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Availability of Particle Accelerators: requirements, prediction methods and optimization

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Availability of Particle Accelerators: requirements, prediction methods and optimization

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Kurzfassung

Verfügbarkeit von Teilchenbeschleunigern: Anforderungen, Prognosemethoden und Optimierung

Von der Entwurfsphase bis zum Betrieb stellt die Maschinenverfügbarkeit einen der wichtigsten Indikatoren für die Leistungsfähigkeit eines Teilchenbeschleunigers dar. Die Verfügbarkeitsanforderungen werden typischerweise zu Beginn eines Projekts festgelegt und sollten während der Betriebsphase eingehalten (oder nachgewiesen) werden. In den frühen Entwurfsphasen eines Beschleunigers wird eine effektive Zuordnungsmethode benötigt, um das Ziel der Gesamtverfügbarkeit des Beschleunigers in Verfügbarkeitsanforderungen für jedes Teilsystem zu übersetzen. Dies ist von besonderer Bedeutung für Anwendungsfälle, in denen das detaillierte Design nicht bekannt ist oder in denen neue Technologien entwickelt werden und keine Ausfalldaten verfügbar sind. In dieser Arbeit wird eine neuartige Methode zur Aufteilung der Verfügbarkeitsanforderungen basierend auf der Komplexität der Beschleuniger-Subsysteme vorgeschlagen.

Bei der Auslegung komplexer, verfügbarkeitskritischer Teilchenbeschleuniger ist die Implementierung eines detaillierten Verfügbarkeitsmodells, das die Zuverlässigkeitsdaten der Komponenten zur Abschätzung der Gesamtsystemverfügbarkeit nutzt, besonders nützlich, um deren Machbarkeit zu demonstrieren und Änderungen mit hohem Verbesserungspotential der Verfügbarkeit zu identifizieren. Um die Vollständigkeit und Konsistenz der Studien zu gewährleisten, wird eine mehrstufige Methode für die Definition von Verfügbarkeitsmodellen vorgestellt. Beim Betrieb von Teilchenbeschleunigern werden Verfügbarkeitsmodelle auch zur Optimierung der Maschinenleistungsfähigkeit eingesetzt. In beiden Fällen hängt die Zuverlässigkeit der Ergebnisse stark von der genauen Kenntnis der Eingangsdaten ab. Daher sind Werkzeuge zur Verfügbarkeitsüberwachung von entscheidender Bedeutung, um eine zuverlässige Datenerfassung zu gewährleisten. In dieser Arbeit wird die Leistungsbewertung des Linac4 während eines Zuverlässigkeitstestlaufs unter Verwendung des am CERN entwickelten Accelerator Fault Tracking Systems vorgestellt.

Das letztendliche Ziel von Studien zur Verfügbarkeit von Beschleunigern ist es, die Systemdesigns und Betriebsmodi zu identifizieren, die zu der besten Leistung des Beschleunigers bei geringsten Kosten führen. Zu diesem Zweck wird eine Methode zur Sensitivitätsanalyse vorgeschlagen, um die Komponentenupgrades zu identifizieren, die zur effektivsten Erhöhung der Systemverfügbarkeit für eine bestimmte Investition führen. Darüber hinaus hilft die vorgestellte Sensitivitätsanalyse auch bei der Identifizierung potenzieller Ausfälle mit gemeinsamer Ursache (die in den Verfügbarkeitsmodellen nicht berücksichtigt werden)

und anderer kritischer Komponenten, die die optimale Leistung des Beschleunigers erheblich beeinträchtigen können.

Die vorgeschlagenen Methoden werden mit Beispielen von Beschleunigern in der Entwurfsphase und im Betrieb veranschaulicht: für Linearbeschleuniger anhand von CLIC und Linac4 und für Kreisbeschleuniger am Beispiel des FCC und des LHC.

Abstract

From the design phase to operation, machine availability represents one of the key indicators for the performance of a particle accelerator. Availability requirements are typically set at the beginning of a project and should be kept (or demonstrated) during the operation phase. In the early design stages of an accelerator, an effective allocation method is needed to translate the overall accelerator availability goal into availability requirements for each subsystem. This is of particular value for cases in which the detailed design is not known, or where new technologies are developed and no failure data is available. In this thesis a novel method is proposed to allocate availability requirements based on accelerator subsystems complexity.

During the design of complex availability-critical particle accelerators, the implementation of a detailed availability model that uses component reliability data for estimating the overall system availability, is particularly useful to demonstrate their feasibility and to identify improvements with high performance benefit. To ensure the completeness and consistency of the studies, a step-wise methodology for the definition of availability models is presented. In operating particle accelerators, availability models are also used to optimize machine performance. In both cases, the reliability of the results strongly depends on the precise knowledge of the input data. Hence, availability-tracking tools are of crucial importance to ensure reliable data capture. This thesis presents the performance evaluation of Linac4 during a Reliability Run using the Accelerator Fault Tracking system developed at CERN.

The ultimate goal of accelerator availability studies is to determine the system designs and operation modes that would lead to the best performance of the accelerator at lowest cost. To this end, a sensitivity analysis method is proposed to identify the component upgrades that would lead to the best improvement of system availability for a certain investment. Moreover, the presented sensitivity analysis also helps to identify potential common cause failures (which are not considered in the availability models), and other critical components that may compromise significantly the optimal performance of the accelerator.

The proposed methodologies are illustrated with examples of accelerators in the design phase and under operation both for linear accelerators: CLIC and Linac4, and circular accelerators: FCC and LHC.

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Nire betiko laguneri eskerrak emon nahi dizkiet beti nirekin egoteagatik. Nahiz eta urte luzez kanpoan bizi, bueltatzen nahizen bakoitzean hor jarraitzen dutelako bere babesa emoten. Eskerrik asko zuen bizitza urruntasunean ere nirekin konpartitzeagatik.

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1 Introduction

Particle accelerators are used in a wide variety of applications that range from scientific research to industrial processing. In nuclear and particle physics, the aim is to produce the simplest kind of interactions at higher energies to study the fundamental constituents of matter and the forces that act upon them. For this purpose, particle beams are accelerated in either circular or linear accelerators and are made to collide in the experiments. Particle accelerators also play a key role in the study of the structure and dynamics of materials and their properties. At Synchrotron Light Sources, the electromagnetic radiation emitted when charged particles are being accelerated (synchrotron radiation) is used for powerful diffraction and spectroscopy techniques. In Neutron Spallation Facilities, neutron beams are used towards the same objectives. In such facilities, neutron beams are generated via the so-called spallation process: a proton beam is accelerated to high energies in a linear accelerator and made to hit a target. From the collisions neutrons are expelled at high energies and then slowed down before being directed towards the experiments. Neutrons generated via the spallation process are also used in Accelerator Driven Systems (ADS), which provide new possibilities for the transmutation of highly radioactive nuclear waste generated in nuclear reactors. An ADS consist of a sub-critical reactor in which neutrons produced by an accelerator are directed at a blanket assembly containing the waste and are used to maintain the the fission chain reaction in a safer way. Another essential application of particle accelerators is the treatment of cancer, where a particle beam is directed onto the tumor.

Fulfilling the challenging objectives of the current and future particle accelerators poses strong requirements on their performance. In particle physics, for example, the objective is to find the optimal machine performance to get the most particle collisions. One of the key indicators of accelerators performance is

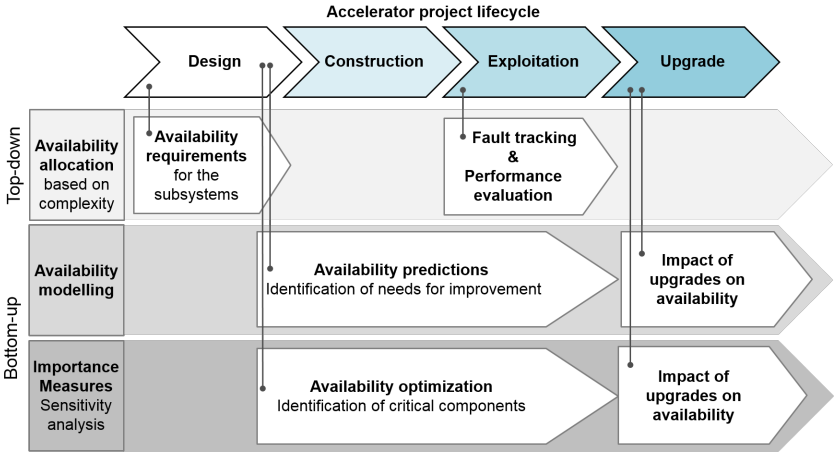


Figure 1.1: Methodology to study and optimize the performance of high energy particle accelerators in terms of availability, from its conceptual design to its exploitation and upgrades.

machine availability, as measure of the time that the particle accelerator spent in operational state without failure. The study and optimization of machine availability is therefore essential through the lifetime of an accelerator. Fig. 1.1 shows the two-pronged strategy presented in this thesis to study the availability of high energy particle accelerators through their lifetime.

In early stage or design phase of an accelerator project, availability studies aim at assessing the feasibility of the project in terms of availability. In other words, the purpose of the studies is to evaluate whether the accelerator project will comply with the target availability requirement. This availability requirement is typically set at the beginning of the accelerator project and should be kept (or demonstrated) during the operation phase. Meeting the overall availability goal directly depends on the availability performance of its subsystems. By setting adequate availability requirements to the subsystems already during the design phase, one can ultimately ensure that the overall accelerator availability goal can be met. In this thesis a

novel availability allocation method for particle accelerators is proposed based on complexity criteria. This method translates the overall accelerator availability goal into availability requirements for its subsystems. The complexity of a system is determined by the evaluation of factors with high impact on machine availability. The more complex a system is, the less stringent its availability requirements will be. This top-down method is particularly useful to set availability requirements in cases where the detailed design is not known, or where new technologies are developed and no failure data is available.

From its design to its construction and upgrade, the availability of a particle accelerators can be studied in detail by the implementation of the so-called availability models. Availability models use component reliability data to estimate the overall accelerator availability. In the design phase, availability models are used to demonstrate the applicability of the accelerator project and understand the failure behaviour of the accelerator even before its operation starts. During operation, they are used to identify the components that drive availability and to provide guidelines for improvements that lead to the greatest benefit. Moreover, availability models can be used to find the optimal technical stops and operational schedule that maximizes availability. And finally, availability models are essential to study the implications of accelerators upgrades on machine availability. A stepwise methodology for the definition of availability models is needed to ensure the completeness and consistency of the studies.

For already operating particle accelerators the ultimate goal is to boost machine performance to its limits. To this end, adequate procedures need to be first established to properly evaluate the current performance of the accelerator and its evolution over time. A initial step towards this goal is to accurately and systematically collect the accelerator operation and failure data. The benefits and importance of availability tracking tools are discussed by the example of the Accelerator Fault Tracking system implemented at CERN. These tools can additionally serve as a database for future machines availability studies. A conclusive evaluation of the accelerator performance could be done by comparing the results obtained from the subsequent analysis of the gathered operation data with an objective performance target. As objective performance targets are not available for the high

energy accelerators discussed in this thesis, a performance evaluation method for particle accelerators is proposed based on the novel availability allocation method.

Once the current performance of the accelerator has been properly evaluated and understood, the adequate strategies for its optimization can be identified. The optimization strategies should determine the system designs and operation modes that would lead to the best performance of the accelerator at lower cost. The sensitivity analysis method based on importance measures proposed in this thesis is used to identify the component upgrades that would lead to the best system availability improvement for a certain investment. Moreover, this method shows the criticality of each component based on their availability parameters and identifies situations where common cause failures could significantly compromise the accelerator performance. In addition, the proposed sensitivity analysis method is also useful to study the the effect that a limited knowledge of an input parameter has on the results of the availability models.

Finally, the implemented availability models, as well as the sensitivity analysis method based on importance measures, are proposed to study the impact of accelerator upgrades on machine availability. This feedback allows to react in case that the accelerator upgrade will seriously affect machine performance due to the added complexity.

The scope of this thesis is therefore to provide a methodology to study and optimize the performance of high energy particle accelerators in terms of availability, from its conceptual design to its exploitation and upgrades. Examples of availability studies for accelerators in the design phase and under operation are given both for linear accelerators, CLIC and Linac4, and circular accelerators FCC and LHC.

Chapter 2 gives an overview of the particle accelerators that are used as examples for the study of availability throughout the thesis.

Chapter 3 presents a novel availability allocation method for particle accelerator subsystems based on complexity criteria. The standard reliability allocation methods used for military and industrial applications are first reviewed. The complexity of an accelerator subsystem is determined by the

evaluation of factors with high impact on machine availability. The complexity assessment techniques are described in detail. The proposed allocation method is applied to the Compact Linear Collider (CLIC) and the Future Circular Collider (FCC) accelerator projects.

Chapter 4 describes a step-wise methodology for the definition of availability models of particle accelerators together with the availability terminology. An overview of the methods and software tools available for the implementation and simulation of availability models is given. In particular, the Common Input Format framework, which proposes a set of interrelated tables to completely define an availability model, is presented in detail. LHC and CLIC availability models serve as an example of the proposed availability modelling methodology. Results obtained from the simulation of the models with the AvailSim software are discussed in detail.

Chapter 5 explains the importance of tools for collecting accelerator operation and failure data as a basis for the performance evaluation of particle accelerators. The Linac4 availability during a Reliability Run is assessed using the Accelerator Fault Tracking (AFT) system implemented at CERN. The availability allocation method presented in Chapter 3 is proposed here as a baseline reference to evaluate the accelerator system performance during operation. The performance evaluation of Linac4 during the Reliability Run and of the Large Hadron Collider(LHC) during 2017 show the advantages of the proposed method.

Chapter 6 introduces the Differential Importance Measures (DIM). These sensitivity analysis measures allow for the identification of components with high impact on machine performance as well as the potential common cause failures that could significantly comprise machine availability. The optimization strategy that identifies the components with substantial improvement potential is explained. Finally, the presented results from the sensitivity analysis of the CLIC availability models provide clear guidelines for the optimization of their availability.

