

# AVAILABILITY ALLOCATION TO PARTICLE ACCELERATORS SUBSYSTEMS BY COMPLEXITY CRITERIA

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## Abstract

In the early design stages of an accelerator, an effective allocation method is needed to translate an overall accelerator availability goal into availability requirements for its subsystems. During the allocation process, many factors are considered to obtain so-called ‘complexity weights’, which are at the basis of the system availability allocation. Some of these factors can be measured quantitatively while others have to be assessed qualitatively. Based on our analysis of factors affecting availability, we list six criteria for complexity resulting in an availability allocation of accelerator subsystems. System experts determine the scales of factors and relationships between subsystems. In this paper, we consider four availability apportionment techniques to allocate complexity weights to subsystems. Finally, we apply this method to the Compact Linear Collider (CLIC) and we propose another application of the complexity weights to the Large Hadron Collider (LHC).

## INTRODUCTION

The Availability allocation method aims at translating the overall accelerator availability goal into individual availability requirements for its subsystems. This is particularly useful for cases in which detailed designs are not available or when new technologies are developed and no failure data is available for a detailed assessment. The typical application is therefore during the concept phase of a project.

During the allocation process, many factors are considered to obtain so-called complexity weights. These complexity weights are then used to allocate relative availabilities to the system components in relation to their weights.

Many methods exist in literature for reliability allocation [1, 2, 3, 4]. In this paper we present a similar methodology but tailored to the availability allocation for particle accelerators, based on complexity criteria. The proposed method is illustrated by two uses cases.

## CRITERIA FOR COMPLEXITY ALLOCATION

Based on our analysis of accelerator subsystem characteristics affecting availability, the following six factors are considered to evaluate the complexity of an accelerator system.

1. *Repair time.* The repair time of a subsystem represents the time that is needed to restore operation after a failure. This includes the identification of the failure, access to the subsystem, repair and recovery to the nominal operational state. The longer it takes to repair the subsystem, the more complex the subsystem becomes. The repair time is scored on a scale from 1 (short repair time) to 10 (long repair time).

2. *Criticality.* Assuming that machine protection systems are in place for a machine, the criticality of a subsystem represents the fraction of the subsystems interlocks that can trigger a beam abort over the total number of interlocks of the accelerator. It reflects the impact of its failure on the accelerator beam availability. The subsystems with high criticality, are allocated a higher complexity weight. Since it is difficult to calculate the exact number of interlocks in a system under design, the criticality is scored on a scale from 1 to 10. The subsystems with high criticality are rated 10, and the ones with lower criticality 1.
3. *Intricacy.* The intricacy of a subsystem represents the internal complexity of the subsystem. The more complexly interacting parts or elements it has, the more intricate it is. In the same way, highly intricate systems are allocated higher complexity weight. The intricacy is scored on a scale from 1 to 10; the less intricate subsystem is rated 1, while the most intricate subsystem is rated 10.
4. *State of art.* The state of art of a subsystem considers the design maturity or level of development of a given technology. Higher complexity weight will be allocated to more innovative technologies. Possible values are: 10 for innovative subsystems; 6.7 for existing technologies; 3.3 for established technologies.
5. *Performance time.* The fraction of the total operating time that the subsystem is requested to perform its function influences the required subsystem availability. Possible values are: 10 for whole mission time of operation; 6.7 for continuous and long times; 3.3 for instantaneous and shorts times.
6. *Environment.* In an accelerator facility, some subsystems are subjected to high radiation doses. A subsystem experiencing harsh conditions will tend to fail more or will require more development to avoid failures due to radiation. Possible values are: 10 for subsystems under highly radioactive environment; 6.7 for average radioactive; 3.3 for low radioactive.

For a given application, the scores of the factors above are determined by design engineers and experts.

## METHODS FOR COMPLEXITY ALLOCATION

In order to allocate complexity weights to subsystems from the factors scores, four existing availability apportionment techniques are discussed below. The techniques assume that the accelerator has  $n$  subsystems which have to work for the accelerator to be operational.

