Quality Assurance for the Design of Prototypes at the World's Largest Particle Measurement System

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Abstract. *At CERN (European Organization for Nuclear Research, Geneva, Switzerland) is the most powerful particle collider in the world under construction. The aim of the project is to discover more about of the secrets of the different states of matter at the "Big Bang" and the universe. It will be the first time that an accelerator with a diameter of 9 km runs totally on super conductive magnets. Because of this challenging dimensions, the needed accelerator, detectors and machines will be unique in the world and so all of them will be operating prototypes. To reach the product specification of those installations, the project organisation needs purpose designed Quality Assurance tools to fulfil their scientific objects.*

1. Introduction

The Large Hadron[1] Collider (abbr. LHC [1]) project at CERN is a new generation of particle accelerator, which will replace the old Large Electron - Positron (abbr. LEP [1]) accelerator. The LEP collider was in operation from the mid 80's of the last century till November 2000 when the machine was shut down forever. The LHC will bring particles into head-on collisions with energies around 7 TeV[2] for proton beams or for heavy ions such as lead with a total collision energy of 1250 TeV. This will be unique in the world accelerators. Scientists expect, that they will be able to determine the structure of matter with a higher "resolution" than now and recreate so the conditions prevailing in the early universe, only 1 microsecond ($1 \cdot 10^{-6}$ sec) after the so called "Big Bang" [2].

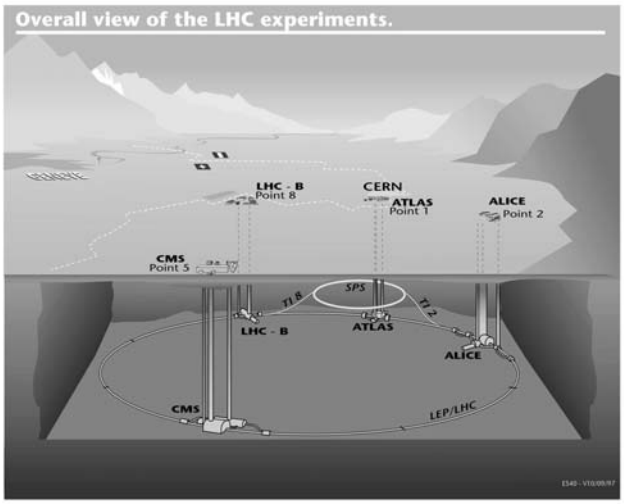

Figure 1:Cross-section of the LHC project [1]

The accelerator is built astride the Franco-Swiss border in the west of Geneva at the foot of the Jura Mountains, where it uses the existing tunnel with some small modifications from the former LEP collider. The tunnel and so the trajectory of the accelerated particles has a main diameter of 9 kilometres.

The commissioning date of the LHC project (the collider plus the four main detectors: ATLAS, CMS, ALICE and LHC-B) is foreseen for the year 2007/08 (state of affairs in December 2004).

[1] A hadron is a nuclear particle, which consists only of quarks - like protons, neutrons and mesons.
[2] TeV = Tera electron volts = 10^{12} eV, 1 eV = 1.602176462 10^{-19} J;
The unit eV is used by physicist to express the amount of energy of particles at the level of the atomic scale.

2. Area of Subject:

The Mechanical Engineering Design Process - MEDP

The MEPD for mechanical parts has normally a non-linear work progress during the project time. The reason for this are following effects [3]:

A) The human influence in the process:
1. Because the process is executed by human species (→ Murphy's law !)
2. The performers are learning to solve the project specifications by doing the project work packages
3. The non-linear run of the human learning curve

B) The technological progress during the process (important for long time projects)

C) The boundary conditions of the resources (budget, time, human recourses, technology, material properties, unforeseen internal and external events, …)

D) The change of the costumer specifications during the time

Because of those reasons, the progress of the engineering evolution can be approximated most times with a step function. This means, that from one level to a new level it stays stable (or with a very flat increase) for a while on the level till it will jump to the next progress step.

