EXTENDED ABSTRACT

REBAR CUTTING AND BENDING EQUIPMENT

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July 2010
1. INTRODUCTION

This study focuses on construction equipment, more specifically on rebar bending and cutting equipment. It endeavors to describe existing equipment and related technical innovations, with the objective of selecting, on a practical basis, the most appropriate solution taking into consideration costs and the production system, i.e., off-site and on-site production on a central and local construction site, respectively. To this end, selection criteria were set to promote understanding of associated advantages and disadvantages of both equipment and rebar production system.

This study is a tool that aims to assist all those involved in this type of work (cutting, bending and tying of rebar) in the selection of this kind of equipment, so that project requirements in terms of costs, time, performance and quality are met.

In order to clarify and standardize the terminology used throughout this work about production of rebar, it is important to describe the process and its associated terms. The cutting and bending of rebar is called molding, followed by tying with gauzed wire, which can be done in on-site or off-site. The last task to be done is the application of rebar at the local defined in project. When tasks are performed off-site, their denominations are preceded by the prefix pre (pre-molding, pre-tying).

2. STATE OF THE ART OF REBAR CUTTING AND BENDING EQUIPMENT

This section presents in 2.1 the rebar equipment used off-site more specifically its classification, the main characteristics and evolution. The following subsections discuss the principal differentiating features between off-site and on-site rebar equipment (CAD / CAM, numerical control, adaptive control, waste management, among others). At 2.2 is presented the rebar cutting and bending equipment that could be found on-site, especially the portable equipment, which most important advantages, among others, is that equipment can be carried by one worker due to its relatively low weight.

When concrete contractors need rebar cut or bent, they have three choices: they can have their crews use manual tools to hand cut or bend it on the job, they can use rebar cutting and bending machines at the jobsite or in their shops or they can have a fabricator pre-cut or pre-bend the rebar. Some contractors say there is no difference in quality or strength between pre-engineered and do-it-yourself machine cut or bent rebar (Feingold, 2007).

When a contractor needs to acquire this type of equipment, the read and understand of the equipment specifications are indeed of great importance. Nowadays, several companies distributed around the globe, with particular focus on the United States, China and Japan, produce several different products related with cutting and bending rebar, each one of these products has its own advantages, therefore their suitability for the job should be carefully evaluated. The cutting and bending speed as well as the maximum diameter of the bars are two of the technical characteristics most common and important to be taken into account. Nevertheless, different models contain different features, such as assembly capacity or a microprocessor capable to bending rebar with accuracy and respecting bending angles. Any of these features can significantly reduce the costs of cutting and bending rebar on-site, therefore obtaining a better understanding of equipment and practices related it requires a careful study of equipment available on the market and proper understanding of the needs of the project.

2.1 Off-site rebar equipment

According to Schwarzkopf (1991) the construction industry is very gradually beginning to move towards automation— at the present stage, mainly in the off-site production of construction components, like happens with the steel bars that are already pre-molded before arriving at the site construction.

One of the first examples, which started in the mid-1980s, is the numerically controlled (NC) rebar cutting and bending (RCB) machine. The RCB machines manufacture rebars automatically. They have a controller, which is a computer that determines bending and cutting locations as well as bending angles and directions. The data for these machines is entered in the controller by the operator prior to actual production (adapted from Navon et al., 1995). In many cases the data for each rebar shape is entered separately for each type of geometry before its production, a large quantity of rebar
can then be produced according to the data introduced. These machines can also receive data entries for a number of shapes, which may provide it with continuous work for a few hours (Navon et al., 1996).

The classification of NC RCB machines depends on factors such as their raw material supply system, their operating principles, the diameters of the rebars they process, and the length of the final product or its type. Navon et al. (1995) classified these machines as A, B, and C. Machines type A produce shaped rebars and stirrups of up to 16 mm diameter. The raw material is continuous and supplied to the machine in coils. The machine pulls the bar from the coil, straightens it, bends it with one bending head, and finally cuts it to size. Machines type B produce long rebars of up to 16 mm diameter. The raw material supply system is identical with that of type A machines, but the machine bends the rebar at both ends with two bending heads. Machine type C differs from both machines in that it receives the raw material only in a discrete form and produces rebars larger than 16 mm diameter. The raw material, in the form of bars which have already been cut to their desired length, is fed manually into the machine. The bars have been cut from longer bars with 12m long, and such as other machine types, these machines also bends the rebar at both ends with two bending heads, each having a rotor and a stator.

![KRB’s ServoForm 1020ES](image1.png)

**Figure 1 – KRB’s ServoForm 1020ES (raw material supplied in coils, at left, raw material supplied in discrete form, at right) (KRB, 2010).**

### 2.1.1 CAD/CAM System

Navon et al. (1995)(2) describes a CAD/CAM system which enables the fully automated data transfer from the design draws (CAD) to the CNC rebar manufacturing machine. Therefore, all the traditional steps of manual manipulation of design data and production of rebar (detailing, documentation, data extraction, etc.) are avoided. In many cases, the various stages of manual manipulation of data is a source of errors. Consequently, with automated data transfer, possible with the CAD / CAM system, it’s possible to reduce costs, increase quality and productivity, starting by reducing the time that the machine is inoperative during their programming.