**FOO Technique** [2]. Feasibility-Of-Objectives is a typical approach mentioned in the MIL-HDBK-338B [5],

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in which subsystems are appraised by only four of the factors mentioned above: Intricacy (I), State of Art (S), Performance (P) and Environment (E). The complexity weight or ISPE factor is derived from the product of the factors  $w_i = I * S * P * E$  and the complexity for availability allocation is calculated as:

$$C_i = \frac{w_i}{\sum_{i=1}^n w_i} \quad (1)$$

**Average weighting allocation methods** [3]. Let  $B_{iF}$  represent the score of the six factor explained above for the  $i$ -th subsystem ( $i = 1, \dots, n$  and  $F = 1, 2, \dots, 6$ ). The subsystem complexity weight can be defined in three different ways:

*Factors product:*  $w_{P_i} = \prod_{j=1}^6 B_{ij}$  (2)

*Factors sum:*  $w_{S_i} = \sum_{j=1}^6 B_{ij}$  (3)

*Bracha technique:*

$$w_{B_i} = B_{i4} * (B_{i1} + B_{i2} + B_{i3} + B_{i5} + B_{i6}) \quad (4)$$

Hence, with allocated complexity weight  $w_i$ , the complexity for availability allocation of the  $i$ -th subsystem is calculated as in Eq. (1).

Note that for each system with allocated complexity  $C_i$ :

$$\sum_{i=1}^n C_i = 1 \quad (5)$$

While the factors product and factors sum give equal importance to the factors, the Bracha technique gives more importance to the State of Art of the subsystem.

In all the considered methods, the possible interactions between subsystems are not considered. To this end, the above techniques can be combined with the DEMATEL procedure [6]. The DEMATEL procedure was first developed in the Geneva Research centre and provides a tool to analyse system interactions in many industrial fields. In this paper we propose to use this method to evaluate the degree to which a failure in subsystem  $i$  affects subsystem  $j$  in terms of the induced downtime. The method will increase the allocated complexity of a subsystem if high impact of a given system on others is observed.

### Outline of the DEMATEL Procedure

The basic steps of the DEMATEL procedure are reviewed below.

**Step1.** Design engineers conduct pair-wise comparisons to evaluate the degree to which a failure in subsystem  $i$  affects subsystem  $j$  in terms of induced downtime. The pair-wise comparison is designated into 4 levels, where scores of 0, 1, 2 and 3 represent the influence levels: “No influence”, “Low influence”, “High influence”, and “Very High Influence”, respectively.

Let  $z_{ij}$  be the degree to which subsystem  $i$  affects subsystem  $j$ . Accordingly, all principal diagonal elements  $z_{ii}$  are set to zero. Hence, the indirect relation matrix,  $Z$ , is an  $n \times n$  matrix:

$$Z = \begin{pmatrix} 0 & \dots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \dots & 0 \end{pmatrix} \quad (6)$$

**Step 2.** Calculate the values of  $R$ - $d$  by computing:

The normalized direct-relation matrix,  $X$ , and the total relation matrix,  $T$ :

$$X = \frac{Z}{s} \text{ where } s = \max_{1 \leq j \leq n} \left( \sum_{i=1}^n z_{ij} \right) \text{ and } T = X(I - X)^{-1} \quad (7)$$

Let  $t_{ij}$  be the elements of the total relation matrix  $T$ ,  $R_i$  the sum of the rows and  $D_j$  sum of the columns of  $T$ , then, the  $R$ - $d$  value is derived by obtaining the  $d$  value through the following formula:

$$d_i = \frac{d_i}{\sum_{i=1}^n d_i} : R_i = \sum_{j=1}^n t_{ij} \text{ and } D_i = \sum_{i=1}^n t_{ij} \quad (8)$$

**Step3.** Use Eq. (9) to calculate the allocated complexity weight:

$$w_i^D = w_i * (R - d)_i \quad (9)$$

where  $w_i$ : the allocated complexity weight according to one of the above techniques and  $(R - d)_i$ : the  $R$ - $c$  value of the subsystem  $i$ .