Chapter 7 gives an overview of the presented methodology and draws conclusions on the importance of availability studies for particle accelerators.

2 Introduction to High-Energy Particle Accelerators

2.1 Circular Particle Accelerators and Colliders

2.1.1 The Large Hadron Collider (LHC)

The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator. Located 100 m beneath the France-Swiss border near Geneva, the LHC consist of a 27 km circumference tunnel of superconducting magnets with a number of accelerating structures that provide the means to accelerate proton beams up to 7 TeV. Inside the tunnel, two high-energy particle beams circulate in opposite directions in separated beam pipes before they are made to collide in four interaction points, serving seven experiments: ATLAS, CMS, ALICE, LHCb, LHCf, TOTEM and MoEDAL. These experiments aim to study the open mysteries of the Standard Model of particle physics, i.e., the model that describes the basic constituent of matter (fundamental particles), and the way these particles interact.

In the early 1980s scientist started to consider the LHC as a successor of the existing Large Electron-Positron Collider (LEP)[1]. The aim was to reach unprecedented beam energies and intensities for the discovery of Higgs particles and the study of rare events with centre of mass collisions up to 14 TeV. Such ambitious project presented several operational and technical challenges. The damage potential of the high energy stored in magnets and beams imposed unprecedented requirements on the reliability of the protection systems [2]. In addition, the design of 9T superconducting magnets, high speed electronics and cryogenics were among the main technological challenges of the LHC. Due to the increased complexity and technological challenges of the LHC, reliability studies (a first step towards availability studies) became of crucial importance. In December 1994, after many years of work on technical aspects and physics requirements, the CERN council approved the construction of the LHC and in October 1995, the LHC

technical report was approved. Commissioning and test of the machine started with the first protons in the tunnel in 2008. In September 2008, a serious fault in a superconducting magnet which damaged many other superconducting magnets, required a long technical intervention [3]. Until November 2009, the LHC was not in operation again. The first operational run took place from 2009 to 2013, including the first high-energy collisions at 6 TeV in March 2010. After a 2 years upgrade [4], the LHC second operational run started in 2015 with an operating energy of 6.5 TeV per beam (i.e. 13 TeV collision energy). The luminosity design value was first reached in June 2016 and later, in 2017, the luminosity reached twice the design value. Among the many discoveries of the LHC, the discovery of the Higgs Bosson in July 2012 was the most significant [5]. The second run stopped in December 2018 and will be followed by a third run from 2020 to 2023, after a two years shutdown.

The performance of the LHC is measured in terms of integrated luminosity delivered to the experiments. The integrated luminosity gives a measure of the expected number of particle collisions over a given luminosity production period. In order to produce collision and hence accumulate luminosity, the LHC needs first to be prepared. Starting from *Injection*, a complete LHC cycle includes all the phases needed to get to luminosity production [6]. The accelerator complex at CERN, shown in 2.1, is a succession of machines with increasingly higher energies. Each machine accelerates a particle beam before injecting the beam into the next accelerator in the chain. During LHC *Injection*, the beam from the Super Proton Synchrotron (SPS) is injected into the LHC, the last accelerator in the chain. Inside the LHC tunnel, two beams travel in opposite directions in separated vacuum tubes, guided by a strong magnetic field generated by superconducting magnets. During *Ramp-up*, acceleration systems located on a certain positions at the circumference boost the energy of the beams in each turn. The LHC can accelerate two beams, each beam of the same kind of particles, producing collisions of either proton proton, proton lead-ion or lead-ion lead-ion, which are the most effective particles to obtain high energy collisions in a circular collider. Once the beams reach their target beam energy, the beams are made to collide at the experiments during the so-called *Stable Beams* or *Production* phase. The optimum length of the *Production*

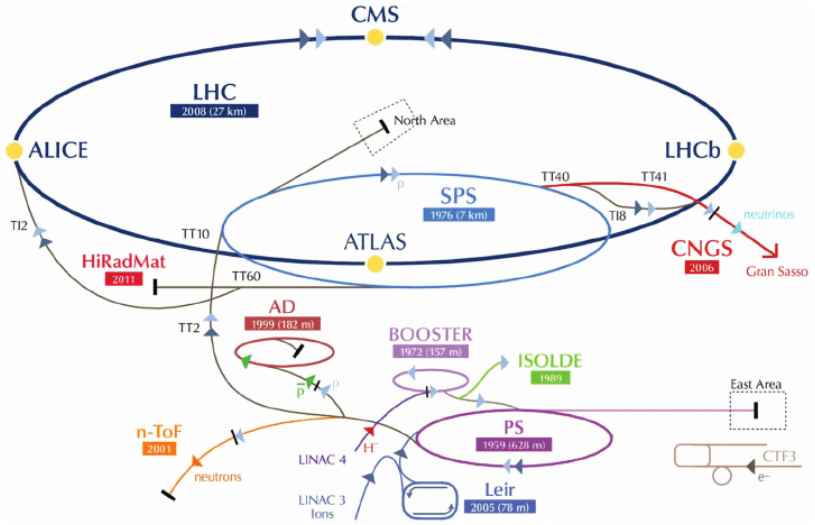


Figure 2.1: CERN Accelerator Complex.

phase is determined by the beam lifetime, and corresponds to the time interval after which the beam intensities are too low for an optimal luminosity production. In order to produce collisions during the maximum time, the LHC needs to complete its cycle without failure. All of this leads to regard the availability as another key indicator of LHC performance.

In order to fully exploit its physics potential, the LHC will be upgraded in 2023 in the framework of the High Luminosity LHC project (HL-LHC)[7]. This upgrade aims at collecting ten times more data by 2030 than during the initial design phase. This project demands significant upgrades not only of the experiments and LHC equipment, but also of its injection chain. The LHC Injectors Upgrade Project (LIU)[8] was launched at CERN to guarantee the improved beam characteristics required for the HL-LHC.

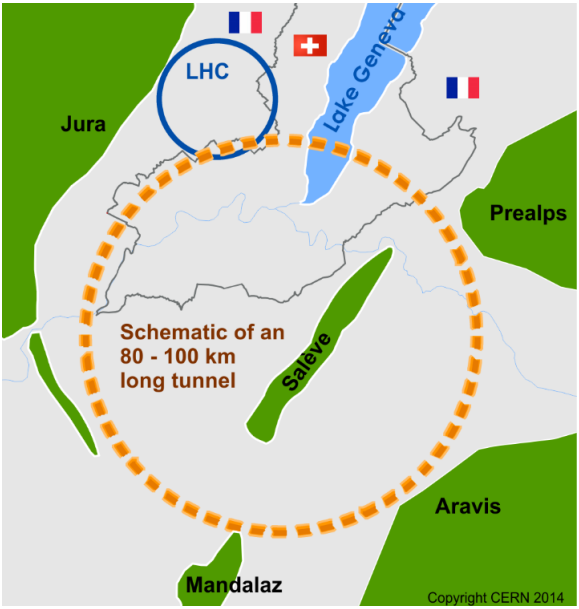


Figure 2.2: Schematic of the Future Circular Collider.

2.1.2 The Future Circular Collider (FCC)

The Future Circular Collider (FCC) study, hosted at CERN, is developing designs for a future particle collider with a centre of mass energy up to 100 TeV, with the aim to extend the research currently being conducted at the LHC [9]. With a setup similar to the LHC but four times bigger, the new 80-100 km circumference tunnel for the FCC is shown in Fig. 2.2. This ambitious project examines scenarios for three different types of particle collisions: hadron (proton or heavy ion) collisions; electron-positron collisions; and proton-electron collisions. The required injector chain is part of the study, taking into account the existing CERN accelerator infrastructure and long-term accelerator operation plans. The baseline is to use a modified LHC to inject beam into the FCC [10, 11].

In order to ensure reliable and efficient operation, several technological and experimental challenges must be overcome. Among these are the design and implementation of 16 T superconducting magnets, design of an efficient 100 MW RF acceleration system and implementation of a reliable Cryogenics system with 4 times the capacity of the one for the LHC. Studies are on-going to demonstrate the feasibility of the project.

The most recent step was the submission of a conceptual design report [9], as input to the 2019 update of the European Strategy for Particle Physics.

2.2 Linear Particle Accelerator and Colliders

2.2.1 Linac4

Linac4 will replace Linac2 as the first element in the CERN proton injection chain from 2020 in the framework of the LIU project. Linac4 is located in an underground tunnel that connects to the Proton Synchrotron Booster (PSB). The RF equipment, power supplies and other infrastructure are located in a surface building.

The basic architecture of Linac 4 is shown in Fig. 2.3. The new injector comprises an H^- source, a low-energy beam transport section bringing the beam to a Radio Frequency Quadrupole (RFQ) structure for capture, bunching and acceleration up to 3 MeV, and three further types of accelerating structures where the particles are accelerated in stages up to 160 MeV: a Drift-Tube Linac (DTL), a Cell-Coupled DTL (CCDTL) and a Pi-Mode Structure (PIMS) linac. Exiting Linac4, the beam will follow the transfer line that connects Linac4 with the PSB, which is part of the LHC proton injector chain. The main improvements, provided by Linac4, and also its main challenges, are the use of negative hydrogen ions instead of protons and a higher injection energy into the PSB. Moreover, Linac4 has been designed to be more flexible and more environmental clean than Linac2.

Due to the demand of continuous operation and with more than three times in both energy and number of components compared to its predecessor, Linac4 will have to meet strict requirements in terms of availability. Ultimately this should approach the availability of Linac2, which runs with an availability above 98%

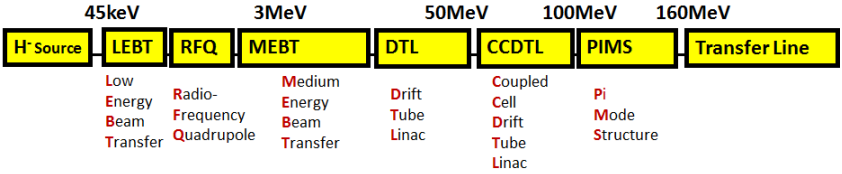


Figure 2.3: Linac4 architecture.

after its many years of operation.

The civil engineering and construction works for Linac4 started in October 2008. In Spring 2017, the Linac4 was fully commissioned and entered the so-called Reliability Run, a period to assess and improve its availability, prior to being connected to the CERN accelerator complex. The Reliability Run was divided into three phases from mid-July to mid-May 2018. The machine reached an overall availability of 91% during this period. The details of the performance of Linac4 during the reliability Run are discussed in Section . Linac4 will be connected to the PSB in 2019 and subsequently, from 2021 onwards, it will be the unique source of protons at CERN.

2.2.2 The Compact Linear Collider (CLIC)

The Compact Linear Collider (CLIC) is a study, hosted at CERN, for a future accelerator project to collide electrons and positrons up to 3 TeV centre of mass collision energy, which are unprecedented energies for such particle accelerators [12]. At these high energies, electrons and their antimatter twins would lose almost all their energy while circulating in a ring collider like the LHC. The linear collider CLIC will provide unique opportunities for the exploration of the Standard Model, with emphasis on the Higgs Bosson and a wide range of open questions related to possible new phenomena beyond the Standard Model, and this with much higher precision than possible with the HL-LHC.

The layout of the CLIC accelerator complex is presented in Fig.2.4. The electron and positron beams (Main Beams) are generated and pre-accelerated in the injector

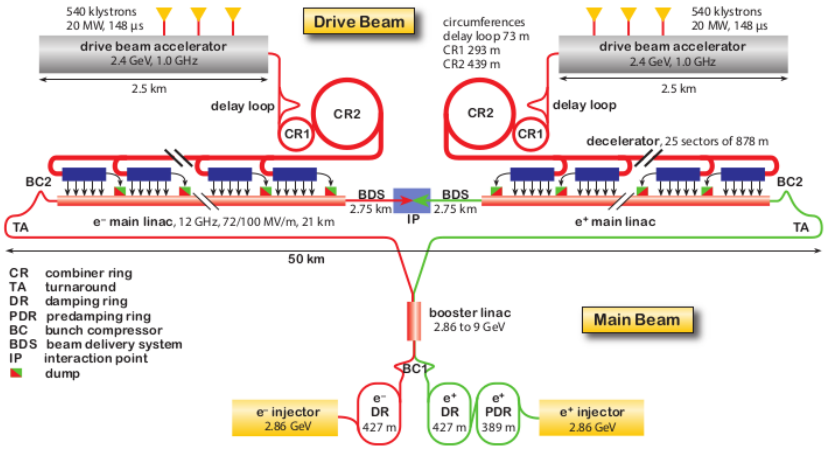


Figure 2.4: CLIC layout at 3 TeV.

linacs (Main Beam Injectors). The beams emittance is then reduced in damping rings (Damping Ring Complex) before being transported through the Ring To Main Linac (RTML) system into the main linacs. The RTML also accelerates the beams to some extent and compresses their length. Then, the particles are accelerated in two linear accelerators facing each other, such that the beams collide in the central physics detector. Before colliding, the Beam Delivery system removes transverse tails and off-energy particles from the beam with collimators and compresses the beam to the small sizes at the collision point. After the collision the beams are transported by the Post Collision Line to the Beam Dump.

Under this configuration the particles need to gain the energy in a single passage trough the accelerating structures. In order to reach the energy of 3 TeV in a realistic and cost efficient scenario, an accelerating gradient of at least 100 MV/m is needed, 20 time higher than the LHC. To this end, the novel two beam scheme has been proposed: a second beam, a high intensity,low energy Drive Beam, is decelerated in special Power Extraction and Transfer Structures (PETS) and the generated RF power is transferred to the Main Beams accelerating structures as

shown in Fig 2.5. The Drive Beam Accelerators or Linacs (DBL) generate and accelerate the Drive Beams. In order to efficiently power the PETS, the beams coming from the DBLs are compressed in time in the Drive Beam Recombination Complex (DBRC).