Besides the economic component, the CAD / CAM system has inherent benefits, both direct as indirect, such as fewer workers involved in the process, reduction waste of raw materials (steel), labor reduction related with correction of possible production errors shortening and consequent acceleration of the production process, reduction production costs resulting from not having to work overtime, and greater satisfaction for workers because they perform tasks with higher level of sophistication (Navon et al., 1996).

### 2.1.2 Numerical control machines

The first generation of NC machines, in the 1950s was based on hardware without memory or computing capabilities. The machines were programmed in a low-level language, which was based on a collection of codes called G-Codes, and the program was fed into the machines with a punched tape. The program was executed step by step, i.e. the machine would read the instructions for one step, execute it, and only then read the instructions for the next step, and so forth until all the instructions had been carried out. The introduction of microprocessors, together with a drop in computer costs, enabled the connection of NC machines to computers. Such machines are called Computerized Numerically Controlled (CNC) machines. An additional development is the Direct Numerical Control (DNC), whereby a central computer controls a number of NC machines via direct links. It downloads the appropriate program to each machine individually (Navon et al., 1995).
2.1.3 Raw material feeding system

The raw material feeding system studied by Navon et al. (1995) was designed for the continuous flow of raw material into the machine. The large-diameter raw material is supplied to the rebar manufacturing plant in the form of discrete bars of a finite length. The bars are stored in containers, the number of which is determined by the number of different bars to be processed in each session. From these containers the bars are moved into the cutting and bending machine. The sequence of feeding the bars depends on the strategy of temporarily storing the finished product.

2.1.4 Cutting and bending system

Navon et al. (1995) studied a machine with the next features here presented, the machine has two bending heads, which comprise means for longitudinal motion, a table, a pulling system, and a cutting head. The table is the main structure of the system, it has an open track in the middle for the bending heads’ motion. The table has two principal tasks, the first being to support the bar during the bending operation and keep it in one plane, the second, to serve as a sliding surface for the finished product on its way to the temporary storage, this is why the table is tilted.

The actual bending operation is done with the bending head protruding out of the table's plane. The bar enters the bending head, the stator then closes to keep the bar static. The rotor then starts rotating, the direction and rotation angle being determined by the desired bar shape. The bending operation is carried out in two stages. The bar is then released and moved to the next bending position, where the second bending takes place in the opposite direction. To complete the first stage, the bar is moved to the cutting position and cut to the desired total length. The second bending stage begins with the bar being moved to the new bending position, a motion that can be either forward or backward, depending on the bar geometry. As the bar is already cut, its motion can no longer be caused by the pulling system, consequently the task devolves on the first bending head while the bar is still clamped. The bar is bent at the new bending position from this stage onwards it no longer moves, but rather the second bending head does.

When the bending operation is finished, the bar is released, and the two bending heads are lowered beneath the surface of the table. As a result the rebar slides down into temporary storage.

2.1.5 Adaptive control

Steel is a material when subject to bending forces has an elastic response variable, known as springback, this fact requires a folding mechanism capable to guarantee the quality and accuracy of bending. Most of rebar are bent using traditional hand operated machines, whose basic technology remains the same for over 50 years, with only some innovations in electronic controls and safety systems (Dunston et al., 2000).

When rebar is bended incorrectly, quite often by operator error, the bars can’t therefore be redoubled and applied. Because of this fact, an automated system with an associated database would be able to drastically reduce the amount of steel wasted due to bending errors (Dunston et al., 2000).

The performance of the operation with precision bending of rebar is one of the most critical parameters of an integrated rebar production system. In order to automate the bending rebar, given the quality standards required by customers and the industry itself, it becomes necessary to implement an intelligent control system which can compensate springback. An adaptive control algorithm, which automatically adjusts the specific properties of any kind of bar, can significantly reduce the setup time of the machine, increasing the productivity without sacrificing quality. In order to achieve automatic control for bending rebar, either the bar or the machine and machine-object interaction must be understood and monitored through the application of representative models (Dunston et al., 2000).

2.1.6 Management of rebar waste

Machines types A and B receive a continuous supply of raw materials from coils. As a result there is no excess-bars problem with those machines. Machines type C, like the one presented herein, which deal with large-diameter bars, do present such a problem. This is because a number of rebars of finite lengths have to be cut and bent from each standard length bar. In most cases, after cutting all the rebars from a raw-material bar, there is an excess bar remaining, which is shorter than the desired length for the next rebar. The excess bar remains even if the raw material is supplied in a variety of lengths (Navon et al., 1995).
The solution for minimizing excess bars was to optimize the sequence of rebar production at the CAD stage, before the data transfer. But although the optimization meaningfully reduces the problem, excess bars remain and have to be removed. After the last rebar has been cut, one end of the excess bar remains in the pulling system. The other end rests on the supporting columns. Before being removed the excess bar is slid backwards, until it completely rests on the supporting columns. From there it is removed by the excess bar handler, which has a number of levers (Navon et al., 1995).