## AVAILABILITY ALLOCATION METHOD BASED ON COMPLEXITY

Let  $A_T$  be the overall availability goal for the accelerator machine and  $C_i$  the allocated complexity for the  $i$ -th subsystem. Then, the availability requirement for the  $i$ -th subsystem is defined as:

$$\tilde{A}_i = A_T^{C_i} \quad (10)$$

Note that  $A_T = \prod \tilde{A}_i$ ; the subsystems are allocated the required availability to ultimately meet the overall machine availability target.

### CASE STUDY I: CLIC

The proposed method is applied to the Compact Linear Collider (CLIC), the study for a future accelerator to collide electrons and positrons [7]. The ultimate availability target for CLIC is set to 80%. For this example, the major subsystems of CLIC are considered (see Figure 1). System experts determined the scales of the factors and performed the DEMATEL procedure to assess the dependencies among subsystems.

The comparison of the four methods for availability allocation is shown in Figure 1. The results are shown in terms of unavailability, expressed as 1 minus availability.

The Two Beam modules and the Damping Ring Complex are considered the most complex subsystems and therefore, are assigned the lowest availability requirements. Consequently, less complex systems such as the Access and Technical Alarm System are given the higher availability requirements.

While the four techniques for complexity allocation together with the DEMATEL procedure show similar results, the factors product seems to represent better the complexity of a system, according to expert evaluations, this is therefore taken as a reference for the second case study.

### CASE STUDY II: LHC

For already operating accelerator machines, the proposed method could be used to compare the observed availability and the allocated or expected availability according to the complexity criteria.

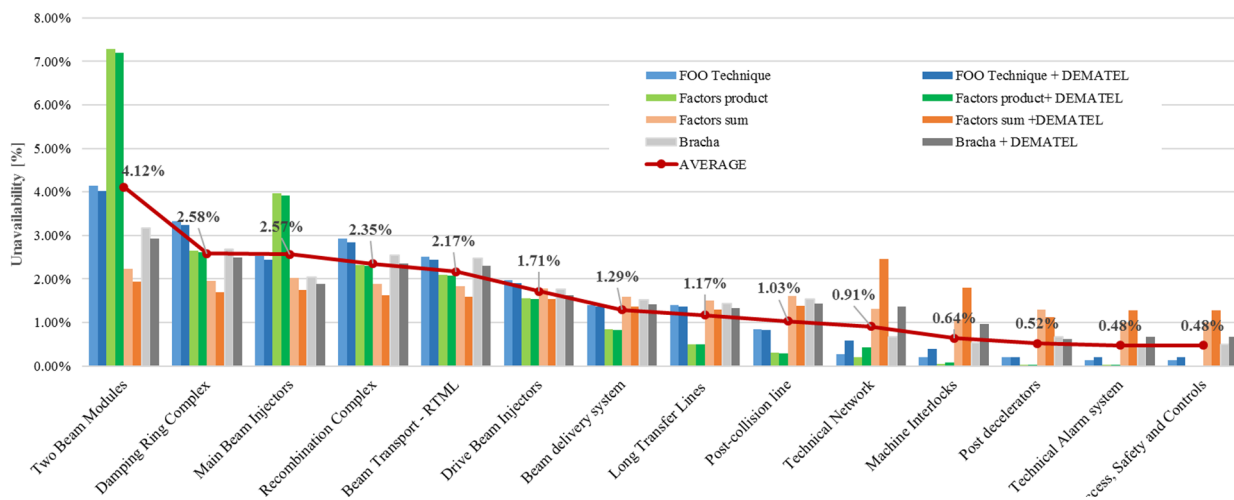


Figure 1. Availability allocation to CLIC subsystems based on complexity criteria.