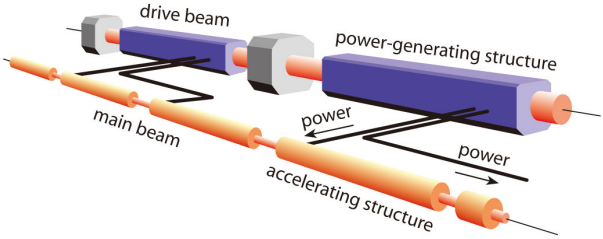


Figure 2.5: CLIC two beam accelerating scheme.

CLIC is designed to be built-in stages of increasing energy: starting at 380 GeV, 1.5 TeV, with a final energy of 3 TeV. For low collision energies, the novel Two Beam modules scheme could be replaced by the classical approach, i.e., the linacs for the acceleration of the Main Beams could be powered by klystrons [13].

The CLIC project will last 34 years, with 27 years of data taking, including the three main energy stages. A stop of two years is needed between the stages. The construction, installation and commissioning duration of the drive beam option at 380 GeV is seven years, compared to the eight years for the klystron based scheme. The subsequent construction and installation periods of both the 1.5 TeV and 3 TeV stages are around 4 years each.

The performance requirements for CLIC are given in terms of integrated luminosity production and availability; to provide $1.2\,10^7$ seconds of yearly luminosity production time, an availability of 75% is assumed for CLIC in 185 days of operation [14]. The remaining calendar time will be shared between maintenance periods, technical stops and extended shutdown.

The advantage of CLIC over circular colliders is almost no luminosity decay during collisions. However, reaching the luminosity goal poses several technical and operational challenges. First, CLIC requires excellent beam quality and control.

Theoretical studies and experimental studies have been crucial to demonstrate the applicability of the concept. The energy stored in the beam also poses strong reliability requirements in the machine protection system, comparable to the one in the LHC. In addition, the novel Two Beams module technology requires high efficiency to achieve the target high accelerating gradient. Prototype modules are under study and their performance will be qualified. Secondly, one of the main operational concerns is to safely bring the machine back to luminosity production from a state with no-beam after a system failure. The longer the machine operation is interrupted, the longer it will take to bring the beam parameters back to nominal value. Nonetheless, not all the system failures interrupt CLIC operation. For example, short hardware failures are recovered by automatic procedures while some others by adequate machine design. Due to the high amount of RF systems in the main linac, hot spares are installed in the tunnel to allow for failure tolerant operation. For the same reason, magnet power converters failures are mitigated by adequate machine design. Availability studies allow to demonstrate that these solutions are sufficient for the optimal operation of CLIC. Throughout this thesis studies of the most critical CLIC systems are discussed in detail.

The most recent achieved milestone was the submission of the CLIC project implementation plan [15] for the 2019 update of the European Strategy for Particle Physics.

3 Availability requirements based on complexity criteria

This chapter presents an availability allocation method for particle accelerator subsystems based on complexity criteria. The method aims at translating the overall accelerator availability goal into individual availability requirements for its subsystems. This is particularly useful in the early stage of an accelerator project where no detailed design is available or where new technologies are being developed and no failure data is available for a more exhaustive assessment.

The first section of this chapter reviews the standard reliability allocation methods used for military and industrial applications. The Decision-Making Trail and Evaluation Laboratory (DEMATEL) procedure[16, 17], which prioritizes actions based on the influence between variables, is also presented.

The remainder of this chapter presents a novel availability allocation method based on conventional reliability allocation techniques and tailored to particle accelerators. The proposed approach determines the complexity of an accelerator subsystem by the evaluation of the factors with high impact on the availability of accelerators. These factors are then combined to obtain the so-called complexity weight of the subsystem, which is the basis for the availability allocation. The DEMATEL procedure is used to better weight the complexity of the subsystems according to the possible interactions between subsystems.

The methodology introduced here is applied to the Compact Linear Collider (CLIC) and Future Circular Collider (FCC) accelerator projects.

3.1 Reliability allocation methods and the DEMATEL procedure

For large complex systems, the purpose of reliability allocation methods is to assign reliability requirements to the subsystems. The results of the method will significantly affect the design process and life-cycle cost of the systems.

The majority of the methods assume that the system consist of n independent subsystems which have all to be operational for the system to be operational. The reliability requirement to the subsystems is allocated in proportion to the so-called allocation weights as follows:

$$\tilde{R}_i = R_T^{C_i} \quad \text{where} \quad C_i = \frac{w_i}{\sum_{j=1}^{n} w_j} \tag{3.1}$$

where w_i represents the allocation weight of subsystem i and R_T the reliability target of the overall system.

The definition of allocation weights varies depending on the allocation method considered. Some of them define the allocation weight as the failure rate of the subsystem[18], while some others as a combination of several factors [19]. The factors considered also depend on the information available about the system and its application. References [20, 21, 22, 23, 24] provide a good overview of existing reliability allocation techniques. Latest advances propose an innovative reliability allocation method using the maximal entropy ordered weighted averaging (ME-OWA) method [25] and its combination with the DEMATEL procedure [26]. However, for both military systems and commercial applications, the Feasibility Of Objectives (FOO) technique and Average Weighting allocation methods have become standard methods in reliability allocation design [25]. As these methods form the basis for the definition of the availability allocation method for particle accelerators, they are described here in more detail.

- **FOO technique** [20]. Feasibility-Of-Objectives is a typical approach mentioned in the MIL-HDBK-338B [27] developed originally as a method for allocating reliability without repair for mechanical-electrical systems. Subsystems are appraised by four factors: Intricacy (I), State Of Art (S), Performance (P) and Environment (E). Each factor is rated based on a scale from 1 to 10 and is estimated using design engineering and expert judgments. The allocation weight, w_i, or ISPE factor of each subsystem i is the derived from the product of the factors:

$$w_i^{FOO} = I * S * P * E \tag{3.2}$$

- **Average Weighting methods** [21]. The Average Weighting allocation method derives the allocation weight based on six influential factors: complexity, state-of-the-art, system criticality, environment, safety, and maintenance. For each of these factors, the subsystem is rated on a scale from 1–10 by p experts, ($p \geqslant 1$). Let $b = B_{Eij}$ represent the score of the influential factors ($j = 1, ..., 6$) for the i-th subsystem ($i = 1, ..., n$) and rated by expert E ($E = 1, ..., p$). Then, the average score of factor j and subsystem i is given by:

$$B_{ij} = (\sum_{E=1}^{p} B_{Eij})/p \quad \forall i, j \tag{3.3}$$

The subsystem complexity weight, w_i, can be calculated following two different models:

  - ⋆ Geometric Average Weighting method

$$w_i^G = \prod_{j=1}^{6} B_{ij} \tag{3.4}$$

  - ⋆ Arithmetic Average Weighting method

$$w_i^A = \sum_{j=1}^{6} B_{ij} \tag{3.5}$$

Due to its analytic simplicity, the Arithmetic Weighting method preserves the variation in the factors scores and therefore, allocates more similar reliability requirements among subsystems. Instead, the Geometric Average Weighting method sets more discriminatory weighting values among subsystems. This is, if the score of a subsystem factor is highly in contrast to the other subsystems factor score, the Geometric Average method reflects this outstanding property of the subsystem and potentially sets a higher reliability requirement. In other words, if one of the subsystem's properties differs significantly from the other's then, while the Arithmetic method provides a more balanced and conservative allocation, the Geometric Average Weighting method gives a broader range

of reliability requirements by assigning higher weight to the subsystems with strong properties. Additionally, in cases in which factors influence each other, only the Geometric Weighting method should be considered, as opposed to the Arithmetic method that can be used only when the factors are independent.

- **Bracha method**[28]. Similar to the FOO and Average Weighting methods, Bracha considers 4 influential factors: state of art (B_{i1}), subsystem complexity (B_{i2}), evaluated by the number of components in the subsystem, operating time (B_{i3}) and environmental conditions (B_{i4}). For each of these factors, the subsystem is rated on a scale of 1–10 and the allocation weight is given by:

$$w_i^B = B_{i1} * (\sum_{j=2}^{4} B_{ij}) \tag{3.6}$$

  While the factor product and factor sum give equal importance to the factors, the Bracha technique assumes that state of the art influences all other factors and hence, gives more importance to it.

Outline of the DEMATEL procedure

The DEMATEL procedure was first developed in the Geneva research center [16] and provides a tool to analyze relationship between criteria in many industrial fields. The procedure is adopted in this thesis to evaluate the degree to which a failure in subsystem i affects subsystem j in terms of the induced downtime. In the proposed availability allocation method, the results obtained from the DEMATEL procedure are used to modify the allocation-weight or complexity of the subsystem according to its effect on the overall system. The method will increase the complexity of a subsystem if a large effect on other subsystems is observed and will on the contrary, decrease the assessed complexity if the subsystem is highly affected by others.

The basic steps of the DEMATEL procedure are given below [17, 29, 30].

Step 1. Design engineers conduct pair wise comparisons to evaluate the degree to which criteria i affects criteria j. 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. As in the Average Weighting allocation method, if more than one expert performs the evaluation, the mean of the scores are considered in the DEMATEL procedure.

Score	Influence
0	No influence
1	Low influence
2	High influence
3	Very high influence

Table 3.1: Scale for the DEMATEL pair-wise comparison.

Let z_{ij} be the degree to which criteria i affects criteria j, $i, j \in 1, 2, ..., n$. Accordingly, all principal elements z_{ii} are set to zero. Hence, the initial direct-relation matrix, Z, is an nxn matrix which indicates the initial direct effects each criteria exerts on and receive from other criteria:

$$Z = \begin{pmatrix} 0 & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & 0 \end{pmatrix} \tag{3.7}$$

Step 2. Calculate the $r-d$ values by computing:

The normalized direct-relation matrix, X,

$$X = \frac{Z}{s} \quad \text{where} \quad s = max_{1 \leqslant i \leqslant n}(\sum_{j=1}^{n} z_{ij}) \tag{3.8}$$

and the total-relation matrix,T, the infinite series of direct and indirect effects

of each criteria, can be obtained by the matrix operation of X:

$$T = X(I - X)^{-1} \tag{3.9}$$

Each element t_{ij} of the total-relation matrix provides information about the effect criteria i exerts on criteria j or in order words, criteria j receives from criteria i. The sum of the rows, R_i, and the sum of the columns, D_i, can be obtained through the following formula:

$$R_i = \sum_{j=1}^{n} t_{ij} \quad i = 1, .., n \tag{3.10}$$

$$D_j = \sum_{i=1}^{n} t_{ij} \quad j = 1, .., n \tag{3.11}$$

While the R_i value presents the sum of direct and indirect effects dispatched from criteria i to the other criteria, D_i presents the sum of influence that criteria i receives from other criteria both directly and indirectly. Consequently, the difference $(R_i - D_i)$ shows the net effect the i-th criteria contributes to the overall system. When $(R_i - D_i)$ is positive, the i-th criteria is a net causer and when $(R_i - D_i)$ is negative, the i-th criteria is a net receiver.

Let r_i and d_i be the normalized values of R_i and D_i:

$$r_i = \frac{R_i}{\sum_{i=1}^{n} R_i} \tag{3.12}$$

$$d_i = \frac{D_i}{\sum_{i=1}^{n} D_i} \tag{3.13}$$

Then the $(r - d)_i$ value of criteria i is obtained by:

$$(r - d)_i = r_i - d_i \tag{3.14}$$

Finally, the $(r-d)_i$ value represents total net effect of criteria i on the overall system. As before, when $(r-d)_i$ is positive the i-th criteria is a net causer and when $(r-d)_i$ is negative,the i-th criteria is a net receiver.

3.2 Availability allocation based on complexity criteria

In this section, the reliability allocation methods and DEMATEL procedure discussed in the previous section will be extended to an availability allocation method specific for high energy particle accelerators.

Consider an accelerator that consist of n subsystems in series which have to be available in order for the accelerator to be operational. The method requires these subsystems to be independent from each other, i.e. failure of any subsystem is assumed to be an independent event. The subsystems may have redundancies and non-independent failure mechanisms "inside" and are thus considered all together as a block or entity. Let A_T be the target availability for the overall accelerator system. The availability of the system as a function of its components availability, A_i, is given by:

$$A_T = \prod_{i=1}^{n} A_i \tag{3.15}$$

Translating the overall accelerator availability goal to the subsystem level requires an allocation or complexity weight that reflects the properties of the subsystem that make availability more difficult to achieve and have more impact on the overall accelerator performance. Less complex systems are more easily available than more complex systems. Hence, less complex systems are required to be more available while more complex systems are allowed to be less available.

Let C_i the complexity of the i-th subsystem, $i = 1, ..., n$. Then, the allocated availability for the i-th subsystem according to its complexity, C_i, is defined as:

$$\tilde{A_i} := A_T^{C_i} \tag{3.16}$$

The assessed complexities must fulfill two main constraints, namely:

- The subsystems should be allocated the required availability to ultimately

meet the overall machine availability goal. This is:

$$\sum_{i=1}^{n} C_i := 1 \quad \text{so that} \quad A_T = \prod \tilde{A}_i \tag{3.17}$$

- The complexity of the subsystem increases as the magnitude of the factors affecting availability increases.

The factors considered most relevant for our availability studies will be discussed in Section 3.2.2. The apportionment techniques presented in Section 3.1 are adopted to combine the influential factors and obtain the so-called complexity weight, w_i, of the subsystem, which represents the individual and discriminate characteristics of the subsystem.

