Large Hadron Collider Project

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Application of the Learning Curve Analysis to the LHC Main Dipole Production: First Assessment

P. Fessia, L. Rossi, S. Krog-Pedersen*

Abstract

About two third of the LHC main dipoles have been delivered by the three suppliers charged of the production. The training of the staff, mostly hired just for this manufacture, and the natural improvement of the procedures with the acquired experience, decrease naturally the time necessary for the assembly of a unit. The aim of this paper is to apply methodologies like the cost-based learning curves and the time-based learning curves to the LHC Main Dipole comparing the estimated learning percentage to the ones experienced in other industries. This type of analysis, still in a preliminary phase and here applied to about 40% of the total production of the LHC magnets that will end by 2006, shows that our production has a relatively high learning percentage and it is similar to aerospace and complex machine tools for new models. Therefore with the LHC project, accelerator magnets seem to have reached industrial maturity and this production can be used as bench mark for other large scientific projects implying series production.

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Index Terms— Accelerator magnets, large scale superconductivity, production management.

I. INTRODUCTION

THE Large Hadron Collider (LHC) is a 27 km circumference particle accelerator that is under construction at CERN, Geneva [1]. The accelerator is situated in a deep underground tunnel which is almost all filled with superconducting magnets [2] cooled at 1.9 K by means of superfluid helium [3]. The dipoles are the principal and most numerous of these magnets, determining the energy level of the particle beams: in total 1232 dipoles, about 15 m long and 28 tonnes in mass each one are being manufactured in European industries for the LHC [4,5]: Ansaldo Superconduttori in Italy, Babcock Nuclear Noell in Germany and the consortium Alstom-Jeumont in France.

In the present work we try to analyze the production of the LHC Main Dipoles (Fig. 1) applying known techniques that

Fig. 1. LHC main dipole cold mass manufacturing at one of the 3 Cold Mass Assemblers.

are used in industrial production in order to estimate the “cost progress” or “learning”. The two terms describe the reduction in unit production cost as more units have been cumulatively produced over the course of a manufacturing program. The “learning” or “cost progress” can be achieved thanks to:

- The reduction in manufacturing labor hours as workers learn to perform repetitive tasks faster or with fewer mistakes.
- Redesign of the production process; changing worker tasks or introducing new automation means, both tooling and process.
- Learning in the process itself, by selection of the actions that actually affect the final product and by dropping or removing unnecessary constraints (for example too tight tolerances).
- Improvement in logistic efficiency and logistic contracts. This has a non-negligible impact when the production under investigation is a considerable part of the total production of the company. In our case we deal with a very specialized manufacture and this condition is true for all producers, the LHC being about or more than 50 % of the turnover of the business unit.
- Reduction of the relative weight of some type of non-recurrent expenditure, like large tooling, with the increase of the units produced.
- Reduction of the relative weight of general and fixed costs as the production increase.
- Advantage of the scale factor – better price, better conditions – when component supply contracts

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become very large.

The last three terms are common to all large scale production. This study will focus the following issues:

- Define what is the achievable limit in terms of cost progress for the LHC Main Dipole production and estimate the cost progress slope. This might validate (or not) the choice of three manufacturers from the point of view of the cost. However it should be underlined that the choice of three suppliers was more strategy driven than cost driven.
- Determine what is the upper limit until which the production can be scaled up (increase the production rate) without reducing the efficiency, i.e., increase of unit cost.
- Quantify the learning slope describing the reduction in manufacturing labor hours and compare such value with other industries or similar productions.

II. THE DATA

The data used for this analysis come from the following sources:

- A CERN database, containing the dates of each manufacturing operations for each assembled unit, weekly filled by the CERN resident inspector.
- The traveler document of each magnet, containing the time of execution of the mandatory tests that mark the steps in the assembly of each unit.
- Data on manpower provided by the three suppliers [6], which in the following we will indicate as Firm 1, 2 or 3, with no link to previous listing order.
- Cost analysis based on the offers placed by the three firms at the moment of the contract adjudications. It should be noticed that, thanks to a process of re-alignment, the offer were the same in total, but noticeable differences existed in the cost breakdown and cost structure of each manufacturer.

Fig. 2. Assembly of the magnetic yoke before longitudinal welding at one of the 3 Cold Mass Assemblers.

