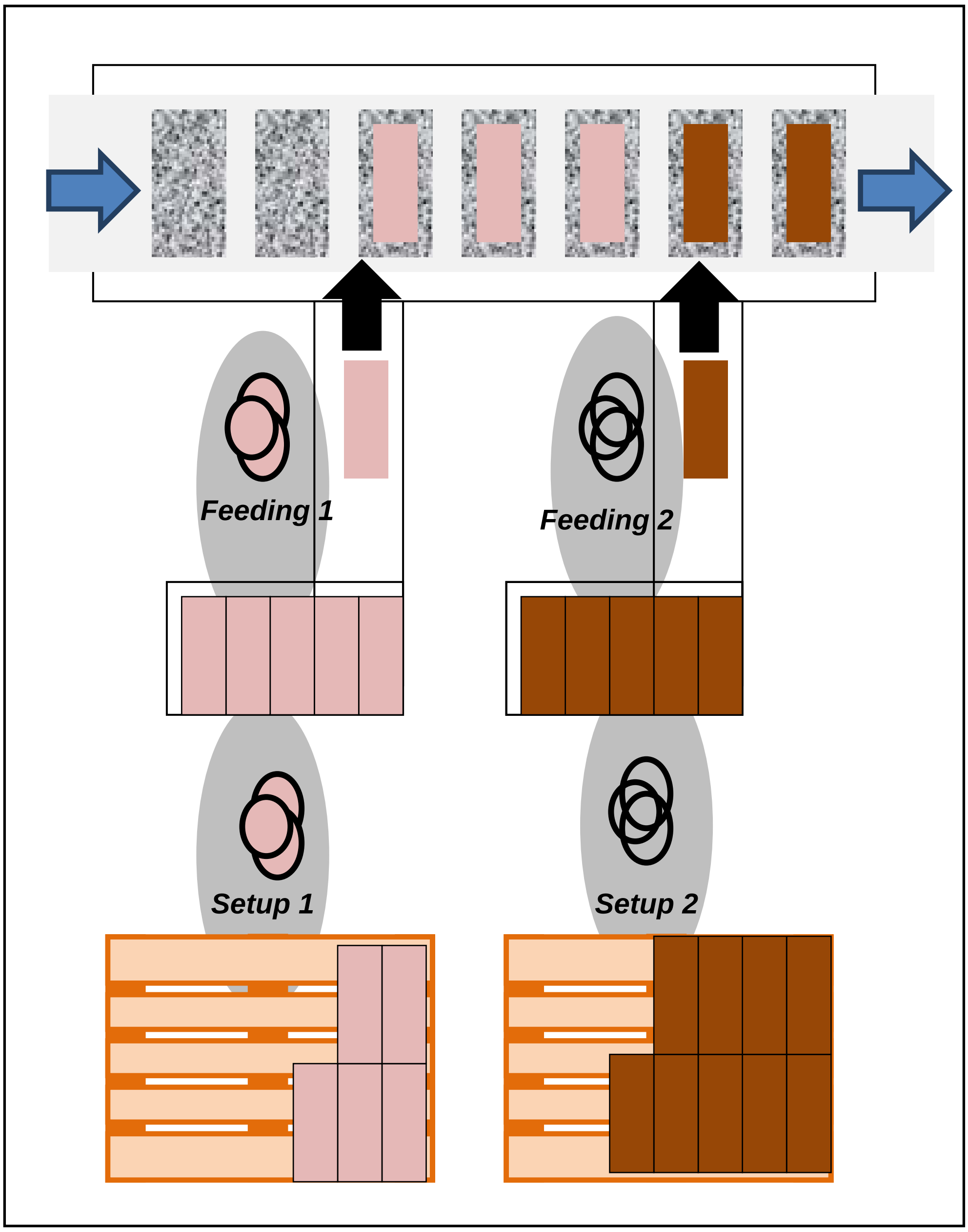

Fig 1. Manual operations (feeding and setup) in two feeding lines (for supplements 1 and 2).

Supplement input			**RESULTS**	
Name	**X**		**Setup time 1 worker**	**hours**
			9.38	
Production	**65000**			
			Setup time 2 workers	**hours**
Number of pallets	**13**		**5.26**	**X**
Units per package	**50**		**Setup time 3 workers**	**hours**
			3.89	
Option 1	**X**			
			Setup time 4 workers	**hours**
Option 2	**Strapping**		**3.20**	

Fig 2: Example of the decision support system to determine the number of hired workers for the setup.