However, a failure of a subsystem might affect the operational state of other subsystems, causing extra downtime and therefore, decreasing the overall system availability. The allocated availability should not only consider the downtime of the subsystem but also, the downtime caused to other subsystems, i.e. the root cause downtime. The root cause downtime of a subsystem is the fraction of the overall system downtime, also due to other subsystems, but which has as the root cause a failure of the subsystem. Likewise, the allocated availability should not consider the subsystem downtime induced by other subsystems, i.e. raw downtime. The raw downtime is the total time the system is down regardless of the cause. For example, the Cryogenics system of the LHC was down 207 hours during the 2017 run, however, half of the time was due to failures of other subsystems. This is, the root cause downtime of the Cryogenics system was only 112 hours. In order to include these effects between subsystems, the DEMATEL procedure, outlined in Section 3.1, is considered. The results obtained from the DEMATEL procedure are used to increase the complexity weight of those subsystems that have a high impact on other subsystems and conversely, decrease the complexity weight of a subsystem that is highly affected by others.

Let w_i be the complexity weight of the i-th subsystem derived from one of the apportionment techniques and, if necessary, adjusted by the DEMATEL procedure. Then C_i, the complexity used for availability allocation, of the i-th subsystem is

given by:

$$C_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{3.18}$$

which satisfies the two conditions mentioned above.

The proposed availability allocation method based on complexity criteria presents several advantages:

- Adaptable to the different phases of an accelerator life-cycle
- Provides realistic and achievable availability targets based on the most crucial information affecting availability
- Designs to an availability requirement rather than an "as best you can" approach
- Identifies priorities and hierarchies based on potential for improvement
- Through the comparison between predictions from availability models (or if available, measured availability) and allocated availability, critical subsystems that prevent achieving the overall availability target can be identified. More efforts should be invested in improving these weak areas.
- Ensures the ultimate availability target is achieved by accounting also for the downtime caused to other subsystems in the allocated availability budget, i.e. the root cause downtime, and not only the raw fault time of the subsystem.

3.2.1 Complexity assessment of accelerator systems

For the particular application of availability allocation to particle accelerators, the complexity of a subsystem must represent the main characteristic of the subsystem affecting availability. These include for example the number of components in the system, the number of critical failures that bring the machine down but also the repair time of the subsystem. However, these factors can be rarely exactly quantified, especially in the case of huge machines, prototypes or innovative systems. Even just the definition is difficult in complex systems, as one needs to compare electronics, software, mechanical parts, etc. Hence, complexity is defined

here based on factors affecting availability, which are scored through a numerical scale.

The detailed procedure for complexity assessment of accelerator systems is described in the following steps:

Step 1. List the n subsystems of the accelerator system. The subsystems need to be available for the accelerator to be available and have independent failure mechanism.

Step 2. Select the influential factors based on the application and determine their scores. One can consider the factors explained in Section 3.2.2, a subset of them, or an enriched set by including other factors with high impact on availability that are not be discussed here.

Step 3. Perform the DEMATEL procedure as explained in Section 3.1 to obtain the $r-d$ values of the subsystems.

(1) 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. In order words, in the event that subsystem i fails it evaluates the additional time that is added to subsystem j to be operational again.

(2) Obtain the elements of the initial direct-relation matrix, Z, by Equation 3.7.

(3) Obtain the elements of the normalized direct-relation matrix, X, by Equation 3.8 and the the total-relation matrix, T, by Equation 3.9.

(4) Calculate the $r-d$ values, by Equations 3.10 - 3.14.

Step 4. Compute the complexity weights emulating one of the assessment methods presented in Section 3.1 and by their combination with the DEMATEL procedure. As well as the scoring of the factors, the design engineers and experts should evaluate which is the most appropriate method based on the life cycle phase of the accelerator system and the information available. The advantages and disadvantages of each of the methods are discussed in Section 3.3, together with the use cases.

The complexity weight of subsystem i, w_i, can be defined as follows:

- **FOO technique.** If the four influential factors of the FOO technique have been considered, then the complexity weight of subsystem i can be calculated by Equation 3.2.

  This method is particularly useful in early design stage of a particle accelerator or for newly developed technology where repair times are uncertain and machine protection systems are still under development and subject to large changes. However, not considering repair time, one of the major factors with severe impact on subsystem availability, might lead to unrealistic allocated availability requirements. For example, for a system located in the underground accelerator tunnel, even if the exact repair time of this system is still unknown, the access for repair will be certainly longer than for an accelerator system located on the surface.

- **Average Weighting methods.** Let B_{if} represent the average score of a set of the influential factors, $f \in F$ for the i-th subsystem ($i = 1, ..., n$), obtained by Equation 3.3. Then, the complexity weight of subsystem i can be calculated by:

  ⋆ Geometric Average Weighting method

  $$w_i^G = \prod_{j \in F} B_{ij} \tag{3.19}$$

  ⋆ Arithmetic Average Weighting method

  $$w_i^A = \sum_{j \in F} B_{ij} \tag{3.20}$$

- **Bracha method**: Let B_{if} represent the score of a set of the influential factors, $f \in F$, for the i-th subsystem ($i = 1, ..., n$), where B_{i1} corresponds to the State Of Art factor score. Following Bracha method, the complexity weight of subsystem i can be calculated by:

$$w_i^B = B_{i1} * (\sum_{j \in F, j \neq 1} B_{ij}) \tag{3.21}$$

The advantage when considering this method is that the State of the Art factor can be determined precisely in any stage of the accelerator project while the others, in some cases, might be undetermined.

Finally, if necessary, use Eq. 3.22 to assess the complexity weight of subsystem i adjusted by the DEMATEL factor:

$$w_i^D = w_i + (r-d)_i * w_i \tag{3.22}$$

where w_i is the assessed complexity weight according to the one of the techniques explained above and $(r-d)_i$ is the $r-d$ value of subsystem i according to the DEMATEL procedure.

Note that when subsystem i is a net receiver, i.e. $(r-d)_i$ is positive, the assessed complexity weight is increased and when subsystem i is a net causer, i.e. $(r-d)_i$ is negative, the assessed complexity weight is decreased. In the case that $r_i = d_i$, then the complexity weight of subsystem i remains the same.

Step 5. Normalize the complexity weights w_i to obtain the complexity, C_i, for availability allocation by:

$$C_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{3.23}$$

3.2.2 Criteria for complexity assessment

In literature, depending on the information available on the system and its application, many factors are considered to obtain the so-called allocation weights for reliability allocation [19, 20, 21, 27, 31, 22]. Some of these factors can be measured quantitatively while others have to be assessed qualitatively. For a given application, the scores of these factors are determined by design engineers and experts based on their know-how and experience. If more than one expert performs

the evaluation, the mean of the scores is considered to produce a less subjective assessment.

The set of factors considered for reliability allocation is not complete for availability allocation, as it ignores any factor related to repair, maintenance or operation. In particular, for availability allocation in the accelerator domain, the factors need to represent the relative complexity of the accelerator system. In other words, system properties that have strong impact on particle accelerator performance and that make availability more difficult and costly to achieve should be considered. As mentioned before, these factors can be rarely exactly quantified, especially in the case of huge machines, prototypes or innovative systems, and therefore factors are determined through a numerical scale. In this context, the following eight criteria are proposed with the corresponding scoring scales:

1. **Repair time**: The repair time of a subsystem represents the time that is needed to restore operation after a failure. This time includes the identification of the failure, access to the subsystem , repair and recovery time to the nominal operational state. By definition, repair time directly affects the availability of the system. Assigning a high availability requirement to a subsystem with intrinsically high repair time, will require the subsystem to be highly reliable in order not to suffer from any repair period. Therefore, the longer it takes to repair a subsystem, the more complex the subsystem becomes. The repair time is scored on a linear scale from 1 (short repair-time) to 10 (long repair time).

2. **Criticality**: Assuming that machine protection systems are in place for the accelerators, the criticality of a subsystem is defined as the fraction of the subsystem interlocks that can trigger a beam abort over the total number of interlocks in the accelerator subsystem. It reflects the impact of its failure in the accelerator beam availability. The subsystems with high criticality are assigned higher complexity weight. Demanding an unrealistic high availability requirement on the most critical subsystems increases the cost significantly in comparison to the alternative of increasing the availability requirements for less critical systems. 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 reflects the internal complexity of the subsystem. The larger the complexity of the interacting parts or elements it has, the more intricate it is. In the same way, highly intricate systems are assigned higher complexity weight. More efforts will be required to make an intricate system highly reliable than a simple system. 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**: State of art of a subsystem considers the design maturity or level of development of a given technology. Setting a high availability requirement of a newly developed technology will increase the development time, cost and number of tests to be done before operating the system. Instead, it will be more feasible to achieve a high availability in an already well established and known technology. Higher complexity weight will be attributed to more innovative technologies. The considered values for this factor are: 10 for innovative technology, 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. More efforts should be invested to develop a system that is required to operate continuously without failure than a system that operates only for intermittent short times. Therefore, higher complexity is assessed to continuously operating systems. The following values are considered: 10 for whole mission time; 6.7 for continuous and long times; 3.3 for short times.

6. **Environment**: In some accelerator facilities, some subsystems are subjected to high radiation doses. Various studies have shown that subsystems under harsh conditions tend to fail more and their recovery will require more resources. Imposing a high availability requirement to a system in a highly

radioactive environment will increase the development time and cost to avoid radiation induced failures. Consequently, systems under severe environmental conditions are assigned higher complexity weight. For the evaluation of these factors, the following values are considered: 10 for systems under highly radioactive environment; 6.7 for average radioactive; 3.3 for low radioactive.

7. **Aging**: The age of a subsystem represents the accumulated hours of operation of the subsystem. In accelerators it is common practice to re-use equipment or infrastructures from accelerators of previous generations. The older the subsystem is, the more likely it is to fail. Imposing a high availability requirement to an old system will increase the upgrade time and cost to avoid age induced failures. Thus, subsystems that have accumulated more hours of operation are assessed higher complexity weight. The aging is scored on a scale from 1 to 10: the subsystem with less accumulated hours of operation or recently upgraded is rated 1, while the subsystem with more accumulated hours and never upgraded is rated 10.

8. **Designed for Reliability**: A subsystem that has been designed for reliability has gone through a design process that guarantees the reliability of an item at all stages of its life cycle. Thus, by definition, the subsystem is highly reliable and can be imposed a high availability requirement. On the contrary, subsystems that have not been designed for reliability can cause undesirable failures and costs of maintenance and repairs. Thus, subsystems not designed for reliability are assessed higher complexity weight than the ones that are designed for reliability. This reliability factor is scored in a scale from 1 to 10: the subsystem designed for higher reliability is scored 1, while the subsystem less designed for reliability is scored 10.

In the complexity assessment process, depending on the application, one might consider as influential factors only a subset of the factors presented above or include other factors which have not been discussed here. In particular, for the complexity assessment of CLIC and FCC subsystems it is appropriate to consider only the 6 first factors, while for the FCC example in Chapter 5.2.2 all but the *Performance*

time factor have been considered. Since CLIC and FCC are accelerator projects under study, the age and design reliability of the subsystems are still unknown. On the other hand, the *Performance time* factor is excluded from the LHC assessment because all the subsystems are required to be operational during the considered time.

3.3 Use cases: Availability requirements based on complexity criteria

3.3.1 Availability requirements for CLIC

After CLIC has been fully commissioned, a nominal year of operation will have 120 days of shutdown and 60 days of scheduled maintenance stops and 185 days of operation, out of which 46 days of fault induced stops are budgeted [14]. This leads to an ultimate availability target for CLIC of 75%.

Considering the major subsystems of CLIC, listed in Table 3.2, the first step for availability allocation to CLIC subsystems based on complexity criteria is to determine the scores of the influential factors explained in Section 3.2.2. Since CLIC is an accelerator project under study, the age and reliability design of the subsystems are yet unknown and thus, have not been considered in the complexity assessment. The influential factors for CLIC subsystems were evaluated by an expert and are given in Table 3.2.

The second step is to perform the DEMATEL procedure. A system expert evaluates the effect of a failure in subsystem i on subsystem j in terms of induced downtime as explained in Section 3.1. Table 3.3 shows an example of initial direct-relation matrix Z of the DEMATEL procedure.

Table 3.4 shows the corresponding normalized direct-relation matrix According to Eq. 3.8. Table 3.5 shows the elements of the total-relation matrix according to Eq. 3.9.

Following Equations 3.10 to 3.14, the outcome for the DEMATEL implementation for CLIC subsystems is shown in Table 3.6. Analysis of the $r - d$ values of the DEMATEL procedure presented in column (6) of Table 3.6 indicate that the Electrical Network, Technical Network and Machine Interlocks are the main net

CLIC subsystem	Repair time	Criticality	Intricacy	State of art	Performance time	Environment
Main Beam Injectors	6	10	9	6.7	10	6.7
Damping Ring Complex	5	10	8	10	10	6.7
Beam Transport - RTML	6	6	5	6.7	10	6.7
Drive Beam Injectors	6	10	7	6.7	10	6.7
Recombination Complex	5	8	7	10	10	6.7
Transfer Lines and Turn Around (TA) Loops	5	6	5	6.7	10	6.7
Two Beam Modules	8	9	10	10	10	6.7
Post Decelerators	7	1	1	3.3	10	10
Beam Delivery System	6	7	6	10	10	10
Post-collision line	8	2	2	6.7	10	10
Electrical Network	4	6	4	3.3	10	3.3
Technical Network	4	6	4	3.3	10	3.3
Machine Interlocks	2	5	3	3.3	10	3.3
Access Safety and Control System	1	5	2	3.3	10	3.3
Technical Alarm System	2	4	2	3.3	10	3.3

Table 3.2: Availability allocation factors scoring for CLIC subsystems.

downtime causers with positive $r-d$ values followed by the Main Beam Injectors, Damping Ring Complex and Drive Beam Injectors. While the Access Safety and Control System with $r-d=0$ is not affected by other subsystems nor affects others, the remaining CLIC subsystems are net downtime receivers with negative $r-d$ values. The Two Beam Modules is the subsystem that is affected the most by others in terms of induced downtime.