The LHC Main Dipole production process can be divided in two parts. The first one, named Collared Coil (CC) production, implies the use of insulation and winding

techniques and it is more related to special electrical machine assembly. The second one, here called Cold Mass (CM) assembly, refers to the positioning of the CC inside the magnetic yoke and enclosing the whole in a mechanical structure which serves also as He II containment vessel. The CM assembly is based on precise heavy mechanics, including welding, alignment and vacuum technologies (Fig. 2). Due to the difference in technologies (with consequent relatively different type of personnel involved) among the two parts of the manufacture and also because of the physical split of the two assembly procedures in all suppliers, the two parts of the assembly will be treated separately.

III. APPLICATION OF THE CRAWFORD AND WRIGHT MODELS

Two cost progress or learning curve models are widely used in industry [7, 8, 9]:

- The Crawford model: it expresses the marginal cost of the unit Q as a power function:

$$MC(Q) = T_1 \times Q^b \quad (1)$$

- The Wright model: it expresses the cumulative average cost of the first Q units as a power function

$$AC(Q) = A_1 \times Q^b \quad (2)$$

and $AC(Q)$ is related to $TC(Q)$, the total cost to produce Q units, by:

$$AC(Q) = TC(Q)/Q \quad (3)$$

The two models are theoretically identical for large samples and when non recurring costs equal to zero. The learning percentage ρ indicates the fraction to which is reduced the production cost per unit every time the number of completed units doubles¹. It is defined as it follows:

$$\rho = MC(2Q)/MC(Q) = 1/2^b \quad (4)$$

Fig. 3, Fig. 4 and Fig. 5 show, for the three firms, the evolution of the production cost of each assembled Collared Coil in function of the quantity of completed units. The cost is expressed in arbitrary units. The analysis of the cost profiles indicates that:

- the Firm 2 and Firm 3 seem to have similar cost structure obtaining similar performance at comparable production stages.
- Fig. 5 presents an increase of unit cost between unit 130 and 150 where, due to production problem, all those units had to be repaired. The learning has affected also the repair itself showing a clear decrease

¹ ρ is not a percentage, as it can be seen in its definition, however here we stick to the name usually employed in the literature for production analysis.

Fig. 3. Application of the Crawford and Wright models to Collared Coil production in Firm 1.

Fig. 4. Application of the Crawford and Wright models to Collared Coil production in Firm 2.

Fig. 5. Application of the Crawford and Wright models to Collared coils production in Firm 3.

in the time necessary to execute the operation.

In Fig. 6, Fig. 7 and Fig. 8 the same plots as for the CC production are reported for the Cold Mass assembly. The starting production phase of Firm 1 was affected by tooling problem, but also by poorer data quality and this results in oscillatory behavior that perturbs the whole curve. For the other two firms there are similar tendencies in the cost evolution. It is important to remark that Firm 2 has a higher initial cost in Cold Mass assembly and therefore a better learning percentage had to be expected, indeed. The learning percentages for the Collared Coil assembly phase are reported in Table I: the values we deduced are remarkably similar in all

three production lines. For the Cold Mass assembly phase the values are reported in Table II, and here the difference among different producers is more visible, though they are all within 10% of a mean value.

Fig. 6. Application of the Crawford and Wright models to Cold Mass production in Firm 1.

Fig. 7. Application of the Crawford and Wright models to Cold Mass production in Firm 2.

Fig. 8. Application of the Crawford and Wright models to Cold Mass production in Firm 3.

TABLE I
LEARNING PERCENTAGE ACCORDING TO CRAWFORD AND WRIGHT MODELS
COLLARED COILS PRODUCTION

Firm	Crawford Model	Wright Model
Firm 1	84%	86%
Firm 2	88%	80%
Firm 3	85%	82%

TABLE II
LEARNING PERCENTAGE ACCORDING TO CRAWFORD AND WRIGHT MODELS
COLD MASS PRODUCTION

Firm	Crawford Model	Wright Model
Firm I	92%	N/A
Firm II	78%	72%
Firm III	82%	88%

IV. RELATIONSHIP BETWEEN UNIT INCREMENTAL COST, MANPOWER EMPLOYED AND WEEKLY PRODUCTION RATE

In order to evaluate the limitations of the production process necessary to assemble an LHC Main Dipole, it is useful to check if the process itself can be scaled up in size. In other terms, the aim is to verify if the main assembly tool provided by CERN is a limiting factor in the cost progress. If this is the case the addition personnel would not generate an increase in the production rate. It would also be visible in a rebound of the unit incremental costs because more hours would be divided among the same numbers of assembled units.