Salem et al. (2007) developed a genetic algorithm model that is efficient in reducing the volume of rebar waste. In some cases, the genetic algorithm was able to reach solutions, through reusing the remains of rebar which would be wasted, and applying them in other cutting patterns, from this resulted a minimization of waste.

2.2 On-site rebar equipment

2.2.1 On-site portable rebar equipment

The development of on-site rebar cutting and bending equipment has been based especially on the development of portable technology, including microchips. With the possibility of using portable batteries with very good level of autonomy, this fact brought the announcement of equipment for cutting and bending which are quite light and durable, and their good efficiency also helps improve the productivity, reduces labor costs, reduces the inactivity conditioned by the weather, increases safety in the work, reduces energy consumption and have a better performance compared to traditional equipment (adapted from Jain, 2007).

This kind of equipment made possible to perform jobs that once were not achievable at the local application of rebar. Although the portable battery-powered still represent a niche market, they are very useful in places with difficult access to electric power (Palmer, 2003). This new category of rebar equipment is characterized by its lightweight, smallness and can be easily transported to the construction site and inside it. Its low weight and resistance to adverse weather conditions due to the fact that this equipment is made of composite materials. There are portable machines with the ability to cut, bend and some even by combining these two functions (adapted from Jain, 2007). The use of hand tools to bend steel bars is physically hard, but with the advent of portable equipment, powered with battery or electric power, this task has became safer and less damaging to occupational health, because the equipment is light enough to be carried at construction site all day long (Palmer, 2003). Sometimes, due to design errors, splicing pillars´ have to be made into the slab, when this happens, bars usually have diameters too large to can be bent by hand using hand tools. Once again the portable equipment can solve this kind of situation, with the additional advantages of respecting the recommended angle of bending and not causing cracking or even breakdown of the pillar part that have been already concreted (adapted from REHANA, 2008).

Many years ago, before the advent of portable equipment, that equipment for cutting and bending rebar on-site is available in the market, but they can weigh over 100 kg, while the portable can weigh less than 20kg and can cut and bend rebar with 16mm diameter (Jain, 2007).

![Figure 2 - EZE Bend's portable bending equipment, which can be used with just one hand (Palmer, 2003).](image)

1 Throughout the document, when referring to portable equipment, it means all the equipment that can be transported by one worker, excluding hand tools.
3. ECONOMIC AND TECHNICAL ANALYSIS OF THE EQUIPMENT

This section presents in 3.1 an introduction to the preparation of rebar systems through brief descriptions of them, i.e., off-site rebar preparation system (industrialized system) and on-site rebar preparation system (traditional system). Subsequently, the selection criteria are set for the rebar equipment as well to the rebar preparation system. Finally, in section 3.3 is performed an economic analysis comparing the two production systems of rebar, which are taken into account the costs of manpower, material and equipment.

3.1 Systems for the preparation of rebar

3.1.1 Off-site rebar preparation system

Off-site rebar preparation system consists at the supply of bars already bent and cut to the construction site. Thus, some of the stages of rebar production, which had been executed by an artisanal way, became industrialized and are performed in a specialized facility for this purpose. Projects are submitted by the contractor to the rebar provider, who then analyses the best solution to be adopted (Praça, 2001).

The initial information, extracted from the rebar detailing drawings contained in the structural project, which initiates the process, is known as list of rebar, this list determines lengths and shapes of rebar. Another fact that the contractor has to inform is the schedule needs of rebar (adapted from Praça, 2001). Since this moment the rebar provider prepares a list of pieces to be produced, which is processed through computer technology for machines that automatically and with good accuracy, perform the cutting and bending of the bars (Chaim, 2001). This method permits the elimination of various activities of transport, storage and inspection that often occurs when rebar is cut and bend on-site (Praça, 2001). However, could be thought that table benders and all tools associated are completely abolished, but as confirmed with several people of the art, the permanence of tools and equipment on construction sites, continue to be needed to avoid the lack of some pieces that have to be produced to not delay the service (Chaim, 2001). The material already cutted and bended is then sent to the site construction in bundles labeled with detailed information so they can be checked when arrive at site.

3.1.1 On-site rebar preparation system

On-site rebar preparation system has the basic characteristic that cutting and bending of rebar are performed at the construction site, occupying a large space and sometimes producing a significant amount of waste (it can also cause accidents to rebar workers), this disadvantage related with the production of waste can be solved through the adoption of appropriate measures, such as the definition and optimization of cutting and bending plans on-site, that be effectively efficient. Another important characteristic of this method is the excessive number of operations on-site related with transport, storage and inspections of rebar, this fact demands more use of manpower throughout the process (Praça, 2001).