In line with the assessment methods presented in Section 3.1 and combined with the DEMATEL procedure, the complexity weights for CLIC subsystems are presented in Table 3.7.

	j	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
i	Z_{ij} 0: No influence 1: Low influence 2: High influence 3: Very high influence	Main Beam Injectors	Damping Ring Complex	Beam Transport - RTML	Drive Beam Injectors	Recombination Complex	Long Transfer Lines and TA Loops	Two-beam Modules	Post Decelerators	Beam Delivery System	Post-collision line	Electrical Network	Technical Network	Machine Interlocks	Access Safety and Control System	Technical Alarm System
1	Main Beam Injectors	0	1	1	0	0	0	3	0	2	1	0	0	0	0	0
2	Damping Ring Complex	0	0	1	0	0	0	3	0	2	1	0	0	0	0	0
3	Beam Transport - RTML	0	0	0	0	0	0	2	0	1	1	0	0	0	0	0
4	Drive Beam Injectors	0	0	0	0	1	1	2	1	0	0	0	0	0	0	0
5	Recombination Complex	0	0	0	0	0	1	2	1	0	0	0	0	0	0	0
6	Long Trasnfer Lines and TA Loops	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0
7	Two Beam Modules	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
8	Post Decelerators	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	Beam Delivery Dystem	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
10	Post-collision line	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	Electrical Network	2	2	1	2	2	1	2	1	2	1	0	1	1	0	0
12	Technical Network	1	1	1	1	1	1	1	0	1	0	0	0	0	0	1
13	Machine Interlocks	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0
14	Access Safety and Control System	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	Technical Alarm System	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3.3: Evaluation of the effects between subsystems of paired alternatives in the DEMATEL procedure for CLIC.

0	0.056	0.056	0	0	0	0.167	0	0.111	0.056	0	0	0	0
0	0	0.056	0	0.000	0	0.167	0	0.111	0.056	0	0	0	0
0	0	0	0	0.000	0	0.111	0	0.056	0.056	0	0	0	0
0	0	0	0	0.056	0.056	0.111	0.056	0	0	0	0	0	0
0	0	0	0	0	0.056	0.111	0.056	0	0	0	0	0	0
0	0	0	0	0	0	0.111	0.056	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0.056	0.056	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0.056	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.111	0.111	0.056	0.111	0.111	0.056	0.111	0.056	0.111	0.056	0	0.056	0.056	0
0.056	0.056	0.056	0.056	0.056	0.056	0.056	0	0.056	0	0	0	0	0
0.056	0.056	0.056	0.056	0.056	0.056	0.056	0	0.056	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3.4: Corresponding normalized direct-relation matrix, X, of CLIC with $s = 18$.

0	0.056	0.059	0	0	0	0.182	0	0.131	0.079	0	0	0	0
0	0	0.056	0	0	0	0.173	0	0.124	0.075	0	0	0	0
0	0	0	0	0	0	0.111	0	0.062	0.065	0	0	0	0
0	0	0	0	0.056	0.059	0.124	0.062	0.007	0.007	0	0	0	0
0	0	0	0	0	0.056	0.117	0.059	0.007	0.007	0	0	0	0
0	0	0	0	0	0	0.111	0.056	0.006	0.007	0	0	0	0
0	0	0	0	0	0	0	0	0.056	0.059	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0.056	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.117	0.124	0.075	0.117	0.124	0.075	0.201	0.073	0.159	0.093	0	0.056	0.056	0
0.056	0.059	0.062	0.056	0.059	0.062	0.101	0.010	0.077	0.020	0	0	0	0
0.056	0.059	0.062	0.056	0.059	0.062	0.101	0.010	0.077	0.020	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3.5: Corresponding total-relation matrix, T, of CLIC.

CLIC Subsystem	R	D	r	d	$r-d$
Main Beam Injectors	0.507	0.228	0.112	0.050	0.061
Damping Ring Complex	0.427	0.297	0.094	0.066	0.029
Beam Transport - RTML	0.238	0.313	0.053	0.069	-0.017
Drive Beam Injectors	0.314	0.228	0.069	0.050	0.019
Recombination Complex	0.245	0.297	0.054	0.066	-0.011
Long Transfer Lines and TA Loops	0.179	0.313	0.040	0.069	-0.030
Two-beam Modules	0.114	1.222	0.025	0.270	-0.245
Post Decelerators	0	0.269	0	0.059	-0.059
Beam Delivery System	0.056	0.705	0.012	0.156	-0.143
Post-collision line	0	0.487	0	0.108	-0.108
Electrical Network	1.273	0	0.281	0	0.281
Technical Network	0.616	0.056	0.136	0.012	0.124
Machine Interlocks	0.560	0.056	0.124	0.012	0.111
Access, Safety and Control System	0	0	0	0	0
Technical Alarm System	0	0.059	0	0.013	-0.013

Table 3.6: The $R-d$ values of the CLIC subsystems based on DEMATEL procedure.

Assuming an availability target of 75% for CLIC, the comparison of the four methods for availability allocation is shown in Fig.3.1. Results are shown in terms of unavailability limits, expressed as 1 minus the availability.

The Two-beam Modules system is evaluated as the most complex subsystem and therefore is allowed to be the less available system, with an average allocated availability of 96%. On the other hand, the less complex subsystems such as the Technical Alarm System and the Access, Safety and Control System have high availability requirements of around 99.5%.

For CLIC subsystems with small absolute $r-d$ value, the assessment methods combined with the DEMATEL procedure show little difference in the allocated availability in comparison to the results obtained without the DEMATEL procedure. This is due to the small effect these CLIC subsystems have on each other, as illustrated by the $r-d$ values in Table 3.3. In fact, it is only for subsystems present throughout all the accelerator with high positive $r-d$ values, such as the Electrical Network and Machine Interlocks, and for the Two Beam Modules which is highly

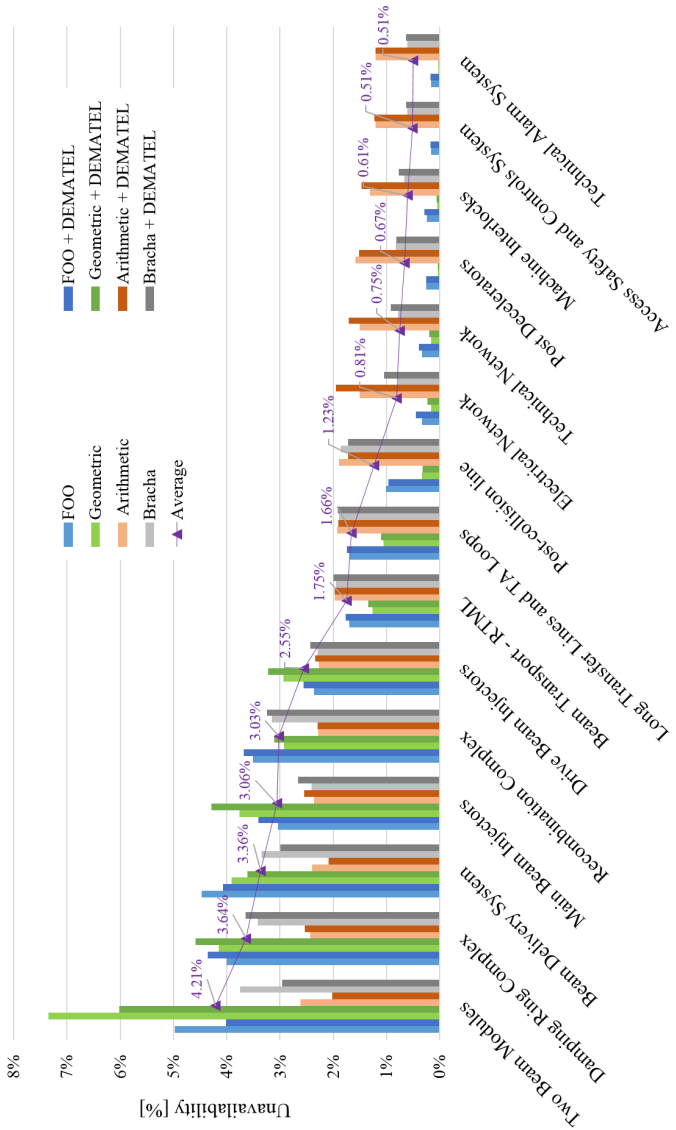


Figure 3.1: Comparison of the availability allocation methods based on complexity criteria for CLIC subsystems, assuming and availability target of $A_T = 75\%$ for CLIC.

Method	FOO	FOO + DEMATEL	Geometric	Geometric + DEMATEL	Arithmetic	Arithmetic + DEMATEL	Bracha	Bracha + DEMATEL
Main Beam Injectors	4.04×10^3	4.29×10^3	24.24×10^4	25.73×10^4	48.40	51.37	279.39	296.55
Damping Ring Complex	5.36×10^3	5.51×10^3	26.80×10^4	27.57×10^4	49.70	51.13	397.00	408.46
Beam Transport - RTML	2.24×10^3	2.21×10^3	8.08×10^4	7.95×10^4	40.40	39.73	225.79	222.04
Drive Beam Injectors	3.14×10^3	3.20×10^3	18.85×10^4	19.21×10^4	46.40	47.28	265.99	271.02
Recombination Complex	4.69×10^3	4.64×10^3	18.76×10^4	18.55×10^4	46.70	46.17	367.00	362.81
Long Transfer Lines and TA Loops	2.24×10^3	2.18×10^3	6.73×10^4	6.53×10^4	39.40	38.24	219.09	212.62
Two Beam Modules	6.70×10^3	5.06×10^3	48.24×10^4	36.44×10^4	53.70	40.57	437.00	330.14
Post Decelerators	0.33×10^3	0.31×10^3	0.23×10^4	0.22×10^4	32.30	30.38	95.70	90.02
Beam Delivery System	6.00×10^3	5.14×10^3	25.20×10^4	21.58×10^4	49.00	41.97	390.00	334.04
Post-collision line	1.34×10^3	1.20×10^3	2.14×10^4	1.91×10^4	38.70	34.54	214.40	191.35
Electrical Network	0.44×10^3	0.56×10^3	1.05×10^4	1.34×10^4	30.60	39.20	90.09	115.42
Technical Network	0.44×10^3	0.49×10^3	1.05×10^4	1.17×10^4	30.60	34.38	90.09	101.23
Machine Interlocks	0.33×10^3	0.36×10^3	0.33×10^4	0.36×10^4	26.60	29.56	76.89	85.45
Access, Safety and Control System	0.22×10^3	0.22×10^3	0.11×10^4	0.11×10^4	24.60	24.60	70.29	70.29
Technical Alarm System	0.22×10^3	0.21×10^3	0.17×10^4	0.17×10^4	24.60	24.28	70.29	69.38

Table 3.7: The complexity weight assessment results for the four methods and their combinations with the DEMATEL procedure.

impacted by other subsystems failure, that the allocated availability with the DEMATEL procedure shows a significant difference in comparison to the allocated availability without the pair-wise comparison.

An important outcome of the allocation methods is that the Two Beam Modules system is the most complex, and therefore, the most critical subsystem of CLIC. The Two-Beam Modules is also the most affected system by other subsystems failures. Thus, dedicated studies should be performed to assess the availability of the Two-beam Modules system and ensure that the availability requirements can be met. Nevertheless, special attention should be paid also to less complex

systems with high availability requirements, since failing to meet these availability requirements will significantly compromise the performance of the whole machine.

3.3.2 Availability requirements for FCC-hh

In order to reach the physics goals, the FCC requires a machine availability of about 70% [14]. Although comparable availability numbers have been achieved for the LHC, the increased machine complexity and size of the FCC makes the realization of the availability goal extremely challenging. The availability allocation procedure is applied here to the FCC in order to establish realistic and achievable availability targets for its subsystems.

The scores of the complexity factors for the FCC subsystems, explained in 3.2.2 and based on one expert assessment, are given in Table 3.8.

While the complexity of the FCC subsystems will increase in comparison to the LHC, the effects that subsystems have on each other in terms of induced downtime, are assumed to remain the same. Therefore, the effects between FCC subsystems are evaluated based on the experience acquired with the LHC operation. The initial direct-relation matrix, Z, of the DEMATEL procedure for the FCC subsystems, and likewise for the LHC subsystems, is shown in Table 3.9.

Following Equations 3.8 and 3.9, the elements of the normalized direct-relation matrix, X, and the total-relation matrix, T, for FCC subsystems, are shown in Tables 3.10 and 3.11, respectively.

The $r-d$ values of the DEMATEL procedure for FCC subsystems are derived from Equations 3.10 to 3.14 and shown in Table 3.12, in columns 1 to 6. The $r-d$ values provide a tool to identify the net causers and net receivers of the FCC, i.e. the subsystems that cause downtime on others and the subsystems that suffer from downtime induced by others. For example, the Electrical Network, with the highest $r-d$ value of 0.192, is the FCC subsystem with the highest net effect on the operation of other subsystems in terms of induced downtime. This is because the subsystems affected by an Electrical Network failure require additional recovery time to get back to their nominal operating state once the failure is repaired.