For a given machine of  $n$  subsystems, let  $A_S$  be the achieved machine availability over a given period and let  $A_i$  be the observed availability of the  $i$ -th subsystem. With allocated complexity  $C_i$ , the allocated availability of the  $i$ -th subsystem,  $\tilde{A}_i$ , based on its complexity is calculated following Eq. (10). Note that the product of the subsystems allocated availability is the observed machine availability, i.e.:  $A_S = \prod A_i = \prod \tilde{A}_i$ . Therefore, it provides a tool to evaluate if the machine subsystems performed better or worse than required based on complexity.

- If  $\tilde{A}_i > A_i$ , the subsystem was required higher availability based on complexity, i.e. it performed worse than required.
- If  $\tilde{A}_i = A_i$ , the subsystem performed as required based on complexity.
- If  $\tilde{A}_i < A_i$ , the subsystem was allocated lower availability based on complexity, i.e. it performed better than required.

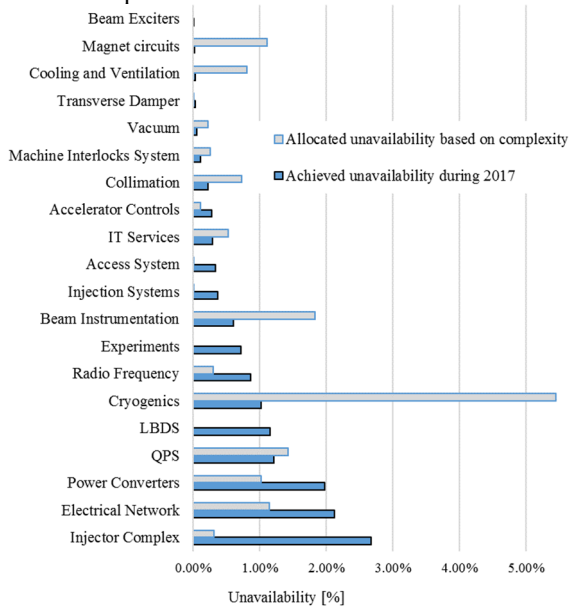


Figure 2. LHC subsystems 2017 unavailability and allocated unavailability based on complexity criteria.

**Case study** The Large Hadron Collider (LHC) 2017 performance data [8] is used to illustrate the proposed methodology. The availability of the LHC in 2017 was more than 85%.

Based on system experts evaluation of the factors and the DEMATEL procedure, the LHC subsystems complexity is allocated following the factors product technique together with the DEMATEL procedure. Figure 2 shows the comparison between the achieved unavailability of the LHC subsystems during the 2017 run and the allocated unavailability based on complexity.

Magnets circuits and Cryogenics showed a better performance than estimated; during 2017 no quenches of the magnets circuits and only few long stops of the Cryogenics were observed. Although the injector complex performance was better than expected during 2017 in comparison with previous years of operation, the allocation method is showing the opposite. This is due to the fact that the Injector Complex is only required to operate for the LHC while injecting beam, which cannot be adequately taken into account in the DEMATEL procedure.

## CONCLUSIONS

A comprehensive method is proposed in this paper for allocating the accelerator availability goals to each of its subsystems. This method can also be used to evaluate existing machine performance with respect to the expected performance.

From the four complexity allocation techniques, the factors product seems to represent better the complexity of an accelerator machine. Using the DEMATEL procedure interactions between subsystems are also considered.

It is recommended that more than one expert perform the factors evaluation and DEMATEL procedure in order to limit the subjectivity of the method.

Finally, we have shown the advantages and potential of the presented methods with their application to two different accelerators. For CLIC, an accelerator under design, the method allows identifying the subsystems to which particular attention needs to be paid in the design phase to be able to achieve the overall availability requirements. For the LHC, an already operating accelerator, the method seems

to give intuitive results and the few observed deviations can be explained.

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