3.2 Criteria selection of equipment and rebar production systems

3.2.1 Equipment selection

When a contractor pretends to acquire a rebar cutting and bending equipment, the first task should be a survey of the number of pieces, their geometries and sizes. Thereafter, should be listed the pieces that can be molded off-site and those which will necessarily be produced on-site (EHOW, 2010).

Johnston (1993) stated in 1993 that before the acquisition of rebar equipment, several factors must be taken into account, that because it is an investment that cannot just look for the equipment function and its cost, but also to the requirements that are intended that equipment guarantee. Table 1 presents the main criteria for selecting the equipment.
Table 1 - Criteria selection of rebar equipment.

<table>
<thead>
<tr>
<th>Criteria selection of rebar equipment</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Cost</td>
<td>In any type of investment this parameter is always a factor to take into account. Depending on the equipment cost and volume of work, the contractor can choose between three choices: purchase, rental or leasing. Typically, for large volume of work the acquisition is more attractive.</td>
</tr>
<tr>
<td>• Function: cut, bend or combined</td>
<td>Intrinsically related to quantity of rebar, the function of cutting, bending or combined cutting and bending rebar also should be considered, because for great volume of rebar to produce, equipment with separate functions are more efficient. If the volume of rebar isn’t too high, so the combined machines are a good option.</td>
</tr>
<tr>
<td>• Quantity of rebar</td>
<td>This is one of the most decisive criteria because its correct evaluation allows to conclude if is more profitable or not buy already pre-cut and pre-bend rebar, or acquire by purchase or rental the equipment to produce rebar.</td>
</tr>
<tr>
<td>• Geometry and size of the pieces</td>
<td>For standard geometries of rebar and lengths of rebar relatively large, off-site equipment is the most appropriate. In the remain cases, on-site equipment complies, but the quality of molding is not as good as that achieved off-site.</td>
</tr>
<tr>
<td>• Predominant diameter of the rebar</td>
<td>Although this is a criteria less stringent than the equivalent diameter, its consideration is important, so the equipment must be chosen to have greater efficiency in the molding of rebar predominant diameter. Consequently, labor productivity will increase.</td>
</tr>
<tr>
<td>• Equivalent diameter</td>
<td>To the higher equivalent diameter of rebar, correspond more kilograms of steel which will be needed for each meter processed, this fact increases productivity. It’s more efficient acquire a machine that is optimized to work with the respective equivalent diameter, because it is faster and consequently more productive.</td>
</tr>
<tr>
<td>• Energy supply capacity</td>
<td>There are certain cases that work has to be done in a remote location without electricity or enough power to supply certain types of machines for cutting and bending. Portable equipment is considered a good alternative or the supply of rebar pre-cut and pre-bend.</td>
</tr>
<tr>
<td>• Mobility of the equipment at construction site</td>
<td>When is needed mobility of the equipment in site construction, portable equipment meets this requirement, and is capable of doing splicings with good quality.</td>
</tr>
</tbody>
</table>

3.2.2 Rebar production system selection

Branz (2004) says that most builders prefer to have all their reinforcing steel delivered to site pre-bent and ready for tying into cages. Sometimes, however, it is advantageous to modify or fabricate it on-site to suit specific needs.

Feingold (2007) states that contractors say that pre-molding has two disadvantages, it is more expensive and the waiting time for bent pieces can be 2-3 days, which often takes the contractor to order more bars to avoid stock ruptures and delays to complete the work. This author also points out when a contractor use prefabricated materials, can occur delays caused by design changes. When projects have standardized dimensions and pieces, the use of prefabricated materials is a good choice.

Polat and Ballard (2005), Pheng and Hui (1999), Pheng and Chuan (2001) and Formoso et al. (2002) reported that the main advantages of off-site fabrication of rebar are as follows:
• Reduces investment cost: the investment cost for the generally automated machines used in off-site fabrication is much higher than the cost of the relatively primitive setup used in on-site fabrication, but the investment cost per unit of rebar produced is down because these machines are in constant and continuous use for mass production;
• Reduces labour cost: the operation is highly automated and consequently labour cost is minimized;
• Reduces waste: waste is expected to be much less in off-site fabrication as the production is mostly computerized and includes more standardized and sophisticated quality control/assurance procedures;
• Reduces inventory cost: when deliveries are made Just in Time (JIT) in small batches from off-site fabricators, the contractor can avoid those inventory costs;
• Reduces cycle time: rebar fabricators utilize computer integrated machines to fabricate cut and bent rebar. The productivity of these automated machines is much higher than the cutting and bending machines utilized in on-site fabrication. Therefore, the time required for fabrication is greatly reduced. Furthermore, since off-site fabrication can be done concurrently with the installation of previously delivered materials, project durations are reduced.