Given the availability target of 70% for the FCC, Table 3.12, columns 7 to 10,

FCC subsystem	Repair time	Criticality	Intricacy	State of art	Performance time	Environment
Accelerator Controls	2	2	2	3.3	10	3.3
Access System	5	2	3	3.3	10	3.3
Beam Exciters	3	2	4	6.7	3.3	6.7
Beam Instrumentation	5	8	9	10	6.7	6.7
Collimation	5	5	6	10	6.7	10
Cooling and Ventilation	7	2	3	3.3	10	3.3
Cryogenics	10	5	8	10	10	6.7
Electrical Network	8	4	5	3.3	10	3.3
Experiments	3	2	10	10	6.7	10
Injection Systems	5	4	7	6.7	6.7	6.7
Injector Complex	8	7	10	10	10	6.7
IT Services	2	2	2	3.3	6.7	3.3
Beam Dumping System	7	6	10	10	6.7	6.7
Machine Interlocks System	3	4	5	6.7	6.7	6.7
Magnet circuits	10	8	10	10	6.7	6.7
Power Converters	5	10	9	10	6.7	10
Quench Protection System	5	10	9	10	6.7	10
Radio Frequency	5	4	5	6.7	6.7	6.7
Transverse Damper	3	2	6	10	6.7	6.7
Vacuum	5	5	5	3.3	6.7	6.7

Table 3.8: Availability allocation factors scoring for the FCC subsystems.

i	j	1 Accelerator Controls	2 Access System	3 Beam Exciters	4 Beam Instrumentation	5 Collimation	6 Cooling and Ventilation	7 Cryogenics	8 Electrical Network	9 Experiments	10 Injection Systems	11 Injector Complex	12 IT Services	13 Beam Dumping System	14 Machine Interlocks System	15 Magnet circuits	16 Power Converters	17 Quench Protection System	18 Radio Frequency	19 Transverse Damper	20 Vacuum
	Z_{ij} 0: No influence 1: Low influence 2: High influence 3: Very high influence																				
1	Accelerator Controls	0	1	2	3	2	1	2	1	0	1	1	1	2	2	1	2	2	2	2	2
2	Access System	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0	0
3	Beam Exciters	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
4	Beam Instrumentation	0	2	1	0	3	0	0	0	3	0	0	0	2	0	0	0	0	2	3	0
5	Collimation	0	0	0	0	0	0	2	0	2	3	0	0	0	3	0	0	0	0	0	1
6	Cooling and Ventilation	0	0	2	1	3	0	3	0	3	3	0	0	2	1	3	3	0	3	3	2
7	Cryogenics	0	1	0	0	0	3	0	0	3	0	0	0	0	1	3	0	3	3	0	0
8	Electrical Network	1	3	3	3	3	3	3	0	3	3	0	3	3	3	3	3	3	3	3	3
9	Experiments	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2
10	Injection Systems	0	0	0	0	3	0	0	0	2	0	0	0	0	1	0	0	0	0	0	3
11	Injector Complex	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0
12	IT Services	3	1	1	1	1	1	1	1	3	1	0	0	1	1	0	1	1	1	1	1
13	Beam Dumping System	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
14	Machine Interlocks System	0	0	0	0	0	0	0	0	0	2	2	0	3	0	2	2	3	0	0	0
15	Magnet circuits	0	2	0	0	0	0	3	0	0	0	0	0	0	1	0	1	3	0	0	0
16	Power Converters	0	2	2	0	0	0	0	0	0	0	0	0	0	1	3	0	2	0	0	0
17	Quench Protection System	0	0	0	0	0	0	3	0	0	0	0	0	0	1	3	2	0	0	0	0
18	Radio Frequency	0	0	1	2	0	0	0	0	0	0	0	0	3	1	0	0	0	0	1	0
19	Transverse Damper	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
20	Vacuum	0	0	2	1	1	0	2	0	1	3	0	0	2	1	0	0	0	0	0	0

Table 3.9: The initial direct-relation matrix Z of the DEMATEL procedure for the FCC subsystems.

$$10^{-3} \times \begin{bmatrix}
0 & 19 & 38 & 58 & 38 & 19 & 38 & 19 & 0 & 19 & 19 & 19 & 38 & 38 & 19 & 38 & 38 & 38 & 38 & 38 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 19 & 0 & 0 & 0 & 0 & 19 & 19 & 19 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 19 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 38 & 19 & 0 & 58 & 0 & 0 & 0 & 58 & 0 & 0 & 0 & 38 & 0 & 0 & 0 & 0 & 38 & 58 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 38 & 0 & 38 & 58 & 0 & 0 & 0 & 58 & 0 & 0 & 0 & 0 & 0 & 19 \\
0 & 0 & 38 & 19 & 58 & 0 & 58 & 0 & 58 & 58 & 0 & 0 & 38 & 19 & 58 & 58 & 0 & 58 & 58 & 38 \\
0 & 19 & 0 & 0 & 0 & 58 & 0 & 0 & 58 & 0 & 0 & 0 & 0 & 19 & 58 & 0 & 58 & 58 & 0 & 0 \\
19 & 58 & 58 & 58 & 58 & 58 & 58 & 0 & 58 & 58 & 0 & 58 & 58 & 58 & 58 & 58 & 58 & 58 & 58 & 58 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 19 & 0 & 0 & 0 & 0 & 0 & 38 \\
0 & 0 & 0 & 0 & 58 & 0 & 0 & 0 & 38 & 0 & 0 & 0 & 0 & 19 & 0 & 0 & 0 & 0 & 0 & 58 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 19 & 58 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
58 & 19 & 19 & 19 & 19 & 19 & 19 & 19 & 58 & 19 & 0 & 0 & 19 & 19 & 0 & 19 & 19 & 19 & 19 & 19 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 19 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 38 & 38 & 0 & 58 & 0 & 38 & 38 & 58 & 0 & 0 & 0 \\
0 & 38 & 0 & 0 & 0 & 0 & 58 & 0 & 0 & 0 & 0 & 0 & 0 & 19 & 0 & 19 & 58 & 0 & 0 & 0 \\
0 & 38 & 38 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 19 & 58 & 0 & 38 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 58 & 0 & 0 & 0 & 0 & 0 & 0 & 19 & 58 & 38 & 0 & 0 & 0 & 0 \\
0 & 0 & 19 & 38 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 58 & 19 & 0 & 0 & 0 & 0 & 19 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 19 & 0 & 0 & 0 & 19 & 0 & 0 \\
0 & 0 & 38 & 19 & 19 & 0 & 38 & 0 & 19 & 58 & 0 & 0 & 38 & 19 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

Table 3.10: Corresponding normalized direct-relation matrix, X, of FCC subsystems with $s = 52$.

$$\begin{bmatrix}
0.002 & 0.027 & 0.047 & 0.062 & 0.048 & 0.024 & 0.050 & 0.020 & 0.015 & 0.031 \\
0 & 0.002 & 8.3 \times 10^{-4} & 2.1 \times 10^{-5} & 7.3 \times 10^{-5} & 8.5 \times 10^{-5} & 0.001 & 0 & 0.02 & 8.9 \times 10^{-4} \\
0 & 6.7 \times 10^{-5} & 3.3 \times 10^{-5} & 1.4 \times 10^{-6} & 4.7 \times 10^{-5} & 7.1 \times 10^{-6} & 0 & 0 & 5.6 \times 10^{-5} & 7.9 \times 10^{-4} \\
0 & 0.039 & 0.020 & 0.002 & 0.06 & 1.4 \times 10^{-4} & 0.003 & 0 & 0.061 & 0.004 \\
0 & 0.001 & 0.001 & 6.2 \times 10^{-4} & 0.004 & 0.002 & 0.040 & 0 & 0.044 & 0.062 \\
0 & 0.007 & 0.044 & 0.023 & 0.064 & 0.004 & 0.067 & 0 & 0.069 & 0.066 \\
0 & 0.023 & 0.004 & 0.004 & 0.004 & 0.06 & 0.011 & 0 & 0.063 & 0.005 \\
0.023 & 0.069 & 0.070 & 0.066 & 0.073 & 0.064 & 0.078 & 0.002 & 0.082 & 0.075 \\
0 & 1.3 \times 10^{-4} & 0.002 & 7.5 \times 10^{-4} & 0.001 & 9.6 \times 10^{-5} & 0.002 & 0 & 0.001 & 0.003 \\
0 & 2.4 \times 10^{-4} & 0.002 & 0.001 & 0.059 & 2.8 \times 10^{-4} & 0.005 & 0 & 0.043 & 0.008 \\
0 & 1.6 \times 10^{-5} & 1.7 \times 10^{-4} & 8.3 \times 10^{-5} & 0.003 & 1.8 \times 10^{-5} & 3.1 \times 10^{-4} & 0 & 0.022 & 0.06 \\
0.06 & 0.025 & 0.027 & 0.026 & 0.028 & 0.023 & 0.028 & 0.020 & 0.067 & 0.027 \\
0 & 6.7 \times 10^{-5} & 3.3 \times 10^{-5} & 1.4 \times 10^{-6} & 4.7 \times 10^{-5} & 7.1 \times 10^{-6} & 1.2 \times 10^{-4} & 0 & 5.6 \times 10^{-5} & 7.9 \times 10^{-4} \\
0 & 0.003 & 0.002 & 7.1 \times 10^{-5} & 0.002 & 3.7 \times 10^{-4} & 0.006 & 0 & 0.003 & 0.041 \\
0 & 0.041 & 0.001 & 2.2 \times 10^{-4} & 3.0 \times 10^{-4} & 0.004 & 0.062 & 0 & 0.005 & 0.001 \\
0 & 0.041 & 0.039 & 2.4 \times 10^{-5} & 8.0 \times 10^{-5} & 3.6 \times 10^{-4} & 0.006 & 0 & 0.001 & 0.001 \\
0 & 0.005 & 0.002 & 2.2 \times 10^{-4} & 3.0 \times 10^{-4} & 0.004 & 0.062 & 0 & 0.004 & 0.001 \\
0 & 0.002 & 0.020 & 0.039 & 0.002 & 1.3 \times 10^{-5} & 2.3 \times 10^{-4} & 0 & 0.002 & 0.001 \\
0 & 9.7 \times 10^{-5} & 4.2 \times 10^{-4} & 7.4 \times 10^{-4} & 9.1 \times 10^{-5} & 7.4 \times 10^{-6} & 1.3 \times 10^{-4} & 0 & 1.0 \times 10^{-4} & 8.1 \times 10^{-4} \\
0 & 0.002 & 0.039 & 0.02 & 0.024 & 0.002 & 0.040 & 0 & 0.026 & 0.061
\end{bmatrix}$$

0.021	0.020	0.051	0.053	0.033	0.046	0.050	0.048	0.046	0.044
7.9×10^{-4}	0	0.001	0.021	0.022	0.021	0.003	9.1×10^{-5}	7.8×10^{-6}	8.0×10^{-4}
7.4×10^{-4}	0	0.001	0.02	8.7×10^{-4}	8.1×10^{-4}	0.001	7.6×10^{-6}	6.4×10^{-7}	4.9×10^{-5}
3.3×10^{-4}	0	0.041	0.009	0.001	0.001	7.6×10^{-4}	0.040	0.059	0.004
0.002	0	0.005	0.062	0.005	0.003	0.006	0.002	2.2E-04	0.025
0.001	0	0.047	0.035	0.067	0.061	0.012	0.064	0.060	0.046
0.001	0	0.008	0.027	0.067	0.009	0.064	0.062	0.005	0.005
0.004	0.06	0.076	0.082	0.079	0.072	0.076	0.072	0.069	0.071
7.8×10^{-4}	0	0.003	0.020	0.001	8.6×10^{-4}	0.001	1.3×10^{-4}	5.1×10^{-5}	0.039
0.001	0	0.004	0.025	0.001	0.001	0.002	3.4×10^{-4}	9.1×10^{-5}	0.061
7.1×10^{-5}	0	2.8×10^{-4}	0.002	1.0×10^{-4}	7.9×10^{-5}	1.3×10^{-4}	2.2×10^{-5}	6.3×10^{-6}	0.004
0.002	0.002	0.029	0.031	0.010	0.027	0.028	0.027	0.026	0.028
7.4×10^{-4}	0	0.001	0.02	8.7×10^{-4}	8.1×10^{-4}	0.001	7.6×10^{-6}	6.4×10^{-7}	4.9×10^{-5}
0.039	0	0.06	0.005	0.045	0.042	0.063	4.0×10^{-4}	3.3×10^{-5}	0.003
0.001	0	0.002	0.023	0.011	0.024	0.064	0.004	2.9×10^{-4}	3.9×10^{-4}
8.9×10^{-4}	0	0.001	0.023	0.063	0.005	0.044	3.8×10^{-4}	2.9×10^{-5}	1.2×10^{-4}
8.9×10^{-4}	0	0.002	0.023	0.065	0.041	0.010	0.004	2.9×10^{-4}	3.7×10^{-4}
8.3×10^{-4}	0	0.061	0.022	0.001	0.001	0.001	0.002	0.021	2.0×10^{-4}
7.6×10^{-4}	0	0.002	0.020	8.9E-04	8.3E-04	0.001	0.02	4.1×10^{-4}	5.3×10^{-5}
0.001	0	0.041	0.025	0.004	0.001	0.004	0.003	0.001	0.005

Table 3.11: Corresponding total-relation matrix, T, of FCC subsystems.

show the assigned complexity and availability targets for the FCC subsystems by the Geometric Average Weighting assessment method combined with the DEMATEL procedure.

The comparison of the obtained availability target with the measured availability of the LHC subsystems during 2017 run [32, 33] in Fig.3.2, gives an insight of the feasibility of the availability requirements for the FCC subsystems.