With the same spirit we can try to estimate which is the lower limit to the cost reduction imposed by the design of the magnet itself, defining such limit as the level at which only the multiplication of the man hours allows increasing the output without any further cost reduction. The analysis is focusing here on the second phase of the manufacture, the Cold Mass assembly. For this process the quantity and type of main tooling installed at the three firms is identical and the production differs only for the choices made by each company concerning the production logistics, production flow, internal organization and management of the staff. Comparing the results among the three firms (Fig. 9, Fig. 10, Fig. 11) it is possible to draw the following conclusions:

- The CERN-provided tooling is not limiting the production rate. It is possible to reach production rate of 5-6 units/week without observing increase in unit cost that would indicate inefficiency (see Fig. 11). With adequate organization all the production phases are scalable at least to a level of 4-5 units/week. Of course here we do not discuss items like different labor regulations and social issues and traditions that certainly affect the choice of each manufacturer.
- Higher production rates normally match lower production costs. This is not true for Firm 2 with an output of 3 CM/week. This rate had been very rarely achieved by this company at the moment of study and therefore statistics was certainly not yet reliable. The results of Firm 3 show that there is still margin for an even more pushed optimization. Firm 3 reached a weekly rate higher than 4 units per week 8 times over the about 100 weeks analyzed. It is worth mentioning that it should be verified that very high production rates of 5 or 6 units per week over long periods would not be detrimental for the final product quality.

- The lower limit of the production cost for CM unit is set to values equal or lower than the reached 0.5 A.C.U. (Arbitrary Cost Unit) .

Similar observations are feasible also for the processes related to the collared coil assembly with some remarks

Fig. 9. Incremental cost of produced units respect to number of workers employed and weekly production rates. Firm 1.

Fig. 10. Incremental cost of produced units respect to number of workers employed and weekly production rates. Firm 2.

Fig. 11. Incremental cost of produced units respect to number of workers employed and weekly production rates. Firm 3.

- Firm 1 can suffer of inherent limitation starting from a production rate of 4 CC/week due the smaller winding capacity with respect to the other two firms.
- the lower limit in cost seems to be set at 0.5-0.6 A.C.U., value that has been reached both by Firm 2

and Firm 3. Both of them reaches such cost starting from a rate of 4 CC/week, but it is worth mentioning

Fig.12 . Application of the Log Linear model (dashed line) to the Collared Coil production data of the Firm 3 (dots).

that Firm 3 can produce up to 8 CC/week without incurring in inefficiency.

V. LEARNING IN TERM OF REDUCTION OF PRODUCTION TIME

As discussed in the previous section, the production of the LHC main dipoles is not in a regime which is limited by the tooling availability (except may be for the winding limitation in Firm 1). Therefore it is useful to look at the evolution of the labor time necessary for the assembly of one unit in function of the cumulative quantity of produced units. This will allow appreciating the real effect of learning on the processing time. Different models exist in order to best fit the reduction in production time with the accumulated experience. In this work the following models [4,5] have been taken into consideration:

1. A simple potential relation, called Log Linear model:

$$t_n = t_1 \times n^b \quad (5)$$

where t_1 is the time necessary to assemble the 1st unit. $b < 1$ provides the exponential decrease of the assembly time, see Fig. 12.

2. De-Jung model:

$$t_n = C_{in} + t_1 \times n^b \quad (6)$$

where C_{in} represents the incompressible assembly time which it is not possible to reduce, this time being limited by physical factors like tooling availability.

3. Stanford-B model:

$$t_n = t_1 \times (n + C_{ex})^b \quad (7)$$

in this case C_{ex} represents an evaluation of the benefit that the company can derive from previous similar productions. It is expressed in terms of units.

4. S-curve model:

$$t_n = C_{in} t_1 \times (n + C_{ex})^b \quad (8)$$

that combines the previous 2 models

As previously done for the Crawford and Wright cost model, also for the Log Linear model it is possible to express the ability to learn and to improve as a learning percentage ($l.p.$). This parameter indicates the fraction to which the unit production time is reduced every time the quantity of assembled units doubles (see formula 9).

$$\frac{t_{2n}}{t_n} = \frac{t_1 \times (2n)^b}{t_1 \times n^b} = l.p. \quad (9)$$

The value of b is deduced by fitting the available production data with the equation (5). The results, in terms of $l.p.$, are reported in Table III.