According to Chagas (2010), the advantages of the industrial system, designated by this company as System Armafer, relate to:
• Removal of spaces corresponding to the stock of bars, bending machines, table benders, beds, dorms. So the corresponding spaces are used for other purposes or saved when they are few, like happens in cities;
• Reception in the construction site of material that is really needed to perform the task at the time as planned;
• Minimization of costs, because for a minimum of slack, rebar must be purchased for the construction site with a good advance for not missing during work and compromises the schedule of other activities, such as formwork and concreting;
• The purchased material is nominally exactly and what will be consumed at the quantity stated by the assessment in the project stability;
• Bending angle, REBAP, tensile strength, steel classification, regulamentar splicings, etc. Those terms are fundamental to guarantee the quality of rebar, but are often neglected in the execution on-site due to the pressure caused by deadlines and working conditions. In this system, quality issues are guaranteed;
• The supply is made by the nominal weight, i.e., the client receives exactly the meters that will consume;
• In industrialized system there is no waste, ie the ordered quantity is strictly equal to the amount consumed;
• Reduced construction time, simplified processes and reduced costs when the work is located in remote areas without access to electricity.

Table 2 summarizes the main selection criteria for the rebar production system discussed throughout this subchapter.

Table 2 - Main selection criteria for the rebar production system.

<table>
<thead>
<tr>
<th>Main selection criteria for the rebar production system</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Quality of bending</td>
<td>The steel is bented many times with the same pin (which implies the same diameter) on the bending of bars with different diameters, which in turn compromises the physical integrity of the steel. The upshot is cracking and loss of strength.</td>
</tr>
<tr>
<td>• Space at construction site</td>
<td>The industrialized system permits reduce space in construction site by eliminating the yard of rebar on-site for example.</td>
</tr>
</tbody>
</table>
• Runtime service

The runtime may be less if industrialized system is implemented, especially if the traditional system doesn’t use cutting and bending plans.

• Cost of investment in equipment

Despite the off-site machines are more expensive than traditional machines, the cost per kg of rebar turns out to be smaller because they are in constant production, in addition to achieving better quality of work.

• Cost of manpower

In industrialized system, the probability of the team consist of more rod-busters, compared to teams in the traditional system, causes the manpower endear the first case.

• Standardization of the project and the consequent necessity of rework

The standardization project is one way that suppliers of rebar pre-molded, because sometimes this fact permits to avoid small jobs for the correction of armor, this stems from the low degree of standardization of national structural projects.

• Location of construction site

Works in remote areas or in cities (with limited space) may possibly be more attractive to the use of pre-molded rebar.

• Quality of project management, i.e., quality of the schedule

If the work schedule is not well controlled may happen to arrive at work pre-molded pieces, which will be stored until they are applied, the existence of space available for this could not be verified.

• Level of uncertainty in the supply chain

If for some reason, the off-site production site is late, this could delay the work schedule, which will entail additional costs. One of the reasons that may delay production is the possible need of the designer to make corrections to structural project.

• Variation in wages and unit prices of materials

The volatility of these values may create aversion to the contractor to buy the material earlier, as happens in the industrialized system.

• Workers productivity

The various studies analysed indicated a slightly higher productivity when the system is the industrialized. However, measures like a good plan for cutting and bending can put the traditional system equals to the industrialized system.

• Volume of waste

While the traditional system there are always waste from cutting rebar, this doesn’t happen with industrialized system whose waste are equal to zero

• Traceability of steel

By labeling of pre-molded pieces is possible to trace the whole production process

3.3 Comparative economic analysis between the two rebar production systems

This subsection is intended to carry out economic analysis comparing the traditional system and the industrialized system. The traditional system is that whose cutting and bending of done on-site, followed by its tying and application, with steel supplied to construction local in bundles of bars with 12m each. The industrial system is one whose cutting and bending operations are done off-site, the other operations are still done at the construction site. The tying of rebar could also be performed off-site, however due to transport costs by truck this is not done.

The unitary cost of an operating construction operation consists of the sum of unit costs of manpower (MO), materials (MT) and equipment (EQ) needed for the complete realization of that operation.

3.3.1 Manpower unitary cost (MO)

The costs of manpower should be calculated based on specific records in the companies, given also by the Acordo Coletivo do Trabalho (ACT) for the Construction Industry establishing minimum monthly salaries (Alves Dias, 2010). As such, the CCT (Contrato Colectivo de Trabalho) was

All presented prices do not include IVA (tax).
consulted through AECOPS and values for the minimum remuneration for groups IX and XII were collected, it was considered for analysis 1st class rod-buster and janitor.

To calculated values were also added social charges. For the present year 2010, these charges are estimated at about 145%, according to Alves Dias (2010). Thus, and assuming a team comprised 50% of rod-busters of 1st category and 50% of janitors, the cost will be 7.22 € / Hxh.