The availability requirement for the FCC Injector Complex, for example, is comparable to that of the LHC Injector Complex. However, the FCC Injector Complex will include a High Energy Booster (HEB) as injector. Dedicated studies are being performed to identify the best injector option for the FCC that fulfills the availability and cost requirements [10, 11]. In addition, in order to avoid the high number of rejected injections occurring in the LHC due to insufficient beam quality, advanced beam quality diagnostics will be implemented in the FCC injectors. Regarding the FCC Magnets circuits, although the availability requirement of 97.8% is much lower than the current availability of the LHC circuits, 99.98%, with 12 times more powering circuits installed in the FCC, this becomes a relevant aspect to consider. The Quench Protection system will be another key driver of

i	R	D	r	d	r-d	w_i^G	w_i^{G+D}	C_i	$\tilde{A}_i$ (%)
1	0.736	0.082	0.116	0.013	0.103	871.2	960.7	0.04×10^{-2}	99.99
2	0.093	0.287	0.015	0.045	−0.030	3267.0	3167.6	0.14×10^{-2}	99.98
3	0.025	0.322	0.004	0.051	−0.047	3555.3	3389.6	0.15×10^{-2}	99.98
4	0.342	0.244	0.054	0.038	0.015	161 604.0	164 102.6	7.44×10^{-2}	98.96
5	0.267	0.372	0.042	0.058	−0.017	100 500.0	98 837.8	4.48×10^{-2}	99.37
6	0.738	0.186	0.116	0.029	0.087	4573.8	4970.6	0.23×10^{-2}	99.97
7	0.419	0.463	0.066	0.073	−0.007	268 000.0	266 133.7	12.06×10^{-2}	98.32
8	1.261	0.042	0.198	0.007	0.192	17 424.0	20 764.2	0.94×10^{-2}	99.87
9	0.075	0.527	0.012	0.083	−0.071	40 200.0	37 345.7	1.69×10^{-2}	99.76
10	0.215	0.448	0.034	0.070	−0.037	42 106.8	40 560.6	1.84×10^{-2}	99.74
11	0.091	0.080	0.014	0.013	0.002	375 200.0	375 818.0	17.03×10^{-2}	97.63
12	0.540	0.081	0.085	0.013	0.072	583.7	625.9	0.03×10^{-2}	100.00
13	0.025	0.434	0.004	0.068	−0.064	188 538.0	176 408.7	8.00×10^{-2}	98.88
14	0.314	0.546	0.049	0.086	−0.037	18 045.8	17 385.7	0.79×10^{-2}	99.89
15	0.243	0.479	0.038	0.075	−0.037	359 120.0	345 814.7	15.67×10^{-2}	97.82
16	0.226	0.359	0.035	0.056	−0.021	301 500.0	295 189.3	13.38×10^{-2}	98.14
17	0.226	0.434	0.036	0.068	−0.033	301 500.0	291 651.3	13.22×10^{-2}	98.16
18	0.176	0.348	0.028	0.055	−0.027	30 076.3	29 262.4	1.33×10^{-2}	99.81
19	0.048	0.289	0.008	0.045	−0.038	16 160.4	15 548.6	0.70×10^{-2}	99.90
20	0.300	0.337	0.047	0.053	−0.006	18 517.1	18 408.9	0.83×10^{-2}	99.88

Table 3.12: $r-d$ values of the DEMATEL procedure and assessed complexity and availability values by the Geometric Average Weighting method combined with the DEMATEL procedure for the FCC subsystems. An availability target of $A_T = 70\%$ is assumed for FCC.

FCC machine downtime and will have to achieve an availability similar to the one of the LHC Quench Protection System. To this end, advanced quench detection techniques are under consideration [34, 35] that provoke a fast discharge of the magnet to avoid damage and to simultaneously reduce significantly the recovery time of the magnet. The FCC Cryogenic system, with 2 more cryogenics plants and intrinsically long recovery times, is required to be slightly more available than the one in the LHC. The lessons learned from the LHC operation and the new compressor technology available [36], makes the implementation of a more reliable Cryogenics system for the FCC plausible. With 20 times more extraction kickers than in the LHC, the FCC Beam Dumping System is required to be as available as

the LHC Beam Dumping system in the 2017 run. Thus, the FCC Beam dumping system design should tolerate spurious firing of a single kicker and prevent common cause failures caused by erratic kicks, which are the recurrent failures in the LHC. Conversely, the LHC Beam Instrumentation showed very few problems during 2017 and achieved an availability of 99.39%. For this reason, and despite the fact that Beam Instrumentation scales with the size of the machine, meeting the availability requirement for FCC Beam Instrumentation of 98.96% seems feasible. Regarding the Electrical Network, the FCC will have three connections for electrical supply, instead of one like the LHC, to avoid the effects of electrical glitches observed in the LHC and to meet the assessed higher availability requirement of 99.87%. In the best case, if an electrical source gets unavailable, only a reconfiguration of the network would be needed. For the remaining FCC subsystems, the allocated availability requirements do not present, in principle, major technical challenges, given that no significant failures were observed for these subsystems during the LHC operation.

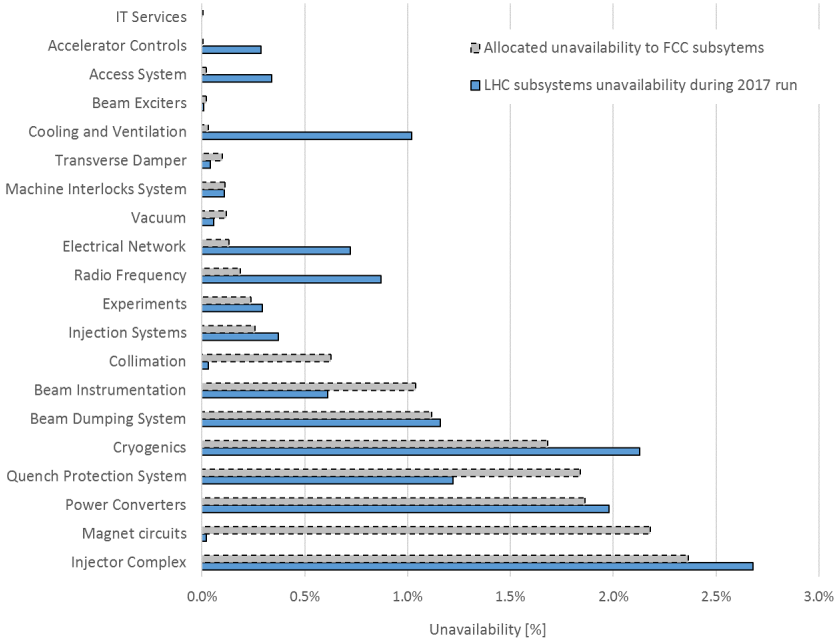


Figure 3.2: Unavailability budgets for the FCC subsystems (according to their assessed complexity by the Geometric Average Weighting method and assuming an FCC target availability of $A_T = 70\%$) compared to the observed LHC subsystems unavailability during the 2017 run.

4 Availability modeling methods and tools

The implementation of a detailed availability model that uses component reliability data to estimate the overall system availability is especially useful for complex availability-critical particle accelerators. In particular, for accelerators under design for which models could have a direct impact on design choices, architecture and component selection. Such accelerators projects are high cost and high impact projects and therefore, the availability requirements, among the many others, need to be demonstrated before constructions works can start. To ensure the completeness and consistency of the availability study, the present chapter proposes a step-wise methodology for the definition of availability models of particle accelerators.

Several commercial and custom software tools are available for the implementation and simulation of the accelerator performance [37]. This chapter gives an overview of the methods and simulation tools used for availability modelling of present and future particle accelerators. In particular, the new Common Input Format framework is introduced, which proposes a set of interrelated tables to completely define an availability model.

This is followed by the LHC and CLIC availability models to serve as an example of the proposed availability modelling methodology. Results obtained from the simulation of the models with the AvailSim software are discussed in detail.

4.1 Definitions for Availability modeling

The use of different terminology can lead to misunderstandings when defining the availability model or reporting on the simulation results, since same terms are used in different domains or even in the particle accelerator community to convey different meanings and vice versa. In this section, definitions are given to ensure

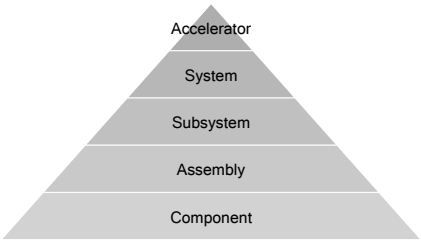


Figure 4.1: Generic hierarchy of an accelerator system.

uniform and consistent availability terminology throughout the thesis and should be applicable to any type of accelerator availability study.

SYSTEM: a set of interrelated items that collectively fulfill a requirement [38]. A system may have a real or abstract boundary. The system structure may be in accordance with the physical hardware hierarchy of the system. In the context of particle accelerators, a generic hierarchy is shown in Fig. 4.1.

FAILURE: loss of ability to perform as required [38]. Failures can be categorized according to the severity of their consequences. The severity can range from degraded operation (minor impact) to damage of the machine beyond repair (catastrophic impact).

MEAN TIME TO FAILURE (MTTF): mean duration of the operating time between failures without taking into consideration what may happen after the failure, i.e. repair time or maintenance [39].

MAINTENANCE: combination of all technical and management actions intended to retain an item, or restore it to a state in which it can perform as required [38].

- On/Off-site maintenance: maintenance of the item can be done remotely, off-site maintenance, or is required to be in situ, on-site maintenance.
- Planned maintenance (or also: Scheduled Maintenance) [38]: maintenance

carried out in accordance with a specified time schedule. Scheduled maintenance may identify the need for some further corrective or preventive maintenance actions. Planned maintenance can be considered a machine phase.

- Preventive maintenance[38]: maintenance carried out to mitigate degradation and reduce the probability of failure. Scheduled stops are set in order to perform preventive maintenance.
  - Condition-based maintenance[38]: preventive maintenance based on the assessment of physical condition. The condition assessment may be by operator observation, conducted according to a schedule, or by condition monitoring of system parameters.
- Corrective maintenance: maintenance carried out after fault detection to restore system function.

MEAN TIME TO REPAIR (MTTR): time it takes to restore the item function [38]. It includes: fault localization, fault diagnosis, fault correction and fault checkout.

ACCESS TIME: time it takes to access the location of the item for repair or maintenance.

RESTART TIME: time it takes to re-establish the nominal operational state of the item after a failure repair or maintenance.

REDUNDANCY: provision of more than one item for performing a function [38]. Types of redundancy:

- Standby redundancy: redundancy wherein the redundant item is activated only when the active item becomes unavailable.
- Active redundancy: redundancy wherein the redundant items operate simultaneously.

- M out of N redundancy: active redundancy wherein at least m of the total n items must be operational to meet the requirement.

SPARE: redundant item which is not in use and could be used if needed. Types of spares:

- Hot spares: units with identical stresses to those that apply to the operational units. It is immediately ready to operate upon request.
- Warm spares: units which have power on but less than the operational units. They might require additional time to switch-on.
- Cold spares: power-off units, i.e. non-operational units. The switch-on process may have an associated failure probability, depending on the reliability of the switch.

SWAP TIME: time needed to replace a failed unit by an available spare.

STANDBY STATE: non-operating UP state during a given period. The standby state refers to the state of an operational item while the accelerator is down or to the state of a spare.

- Cold standby: standby state requiring warm up before a demand to operate can be met. The item cannot fail during cold standby.
- Hot standby: standby state providing for immediate operation upon demand. The item can suffer from failures during hot standby.

SCHEDULED OPERATION TIME (OP): time period that the item is scheduled to operate in order to fulfill its required function. This time does not include Planned Maintenance periods. However, scheduled operation time does account for downtime periods caused by failures and corrective maintenance actions.

DOWNTIME (DT)- FAULT TIME: interval of the operation time in which the item is not operational due to failures or corrective maintenance. Planned maintenance periods are not considered downtime. The failure of a (parent) system might lead to the failure of other (child) systems. In addition, there might be failures occurring in parallel. For these reasons, the following definitions are given depending on the cause of the system downtime:

- **RAW DOWNTIME:** The total time the item is down, regardless the cause of the failure or if it is occurring in parallel to other failures.
- **ROOT CAUSE DOWNTIME:** The time the (parent)item is down due to a root cause failure plus the downtime caused to other (child) items, excluding downtime occurring in the shadow of other on-going failures. Note that the sum of the root cause downtime of the accelerator components is the total downtime of the accelerator system.

EFFECTIVE OPERATION TIME: Fraction of the scheduled operation time that the item is not in failure.

PHASES AND CYCLES: a characteristic period of time in operation or planned maintenance. A phase of an accelerator defines the operation mode and beam parameters of the accelerator. Operation periods and planned maintenance periods can contain phases. These phases can be cyclical, i.e. phases that are repeated one after the other in a specific order forming a cycle. The concept of cycling phases is used mainly in circular colliders. As explained in Section 2.1, in circular accelerators like the LHC, a sequence of tasks (i.e. machine cycles) needs to be carried out to achieve the execution of a successful final luminosity production (cycle) phase.

MISSION TIME (MT): total time for operation and maintenance of an accelerator. The mission time is the total time available for exploitation of the accelerator, including maintenance and operation periods.

AVAILABILITY (A): a general definition of availability in literature is given in the references [39],

> The availability is the probability that a system is in a functional condition at time t or during a defined time span, under the condition that it is operated and maintained correctly.

However, different quantities could be defined depending on the definition of the term functional condition and the considered time span, as discussed in [40].

For the evaluation of the accelerator and its components performance, the availability is defined as follows:

$$A = \frac{OP - DT}{OP} \tag{4.1}$$

In other words, availability is the fraction of the operation time that the item is not in failure. Note that the operation time is specific for each item. Depending on the conditions under which the item is requested to operate, the operation time can be a complete operation phase, a certain cycling phase or the whole mission time. As an example, for an accelerator system which is only requested to operate during a certain machine cycle, its availability must only be considered for the machine cycle duration and not for the total operation time of the accelerator. Whether the intrinsic item downtime, or the root cause fault downtime will be used to calculate the availability depends on the chosen approach. The root cause fault time is used to obtain a clearer idea of the functioning of the item with respect to the overall operation of the system. On the contrary, if the item is considered individually and not as a part of a bigger system, the raw downtime is used in the computation of availability. It will be necessary to specify the definition to be considered for the calculation of the availability of the accelerator and its components. For particle accelerators, the root cause downtime and the total operation time are used without taking into account the individual operation phases. Unless otherwise stated, this availability definition is adopted in this thesis.

4.2 Guide for Availability modeling

As availability is one of the key indicators of machine performance, availability modeling becomes of crucial importance throughout the life-cycle of a particle

accelerator [41]. In the design stage, the goal of the availability study is to demonstrate the applicability of the accelerator project by identifying the potential major contributors to downtime and analyzing different operational scenarios and designs. Further, requirements for spares and manpower can be drawn based on simulation results. All in all, the best compromise between cost, design and availability should be obtained based on available resources.

For already operating machines, availability modeling is used to provide guidelines for performance improvement by identifying the changes that would lead to the greatest benefit. These changes range from component reliability improvements to the reconsideration of maintenance strategies and operational schedules. In the event of an accelerator upgrade, the existing availability model should be adapted to predict its performance and anticipate for future issues that may compromise availability.