Load

The load of a system normally consist of two main parts and a system immanent part:

1. The Net Load Force (abbr.: NLF)
   The definition of the NLF is, that these are the real loads on the mechanical system. These loads are mass- , fluid- , thermal- , magnetic- and electrostatic forces.
2. The Support and Service Weight (abbr.: SSW)
   Samples for the SSW are cables, pipes and very often forgotten the weight of the fluid in the pipes, pumps, ladders, stairs, catwalk + humans on them,… .
3. The SelfWeight of the load-bearing Structure (abbr.: SWS) is the system immanent part, which can't be neglected for big and heavy structures. The SWS is a direct proportional function of NLF and SSW f_{SWS}(NLF, SSW). This is logic, because the higher the NLF and SSW is, the more material must the structure have to bear the load.

The main sub-process in the MEDP is the Design Iteration Process (DIP).

The Design Iteration Process (DIP)

Normally, the NLF is given or can be calculated according to the steady state operation modus of the system (If the maximum exposure is in the start or shout down phase, then of course one has to use these values) [4].
The SSW depends of the NLF and can be estimated directly for certain fields of applications with a percentage rate of the NFL for the first iteration. For this estimation it would be recommended, if experience from previous projects or similar fields of application is available and could be applied on. But also good engineering books offer realistic values for common cases in the field of industrial design.

As stated, the SWS is a function f_{SWS}(NLF, SSW). For the estimation in the first design iteration process, a percentage of 15 % from the Σ (NLF, SSW) can be normally expected. This value depends on the used material of the structure and the yield stress/density ratio (how much stress can be applied on per density unit).

Depending on the customer specifications, there are different kind of ways in which direction the system can be optimisation:

- Maximum stress of the structure (maximum utilisation of the material yield stress without fracture or material fatigue),
- Minimize the strain/deformation of the structure,
- Minimize the weight of the structure,
- Minimize the volume of the structure due to the free space in the environment,
- Target cost/minimize the cost for the structure or
- Combination of those points.

A theoretical model of a virtual design iteration:

Following assumptions have been made for this sample (see Figure 2):

- The loads didn't change for the structure during the design iteration (which is not the case in reality)
- Constant salary and material prices during the virtual project time,
- No major influence from the environment,
- A constant continuous work progress by the engineering team, which is not always reality.
- A smooth transition in the different structure materials. In reality, the transition is more discrete and consists of many single areas.
- Increase of the amount of money by time unit is also not continuous, if one will state it correctly. The personal expense (salary), which I want to express with this increase, is only paid once per month. This means, that there would be some steps in the graphic and than it would be stable.
- Only the salary of the direct on the project working engineer was considered, no
  - Overhead costs or
  - Depreciation on utilised capital goods

1. Iteration start:
   The material properties of a good fitting material will be used for the first structure iteration.
2. The result of the 1st iteration
   The optimisation process result of the structure is positive. This means in term of cost effectiveness, that the personal expenses during the time of iteration for the engineers were lower than the savings on the material costs.
3. Result of the 2nd iteration
   The optimisation process of the structure was also positive. But the boarder of the material properties has been reached. But in the close area exists a material, which has better properties on one hand and on the other it is more expensive. Does it still offer more savings?

4. Result after the change of the material
   With the new material it was possible to decrease the material costs further. This was possible, because the increase of the ratio yield stress/density was higher than the ratio material costs per mass unit/density by the change of the material.
5. Result after the 3rd iteration
   The optimisation process of the structure is further positive.
6. Result after the 4th iteration
   The optimisation process of the structure became negative. This means, that the personal expenses for the last iteration were higher than the savings on the material costs. The maximum of the cost effectiveness (is equal to the minimum of developing and purchase costs) was passed during the last iteration. The designing process should now be stopped because of economical reasons.