When opting for industrialized system the probability that there are more rod-busters to perform the service compared to the number of janitors is higher. This proportion is ambiguous and difficult to quantify, to this system will be adopted that the team is composed by 60% rod-busters and 40% janitors, what corresponds a team cost per Man x hour of 7.31 € which is 1.24% more expensive in relation to previously calculated. However, a higher cost can sometimes be beneficial, if it results on the increase of productivity. To assess the validity of the cost per man x hours obtained (€ 7.22) a search was conducted on the market through contacts established with national big contractors. So, the value considered for use in this study was 9.01 € / Hxh to the traditional system (50% rod-busters and 50% janitors) and 9.12 € / Hxh for the industrialized system (60% rod-busters and 40% janitors).

To calculate the cost of labor per unit of measurement is necessary to refer the concept of labor’s productivity. With the purpose of considering trustable values of labor’s productivity in the service, were consulted various literature sources, as well as a field study to gather data3.

Thus, the unit cost of manpower were then considered the following values

| Table 3 – Values of labor’s productivity considered. |
|-----------------------------------|---------|---------|
| System                           | Traditional | Industrialized |
| Efficiency [Hxh/kg]              | 0.068    | 0.054   |
| Productivity [kg/Hxh]            | 14.70    | 18.56   |

To calculate the unit cost of manpower were then considered the following values

| Table 4 – Manpower unitary cost. |
|-----------------------------------|---------|---------|
| System                           | Traditional | Industrialized |
| Team cost [€/Hxh]                | 9.01     | 9.12    |
| Efficiency [Hxh/kg]              | 0.068    | 0.054   |
| Unitary cost MO [€/kg]            | 0.61     | 0.49    |

3.3.2 Materials unitary cost (MT)

The cost of materials per unit of measurement of a construction operation (MT) is calculated by the sum of the costs of all materials needed for its implementation (Alves Dias, 2010). The cost of simple materials to be considered should include a margin for losses and waste. This value differs from the material type and manufacturer. In this case, production of rebar, there are usually three materials: rebar, wire for tying bars and spacers. In calculating the cost of materials it was assumed 11% as percentage of steel bars waste, since this is the material that has a higher loss due to the numerous cuts suffered by it.

Were consulted two specialized companies in selling this type of construction materials.

In order to get a single value for the price of steel bars, were studied two maps of quantities (from two different big contractors). So, then was chosen for this case the value of 0.67 €/kg for the unit cost of steel bars.

In industrialized system, we must add besides the cost of the materials mentioned above the cost of the service of molding performed by a service provider. the company CHAGAS, SA gave the cost that this company charges for this kind of service, 150 €/ton. The cost of transporting the material to the construction site, is already diluted in the prices charged by suppliers.

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3 See APPENDIX.
So, the unitary cost adopted for each material and the total unitary cost per unit measure (kg) is:

Table 5 – Materials unitary cost.

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<tbody>
<tr>
<td>Traditional</td>
<td>Steel bars</td>
<td>11%</td>
<td>0,75 €</td>
<td>18%</td>
<td>0,61 €</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wire gauzed</td>
<td>0%</td>
<td>0,0098 €</td>
<td>10%</td>
<td>0,0088 €</td>
<td>0,63 €</td>
</tr>
<tr>
<td></td>
<td>Spacers</td>
<td>0%</td>
<td>0,0091 €</td>
<td>0%</td>
<td>0,0091 €</td>
<td></td>
</tr>
<tr>
<td>Industrialized</td>
<td>Steel bars</td>
<td>0%</td>
<td>0,67 €</td>
<td>18%*</td>
<td>0,55 €</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wire gauzed</td>
<td>0%</td>
<td>0,0098 €</td>
<td>10%**</td>
<td>0,0088 €</td>
<td>0,72 €</td>
</tr>
<tr>
<td></td>
<td>Spacers</td>
<td>0%</td>
<td>0,0091 €</td>
<td>0%</td>
<td>0,0091 €</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cutting and bending service</td>
<td>0%</td>
<td>0,15 €</td>
<td>0%</td>
<td>0,15 €</td>
<td></td>
</tr>
</tbody>
</table>

### 3.3.3 Equipment unitary cost (EQ)

The use of construction equipment entails costs, which are related with property of the equipment, its maintenance, repair, use, handling, transportation, assembly and disassembly (Alves Dias, 2010).

The use of rebar equipment can be done by three different ways: **purchase**, **rental** or **leasing** (unusual in Portugal). The **acquisition** of equipment is the way that most contractors use when are expected high utilization rates for equipment. As main advantages of this method has:

- Operational costs that are generally much lower if the level of use is higher
- The availability of equipment when necessary;
- The possibility of having the equipment working with the best possible productivity, through ensuring a proper policy of maintenance.

The modality of **rental** equipment must be considered, particularly in cases when:

- The level of use is low;
- Needs of equipment for occasional short-term works (Alves Dias, 2010).

For this particular analysis, was considered that equipment is acquired. Through the market research, the value adopted for the purchase of a combined machine for molding steel was € 4,349.01 (in this case the machine is quite similar to OFMER TP22/26 machine).

It is presented below, in Table 6, the costs associated to the equipment:

Table 6 – Equipment cost.