TABLE III
LEARNING PERCENTAGE ON MAN HOURS EMPLOYED

Firm	Collared Coil	Cold Mass
Firm 1	78%	87%
Firm 2	68%	66%
Firm 3	74%	63%

It is important to remark the impressive results in Firm 2 both for CC and CM and Firm 3 for CM (63% of $l.p.$!). However this might also be a sign of a very high initial value of hours spent per unit. Applying the De-Jung models the data are better fitted and the learning performance gets closer among the 3 firms (Table IV). For this model the $l.p.$ is not constant along the production: the values for the 30th unit ($l.p.$ (30) end of pre-series) and for the last assembled magnet ($l.p.$ (416)).

TABLE IV
LEARNING PERCENTAGE AND PREVIOUS EXPERIENCE INDICATOR ON MAN HOURS EMPLOYED

Firm	Collared Coil			Cold Mass		
	$l.p.$ (30)	$l.p.$ (416)	C_{ex}	$l.p.$ (30)	$l.p.$ (416)	C_{ex}
Firm I	78%	78%	0	88%	84%	4
Firm II	84%	80%	9	84%	70%	24
Firm III	75%	74%	1	74%	70%	2

Concerning the higher experience coefficient of Firm 2, it is worth mentioning that effectively Firm 2 has been the first company active in the assembly of LHC main dipole participating to the development of all the long models and has been active in the construction of the HERA dipoles, the only previous project somehow similar to LHC in Europe. However the good learning might also be due to slower taking off of the production in Firm 2, which might have helped in labor optimization. This long time accumulated experience seems to be visible in particular from the estimated C_{ex} parameter. The De-jung model and the S-curve model have resulted to be of difficult application due to scattering of the

data that obliges to impose artificial limits for the C_{in} parameter. Referring to the Log Linear model, despite of the large oscillation, we can estimate that the typical learning percentage for the LHC Main Dipole Assembly is between 70% and 80%. During RHIC construction the estimation of similar parameter provided, a value of 85% [10, 11].

TABLE V
LEARNING PERCENTAGE OF SELECTED REFERENCE INDUSTRIES

Industry	$l.p.$
Complex machine tools for new models	75%-85%
Repetitive electrical operations	75%-85%
Shipbuilding	80%-85%
Aerospace	85%
Purchased Parts	85%-88%
Repetitive welding operations	90%
Repetitive electronics manufacturing	90%-95%
Repetitive machining or punch-press operations	90%-95%
Raw materials	93%-96%

Comparing the results obtained from the present analysis with the data available in literature for different industries (Table V) the LHC Main Dipole production positions itself, among the fastest learning activities. It is situated in the range of the activities related to the assembly of complex machine tools and repetitive electrical operations. It is worth remarking that the high $l.p.$ value found are probably related to:

1. The novelty of the fabrication (respect to the more conventional products as those reported in Table V). This caused longer assembly time at the beginning of the production, which translates thereafter in higher learning percentage.
2. The introduction in the assembly line of additional tooling after the beginning of the production. This event has "doped" the learning rate.

To verify the previous statements it is possible to apply the Log Linear mode to progressively reduced subset of data.

Fig. 13 . Evaluation of the learning percentage ($l.p.$) for progressively reduced subset of the production data

The 1st set makes use of the data referring to unit 1 till unit n , where n is the last produced magnet; the second set takes from unit 2 till n ; the i^{th} set from unit i to n . In Fig. 13 the results till $i=100$ for Firm 3 are reported; for smaller subsets the oscillation caused by units where repair actions were necessary (they have longer assembly time) are such that the

results are meaningless. The graph confirms the previous hypothesis: the production of the first units is characterized by a very high learning percentage showing that, in this phase, major tooling improvement, workforce redeployment and procedure optimization were taking place. After this initial phase (till magnet 35-40) a second regime takes over where the learning percentage oscillates between 85% and 95% showing that "standard" improvement due to "slow" day by day learning is now predominant.

VI. CONCLUSIONS

The learning curve analysis has been applied to the first part of the production of the main dipoles for the LHC. A preliminary result is that the production of LHC has a high learning percentage, mainly due to long time required in setting up the process in the first units and to the very effective automation introduced during production. The main tooling installed is not, almost everywhere, a limiting factor and the choice of having three suppliers, taken in order to secure the planning of the project, was actually very good also for cost minimization. However more detailed and complete conclusions will be drawn when the whole production is finished, at the end of 2006, thanks to larger statistics and better and more stable production rate that we are experiencing in the second half of the dipole manufacture.

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