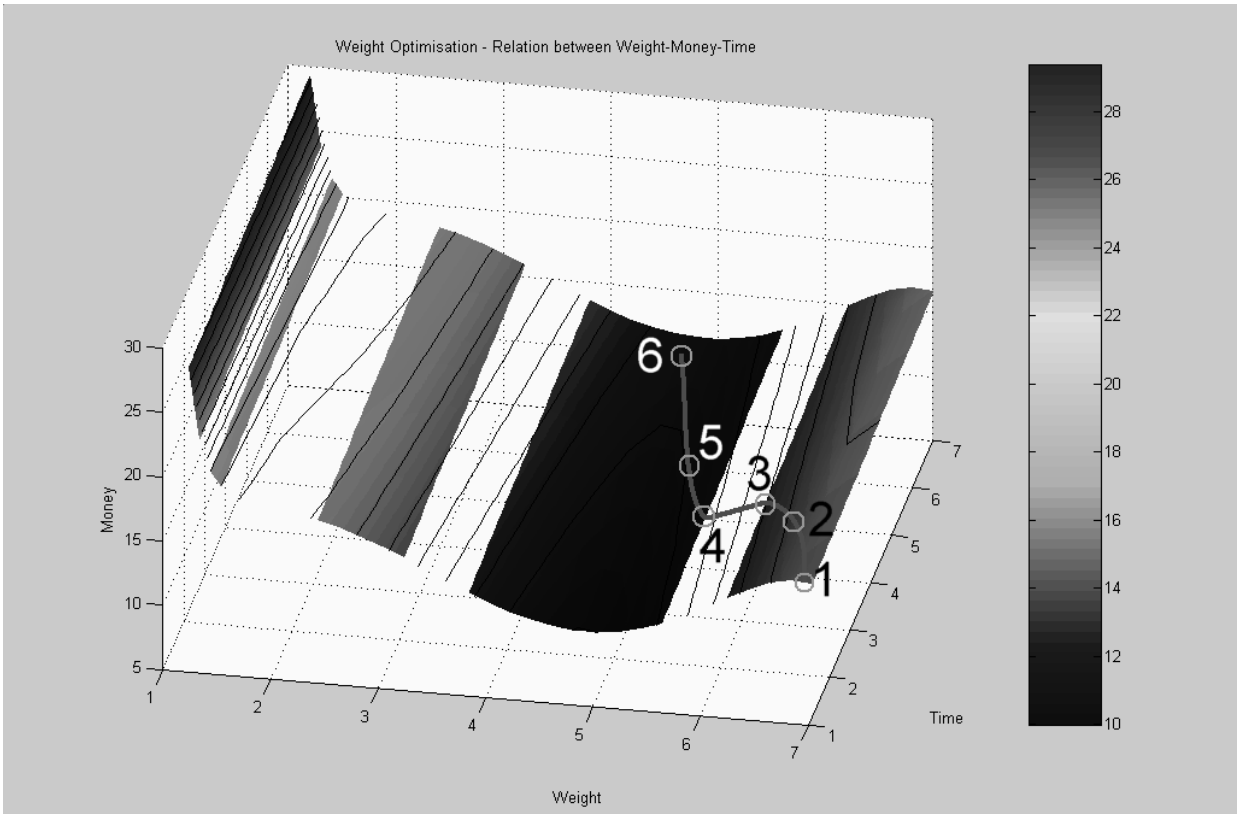

Figure 2: Weight Optimisation – Relation between Weight - Money - Time

A tool, which will help to reduce the project lead time by finding a better starting point (means: a better fitting material) for the iteration process, where less numbers of iterations will be necessary for DIP, is the Material Rating Number (abbr.: X-MRN)

The Material Selection - The Material Rating Number (X-MRN).

The materials, which are used for the manufacturing of the accelerator and the detectors, must fulfil a large number of requirements for their use. Due to the reason that in today's world numerous of materials are available from the raw/basic material industry, which can be applied for the type of the construction, it is not so easy to decide which material is the best in all categories (like in the material properties, the price, the environmental friendliness,...). [5]

And because of the material matrix has most times more than two categories (= columns) to compare for more than two materials (= rows), it is not obvious to choose the right material under this complex conditions. Also it will be hard to retrace years later after the decision was made, why the responsible engineer had chosen that material and not a different one without achieving the reasons. To avoid this cause, the MRN tool was developed. For this reason, I have developed four material rating numbers (Material Rating Number = MRN) also expressed as "X-MRN". The "X-" states here for all four prefixes or the different versions of the method:

A = Absolute	AW = Absolute Weighted,
R = Relative	RW = Relative Weighted

"Absolute" in this case means, that the entry in the matrix states directly the material property, but without their dimensions.
"Relative" in this case means, that the entry in the matrix states the material property depending on the value of the properties of the other materials, which are in the investigation. The maximum possible numbers, which can be related to the materials, is equal to the amount of materials, which are foreseen for the construction, starting with 1.
It is not necessary that one know the correct values of the material properties, the only thing what you have to know is, how the materials are ranked to each other. This method can be understood as a way of describing the situation and express it in numbers. So it can be used for attributive values like, very heavy - very light, beautiful, colourful,... .

The Algorithm

The algorithm, which was defined, is a normative one.
This means, it calculate the X-MRN of each category independent of the size of the values of the entry. The modus operandi of the algorithm is following:

1st: it defines an arithmetic average level for each category (column) and calculate according to this average level the column X-MRN position of each entry.

2nd: it multiplies all local rows X-MRN to get the total X-MRN of the material.

$$\underline{A}_{m,n} = \begin{vmatrix} w_1 \cdot a_{1,1} & \cdots & w_n \cdot a_{1,n} \\ \vdots & \ddots & \vdots \\ w_1 \cdot a_{m,1} & \cdots & w_n \cdot a_{m,n} \end{vmatrix} = (w_j \cdot a_{ij})_{m,n}$$

Equation 1: material property matrix with weighted categories

$$X - MRN_i = \frac{\prod_{j=1}^{n} a_{i,j}}{\prod_{j=1}^{n} \overline{a}_{m,j}} = \frac{\prod_{j=1}^{n} a_{i,j}}{\prod_{j=1}^{n} \left(\frac{1}{m} \cdot \sum_{i=1}^{m} a_{i,j} \right)}$$

Equation 2: X-MRN$_i$ algorithm

$$X - MRN_i = \frac{\prod_{j=1}^{n} w_j \cdot a_{i,j}}{\prod_{j=1}^{n} \overline{w_j \cdot a_{m,j}}} = \frac{\prod_{j=1}^{n} w_j \cdot a_{i,j}}{\prod_{j=1}^{n} \left(\frac{1}{m} \cdot \sum_{i=1}^{m} w_j \cdot a_{i,j} \right)}$$

Equation 3: X-MRN$_i$ algorithm with weighted categories

Attention! The result will be distorted, if you mix maximal (yield strength, E-modulo or Young's modulo,...) and minima (price, density,...) criterions.

Solution:
It is recommended to choose the maxima criteria (the larger the number, the better) because for mankind it is easier to see and realise the difference and ratios in larger numbers than in small ones.
Categories (columns), which belong to the selected criterion, can be filled in directly with the entries. Entries, which belong to the opposite criterion, must take the reciprocal value of the specific entry ($1/x$, x^{-1}) before they can fill in the number in the matrix.

"Weighted":
If one prefer or want to emphasize a category/property especially for the optimisation (like the price or the yield stress), it is possible to multiply those categories with a weight "w". If the maximal criterion was chosen, "w" must larger than 1 ($w > 1$). The bigger the weight "w" is, the more the X-MRN of the material will be influenced by the weighted category.
The same rule is also valid for the minima criterion, but the weight variable "w" must be smaller than 1 ($w < 1$).

3. The Result

As it is state, this is a normative algorithm for the X-MRN and the normative level is defined with 1. This means, that candidates, which have a X-MRN = 1 or ~1, are average performers. If the maximal criterion was chosen for the general strategy, all candidates which have a X-MRN bigger than 1 (X-MRN > 1) are over performers and such with a large positive difference to 1 (X-MRN >> 1) are extremely over performers. They fulfil the specifications best, compare to the other participants.
Vice versa, all candidates, which X-MRN is lower than 1 (X-MRN < 1) are underperformers.

If the minima criterion was chosen, is it the same procedure – only with changed positions (candidates with lower X-MRN are better (X-MRN < 1) and those with large X-MRN aren't preferable (X-MRN > 1).

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[1] With the courtesy of CERN, Genève, CH, © 2005 Copyright CERN

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