<table>
<thead>
<tr>
<th>Hourly utilization cost (CHU):</th>
<th>2,30 €/hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unitary cost equipment (EQ):</td>
<td>0,039 €/kg</td>
</tr>
</tbody>
</table>
Table 7 shows the unitary costs considering the rental modality:

**Table 7 – Equipment cost considering the modality of rental.**

<table>
<thead>
<tr>
<th></th>
<th>Hourly utilization cost (CHU):</th>
<th>Unitary cost equipament (EQ):</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.73 €/hour</td>
<td>0.046 €/kg</td>
</tr>
</tbody>
</table>

As it was expected, when it chooses the type of rental price is higher, by about 19%, the price of EQ when it prefers to purchase the machine. However, the difference between the cost per hour of use is only 0.43 €, so rental modality is a very competitive choice and should be taken into consideration.

### 3.3.4 Production unitary cost

Table 8 summarize the values calculated in the previous subsections:

**Table 8 - Custo unitário de fabrico.**

<table>
<thead>
<tr>
<th></th>
<th>Fabrico</th>
<th>Custo Unitário [€/kg]</th>
<th>Percentagem relat./ ao Custo de Fabrico</th>
<th>Custo Unitário de Fabrico [€/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sistema</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tradicional</strong></td>
<td>MO</td>
<td>0.61 €</td>
<td>47.8%</td>
<td>1.28 €</td>
</tr>
<tr>
<td></td>
<td>MT</td>
<td>0.63 €</td>
<td>49.3%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EQ</td>
<td>0.04 €</td>
<td>2.9%</td>
<td></td>
</tr>
<tr>
<td><strong>Industrializado</strong></td>
<td>MO</td>
<td>0.49 €</td>
<td>40.5%</td>
<td>1.21 €</td>
</tr>
<tr>
<td></td>
<td>MT</td>
<td>0.72 €</td>
<td>59.5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EQ</td>
<td>N/A*</td>
<td>N/A*</td>
<td></td>
</tr>
</tbody>
</table>

* N/A – Not applicable, because the cost of equipment in the industrialized system is diluted in the price of the pre-molding service.

### 4. CONCLUSIONS

Previous studies on off-site cutting and bending equipment highlight a great automation effort, quality improvements and a significant reduction of waste. Considering the ever decreasing human intervention in the industrialized process, the operator assumes a more passive role, mainly as a controller.

As for the on-site equipment, technological developments in the field of portable equipment should be emphasised. These comprise, namely, durability, low weight, autonomy provided by portable batteries, ergonomic advances and the ability to cut and bend rebar on-site.

The criteria to be considered in the choice of rebar cutting and bending equipment used on-site (hand tools, traditional machines and portable equipment), must take into account the following aspects: i) Cost; ii) Function: cut, bend or combined; iii) Quantity of rebar; iv) Geometry and size of the pieces; v) Predominant diameter of the rebar; vi) Equivalent diameter; vii) Energy supply capacity; viii) Mobility of the equipment at construction site.
Regarding preparation of rebar systems, industrialized system seem to be capable to guarantee the objects of the rationalization, cost reduction, and consequently increasing the competitiveness required by today's market. The only cases found that contradicted this trend had problems mainly with the supply chain of pre-molded pieces (delivery time), this fact is caused by changes made by the designer on the structural project.

Thus, the criteria defined in this study and that should be taken into consideration in the choice of preparation rebar system, are: i) Quality of bending; ii) Space at construction site; iii) Runtime service; iv) Cost of investment in equipment; v) Cost of manpower; vi) Standardization of the project and the consequent necessity of rework; vii) Location of construction site; viii) Quality of project management, i.e., quality of the schedule; ix) Level of uncertainty in the supply chain; x) Variation in wages and unit prices of materials; xi) Workers productivity; xii) Volume of waste; xiii) Traceability of steel.

Economic analysis realized concluded that: i) the cost per unit of measurement (kg) of MO from the traditional system is about 25% more expensive than industrialized system ii) the cost per unit of measurement (kg) of MT industrialized system is approximately 14% more expensive than the traditional system iii) the produce cost of rebar per unit of measurement (kg) of the traditional system is about 6% more expensive than the industrialized system, approximately 1.3 €/kg versus 1.2 €/kg, given the fact that labor costs and materials account for a significant proportion of the rebar production cost. This 6% difference obtained is relatively low compared with those obtained by CICHINELLI (2004) and Chaim (2001), about 11% and 8%, respectively.

It was expected that the percentage difference between the two systems of rebar production was superior to 6%. However, it is believed that this difference may be void through implementation of efficient cutting and bending plans, because this difference (≈ 6%) isn’t very significant.

5. FUTUR DEVELOPMENTS

In future, would be interesting evaluate the technical and economic system "mixed", in which the longitudinal reinforcement bars are prepared on-site through the traditional process, and the stirrups and pieces (even longitudinal pieces) which don’t exceed two bending points produced by industrial process. In this case, is expected to have a substantial reduction in execution time and the unitary cost of rebar production, and measure these parameters would be helpful.