Day	Hour	Action
D-2	Any	Input of supplement in the printing plant
D-2	Any	Maximum day for hiring the necessary personnel for day D
D-1	8:00-24:00	Supplement setup, after printing the newspaper of day D-1
D	0:00-delivery time	Print the newspaper of day D. At the same time, supplement feeding
D	Delivery time	Output of the printing plant: delivering of newspapers and supplements

Table 1: Actions related to the manual insertion of supplements, between days D-2 and D.

Group	Name of the element	Time (TMU)	Frequency
Setup	Position supplements oriented to insertion.	1575.2	Once/pallet
	Prepare pallet with the truck to handle the supplement units.	419.3	Once/pallet
Handling	Take a batch of units correctly and position it on the cart. Eventually remove defective units.	472.4	Once/package
	Remove separator layers.	225.2	3 times/pallet
	Operate the lift truck to place properly the pallet.	275.4	3 times/pallet
	Use a cardboard separator to level the height of the batches.	809.6	Once/pallet
Remove	Remove a cart full of supplements prepared to insert.	1301.8	Once/pallet
	Remove an empty pallet and place another full of units to prepare.	1952	Once/pallet
	Place waste generated in a container.	2979.8	Once/pallet
Retractable	Remove shrink wrap plastic from the pallet using a cutter.	5657.2	Once/pallet
Metal bands	Take a cutter and cut strips that hold the supplements package.	68.5	Once/package
	Go to take the waste bin and bring it, to then throw the strips.	533.4	Once/pallet
	Take the cut strips, remove them from a package of supplements and throw them to the bin.	70.1	Once/package

Table 2: Unit times and frequency of the work elements in the Setup.

Theoretical grammage (g/cm^2)	Minimum number of pages	Maximum number of pages	Mean thickness per sheet (μ)	Mean real weight per sheet (g)	Mean real grammage per sheet (g/cm^2)
45	16	16	35.6	1.21	46.13
53	16	16	33.75	1.64	58.62
60	8	44	29.15	1.79	60.06
70	8	52	41.35	1.66	58.84
80	4	44	31.02	1.88	80.25
90	8	32	38.47	2.46	69.78
100	10	48	35.88	2.04	80.29
120	4	16	48.1	2.09	93.07
150	2	40	43.58	2.8	98.41
170	8	8	66.25	5.25	149.95
180	6	6	92	6.12	196.14
250	4	6	88.59	6.43	203.61

Table 3: Mean results for supplements' thickness and real grammage according to the groups based on the theoretical grammage.

Day (t)	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
tot_t	150000	100000	110000	150000	150000	250000	350000
nms_t	1	1	1	2	2	3	3

Table 4: Number of newspaper copies to be printed and number of manual supplements per day in Experiment 1.

Character.	Pages	Grammage	Pallets	Packs/pallet	Units/pack	Retractile	Metal b.
Min	16	45	5	13	50	0	0
Max	80	80	12	500	300	1	1
Mean	32.92	64.62	10.23	185.23	161.54	0.54	0.46

Table 5: Minimum, maximum and mean values for the different characteristics of the manual supplements in Experiment 1.

Day (t)	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
$W_{1,t}$	2	1	2	5	4	6	6
$W_{2,t}$	10	10	10	20	20	30	30

Table 6: Number of necessary workers per operation and day in Experiment 1.

Charact.	Pages	Grammage	Pallets	Packs/pallet	Units/pack	Retractile	Metal b.
Min	4	45	6	57	100	0	0
Max	52	80	14	400	300	1	1

Table 7: Minimum and maximum values for the different characteristics of the manual supplements in Experiment 2.

	Workers operation 1			Workers operation 2			Worker's feeding rate		
Manual supplem.	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
1	1	3	1.64	7	9	8	7,271	11,457	9,465
2	2	4	3.29	18	18	18	6,854	11,457	8,962
3	3	6	4.50	24	27	25.5	6,854	11,457	9,628

Table 8: Minimum, maximum and mean numbers of necessary workers per operation and feeding rates in Experiment 2.

wc_j /*tardp*	1%	2%	3%	4%	5%
1	3	3	3	3	3
10	3	3	3	3	3
20	2 (8)	3	3	3	3
30	2 (8)	2 (15)	3	3	3
40	2 (8)	2 (15)	2 (22)	2 (29)	3
50	2 (8)	2 (15)	2 (22)	2 (29)	2 (36)

Table 9: Number of workers to be hired to feed this supplement and in parenthesis minutes of extra time in Experiment 3.