In the study presented here, the measurement of productivity associated with the manpower was not differentiated (in the vast majority of cases) for construction element (columns, beams, slabs, etc.) So, the measurement of the differentiated productivities would result in better sensitivity analysis to the productivity considered.

Off-site tying should be the natural evolution of this market. However, while this development isn’t accomplished there are some challenges to be overcome, such as complete elimination of tablebenders on-site, equipment and stocks of steel bars on-site, and optimization of the downloading of the material.

A future study that can evaluate and improve cutting and bending plans for implementation on-site, would certainly add value, given the importance that they could have in choosing rebar system.

Adoption of a sense of optimization by structural engineers in defining structural elements in order to maximize the rational use of 12m length bars through the minimization of cuts or even their absence, would not only reduce the workload associated with the rebar production, as well a significantly reduce of rebar waste.
APPENDIX

Table 9 - Productivity and efficiency values of manpower collected.

<table>
<thead>
<tr>
<th>Author (Fieldwork study)</th>
<th>Year</th>
<th>System</th>
<th>Productivity [kg/Hxh]</th>
<th>Efficiency [Hxh/kg]</th>
<th>Productivity [kg/Hxh]</th>
<th>Efficiency [Hxh/kg]</th>
<th>Productivity [kg/Hxh]</th>
<th>Efficiency [Hxh/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Author (Fieldwork study)</td>
<td>2010</td>
<td>Tradicional</td>
<td>44,10</td>
<td>0,023</td>
<td>22,05</td>
<td>0,045</td>
<td>14,70</td>
<td>0,068</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>14,70</td>
<td>0,068</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Coefficient of Variation | 62% |
Standard Deviation        | 0,042 |

Ratio (Ind. vs Trad.)

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>System</th>
<th>Productivity [kg/Hxh]</th>
<th>Efficiency [Hxh/kg]</th>
<th>Productivity [kg/Hxh]</th>
<th>Efficiency [Hxh/kg]</th>
<th>Productivity [kg/Hxh]</th>
<th>Efficiency [Hxh/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luís Araújo**</td>
<td>2000</td>
<td>Industrialized</td>
<td>20,00</td>
<td>0,050</td>
<td>20,00</td>
<td>0,050</td>
<td>20,00</td>
<td>0,050</td>
</tr>
<tr>
<td>Eduardo Praça</td>
<td>2001</td>
<td>Industrialized</td>
<td>16,67</td>
<td>0,060</td>
<td>16,67</td>
<td>0,060</td>
<td>16,67</td>
<td>0,060</td>
</tr>
<tr>
<td>José Chaim</td>
<td>2001</td>
<td>Industrialized</td>
<td>10,62</td>
<td>0,095</td>
<td>10,62</td>
<td>0,095</td>
<td>10,62</td>
<td>0,095</td>
</tr>
<tr>
<td>Luís Araújo</td>
<td>2003</td>
<td>Industrialized</td>
<td>13,75</td>
<td>0,073</td>
<td>13,75</td>
<td>0,073</td>
<td>13,75</td>
<td>0,073</td>
</tr>
<tr>
<td>Tatiana Jucá</td>
<td>2006</td>
<td>Industrialized</td>
<td>22,88</td>
<td>0,053</td>
<td>22,88</td>
<td>0,053</td>
<td>22,88</td>
<td>0,053</td>
</tr>
<tr>
<td>Luís Araújo - Brazil</td>
<td>2006</td>
<td>Industrialized</td>
<td>28,57</td>
<td>0,035</td>
<td>28,57</td>
<td>0,035</td>
<td>28,57</td>
<td>0,035</td>
</tr>
<tr>
<td>Luís Araújo - EUA and Turkey</td>
<td>2006</td>
<td>Industrialized</td>
<td>83,33</td>
<td>0,012</td>
<td>83,33</td>
<td>0,012</td>
<td>83,33</td>
<td>0,012</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>18,56</td>
<td>0,054</td>
<td>18,56</td>
<td>0,054</td>
<td>18,56</td>
<td>0,054</td>
</tr>
</tbody>
</table>

Coefficient of Variation | 48% |
Standard Deviation        | 0,026 |

* Diameters of bars presented about this author ranging from Ø12 to Ø20 (because those are the most common diameters used) and then was made an average for each structural element. Note that Paz Branco in their analysis refers to the concept of predominant diameter of the rebar, ie the diameter most commonly used on a structural element. ** Araujo (2000) made his comparative analysis based on the concept of equivalent diameter, i.e. the weighted diameter of the bar, as shown in the following expression:

\[
A_{\text{eq}} = \pi \times r^2 \Rightarrow \Omega_{\text{eq}} = \frac{\pi}{2} \times \frac{4}{\pi} = 2 \times \frac{\sum \text{Weight net per construction element}}{\pi \times \sum \text{Length steel} \times \text{Density steel} 
\times 1000 \text{ (mm)}}
\]
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