The step-wise methodology presented here aims to provide a common procedure for the definition of accelerator availability models and to ensure the completeness and accuracy of the simulation study at any stage of the accelerator lifetime. To this end, it is first necessary to obtain a complete picture of the accelerators design, the failure behavior and its operation modes. Subsequently, the implementation of the corresponding availability model is followed by the model simulation, results analysis and validation. This systematic approach establishes also a basis to make models comparable as they are defined under the same assumptions and definitions. For the same reason, this approach reduces the likelihood to omit considerations that would lead to unrealistic machine performance simulation and wrong interpretations of the results.

The step-wise methodology for availability modeling of particle accelerators presented in Fig 4.2, is described below.

Step 1. Definition of the problem. Define the specific questions to be addressed by the study. For example, whether the availability requirements for the accelerator will be met, or whether a given luminosity production goal is achievable. Based on the foregoing, identify the performance measures that will be used to evaluate the efficiency of the accelerator. Availability is generally

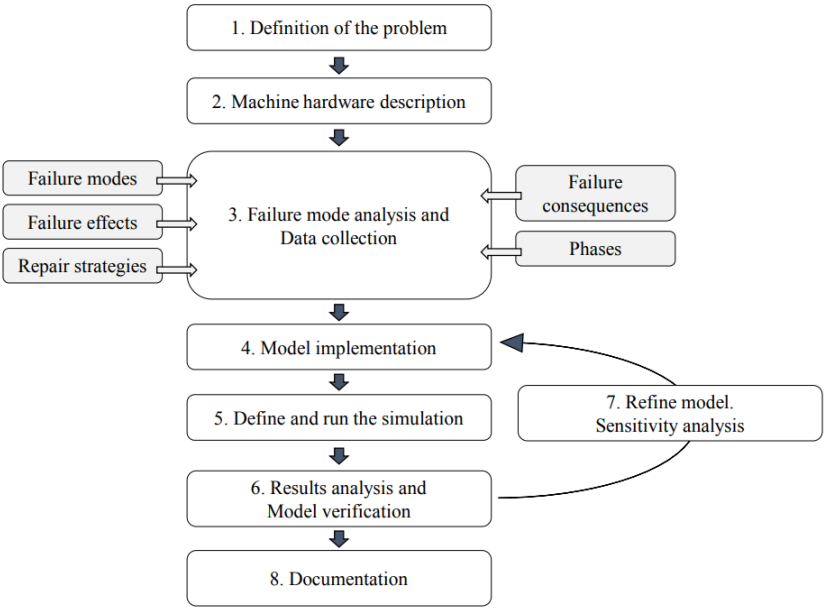


Figure 4.2: Flowchart of the step-wise methodology for availability modeling of particle accelerators.

considered as the performance measure, but other indicators might also be considered, such as cost, luminosity or other accelerator-specific parameters.

Step 2. System hardware description. Define the different functional parts of the machine and the way they interact. The machine could be defined as a hierarchy of elements, according to the definitions in Section 4.1, arranged into a specific design to achieve the desired function. A graphical representation of the accelerator system could be useful for its definition. The level of detail of the system hardware description depends on the data available or the design state of the machine.

One of the major problems encountered when performing an availability study,

is the lack of reliable failure data. Although manufacturers often provide precise information on the reliability of the components, the stress levels applied in accelerators may completely change the failure behavior of the components. To this we add the fact that most of the accelerators systems are rarely used in other industries and hence, there is little knowledge of their performance. Furthermore, no significant credit has been given to the importance of failure tracking of accelerators components in a unified manner until availability studies became a must in new accelerator projects. Nevertheless, system experts often have tracked failures for many years independently, providing an excellent source of information. In conclusion, the level of detail of the accelerator system availability study should be determined based on system experts judgment, experience and available data.

Step 3. Failure mode analysis, data collection and operational cycles After the system hardware definition, a failure mode analysis is performed at the lowest level of the element hierarchy, say at component level. Then, quantities of interest need to be collected, such as failure rates, repair times and failure effects. At the lowest level the following questions should be addressed to ensure the completeness of the study. Although some questions seem obvious, it is important to have them listed here for reviewing purposes.

- which are the component failure modes?
- how often does a given failure occur?
- can the component suffer from a given failure also during downtime (i.e., when the accelerator system is down due to failure of other components)? It should be noted that there might be systems that are kept in an operational state to avoid a long recovery time after the accelerator downtime and therefore, can experience failures.
- can the component fail when the accelerator is down due to planned maintenance work? For the same reason as before, there might be components in operation that can experience failures.
- which are the failure effects? How does a failure affect the operational

state of the accelerator and its parameters? what influence does a the failure have on other systems? For example, does it reduce the output energy, the luminosity, or does it require a beam stop to perform repairs. Some failures might not even affect the performance of the accelerator due to an implemented redundancy or fast recovery.

- what are the consequences of a beam stop and/or a machine parameter outside its limits? E.g., it might be that when the accelerator needs to be repaired, a certain time is needed to cool down the machine from radiation before accessing the accelerator housing.

For each failure mode, it is necessary to define how its repair would be performed by specifying:

- the time it takes to repair the failure,
- the manpower needed to repair the component from failure,
- whether the failure is remotely repairable, i.e. without access to the location of component,
- whether the repair requires a spare part and how many spare parts are available by location,
- the point in time that the failure will be repaired with respect to its occurrence: a) at the moment of failure, b) only when certain parent system/assembly is down, or c) when the whole accelerator system is down,
- whether the repairs can be done in parallel rather than sequentially in order to decrease the total accumulated downtime.

Accelerators are often operated in phases or cycles, as described in 4.1, during which not necessarily all components or systems might be required or may experience failures. Hence, the following questions should be addressed:

- which components are required in each phase?,
- which are the failure modes of the component in each phase?

- are planned maintenance stops foreseen? For how long? Which is the repair strategy during maintenance? a) all failed components will be repaired before starting operation or b) only the ones in specific locations?
- if the accelerator system is brought down during an operational phase due to failure, which failures should be repaired before restarting operation? Several repair strategies could be defined here. For example, to repair only the last issue that caused the stop or to repair everything that failed during the operation time. The repair strategy adopted can have a direct effect on the availability of the accelerator.

Step 4. Model Implementation The data collected in steps 2 and 3 provides all the necessary information to implement a complete availability model to simulate realistic machine operation. The are various methods for representing an availability model, from Reliability Block Diagrams (RBD) and Markov State models to custom made solutions [37]. Two of these representation techniques are explained more in detail in Section 4.3: the Reliability Block Diagrams and the Common Input Format.

Step 5. Define and run the simulation Determine the mission time and number of simulations to perform. Monte Carlo simulations [42] are preferred to simulate the performance of an accelerator over analytic calculations due to the high complexity of the models to analyze. Further, components failure behaviour and often repair, are described by probability distributions. Hence, Monte Carlo simulations are used to evaluate the probability of different outcomes in such random process (failure or repair of the components) for which no analytic expressions are available. Several commercial and custom-made tools are available to model the performance of particle accelerators [37, 43]. These tools are discussed more in detail in section 4.3.3. The number of simulations determines the statistical confidence of the results. Many software tools provide, together with the simulation results, the standard deviation of the simulation sample to better determine the needed number of simulation runs.

Step 6. Results analysis and model verification A deep analysis of the simula-

tion results gives an indication whether the implemented model reproduces real machine operation. In the early stages of the study, a simple model is defined with general assumptions on, for example, repair strategies, available spares and maintenance phases, i.e. quantities usually linked to uncertainty. Once the simplified model is verified and the results obtained are in-line with expectations, more complex assumptions are gradually implemented in the model.

All along this process, close contact with system experts is of crucial importance. First, for the development of a complete and realistic model and second, for validation of the obtained results. Model verification can also be obtained through the implementation of the model in different software packages and comparison of the results. For existing machines, model verification can be also done with real performance data.

Step 7. Sensitivity analysis The objective of the sensitivity analysis is two-fold: to study the effect that a limited knowledge of an input parameter has on the output of the model; and to identify the input variables with strongest impact on the system performance and hence, which are primary candidates for system improvement.

"One-at-a-time" is one of the most commonly used sensitivity analysis methods. The method assesses the sensitivity of the simulation results to the variation of one of the input variables, e.g. failure rate, or assumptions, e.g. repair strategy, while keeping the others at their nominal value. This method can be used to find the optimum repair strategy, planned-maintenance schedule or number of spares that maximizes the availability. For example, the optimum planned-maintenance schedule is the one that gives the highest availability estimation among all possible planned-maintenance schedules.

Differential Importance Measures, which are proposed in Section 6.2, evaluate the effect of a change in one or more input variables on the model simulation results.

The outcome of sensitivity analyses can be useful not only for decision making on components availability requirements, system design and duration of phases

but also for the identification of critical components and common cause failures with high impact on machine availability.

Step 8. Documentation Comprehensive documentation of all the followed steps, data sources and modeling assumptions is of crucial importance for future follow-up activities. A proper documentation should provide the means to understand and verify how the study was conducted. The documentation not only serves as a source of data for other similar availability studies, but also ensures knowledge transfer towards future follow-up activities. Accelerator machines are usually upgraded after some years of operation and at the same time, the availability study must be updated.

The examples presented in Section 4.4 follow the availability modelling guide to define the models, perform simulations and analyze the results.

4.3 Availability model implementation and simulation tools

4.3.1 Reliability block diagrams

Reliability Block Diagrams (RBD) are graphical diagrams that represent the logical ways in which components are required to interact to sustain system operation [44]. The RBD is made of blocks and nodes connected in parallel or in series thought any number of indenture (i.e. nesting) levels following the system hardware hierarchical description. At any level, the diagrams should contain a unique input node and a unique output node. These diagrams can represent, for example, component redundancies, phase dependent configuration changes or switching logic. Each block can be assigned a failure mode and a maintenance strategy. Lines connect blocks to other blocks and nodes. Nodes have their own parameters to indicate, among others, the vote logic and operational capacity target. A failure in a block will disrupt the connection between its neighbouring nodes and blocks. The represented system will operate if at least one of the paths from the input node connects with the output node.

A Fault Tree (FT) is equivalent to a RBD but applying the "negative logic", i.e. it represents the logical ways in which component failures interact to cause a system

failure, and it uses gates instead of nodes.

A graphical interface is usually employed to define the RBD. For large and complex availability models, the definition of the model demands a lot of manual work,in order to define each individual block and node. For example, the availability model of the PS-Booster Radio-Frequency system [45] has more than 45 000 components and this was just a small subsystem of a bigger accelerator under study [46]. Moreover, a deep knowledge of the RBD-implementation environment is needed to define accelerator driven operational modes in such diagrams in case no special features are provided by the tool. The latter often leads to the implementation of incorrect assumptions in the model that subsequently lead to inaccurate results, with no other means of verification than implementing the model through an other interface or with another software tool. The same applies to Fault Tree model definitions. This highlights the need for a more intuitive tool to define and validate availability models for accelerators. Several reliability analysis modelling languages exist in literature [47, 48, 49, 50] that can represent a wide variety of probabilistic models. However, these modelling languages are so general that they are often ill-adapted for the actual application. As none of these languages was specific for modelling accelerator driven systems, we developed the Common Input Format framework.

4.3.2 The Common Input Format framework

The Common Input Format is built on a set of interrelated tables that allow to fully define an availability model. The tables contain all the necessary attributes to input the data gathered in Steps 1 to 3 of the procedure presented in Section 4.2, in an orderly and user-friendly manner. The system relational structures and their parameters are defined independently to be able to change the parameter values while keeping the system structure intact. Efforts have been made to define the system and its failure behavior in an efficient and intuitive tabular format, without the use of any graphical interface or diagram. The proposed framework avoids repetition of identical structures by the definition of entities (i.e. systems, subsystems, assemblies, etc.), as a collection of components. The definition needs

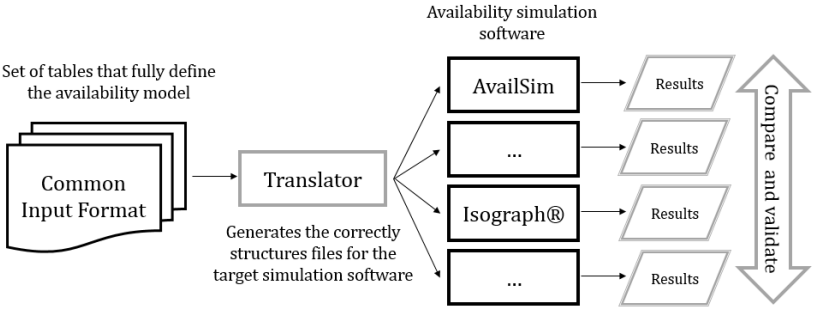


Figure 4.3: Concept of the Common Input Format framework.

to be given only once, while the entity, can be instantiated from anywhere in the system through the use of its unique identifier.

Within the Common Input Format framework, once the model is defined, a translator can generate the correctly structured input files for the target availability simulation software, as illustrated in Fig. 4.3. At present, translators have been developed for the Isograph Availability Workbench and the AvailSim simulation software, see Section 4.3.3, and are available in [51] and [52], respectively.

This framework presents several advantages over other model specification tools. Firstly, no graphical interface is needed to define the model. Secondly, the modeling approach avoids repetition of identical structures and directly allows for easy versioning of the models. Furthermore, a model defined in the Common Input Format becomes common to all simulation software packages for which a model translator exist. Hence, the model can be simulated in various software packages at the same time, allowing to verify the results and model assumptions.

The Common Input format consist of the following 12 tables with attributes, out of which 8 tables are optional that can be used for more advanced modeling features. Optional tables are marked with an asterisks. *Null* columns represent optional data fields for more advanced models. *PK* stands for *Primary Key* and must be unique for each record in the table. *FK* stands for *Foreign Key* and represents a

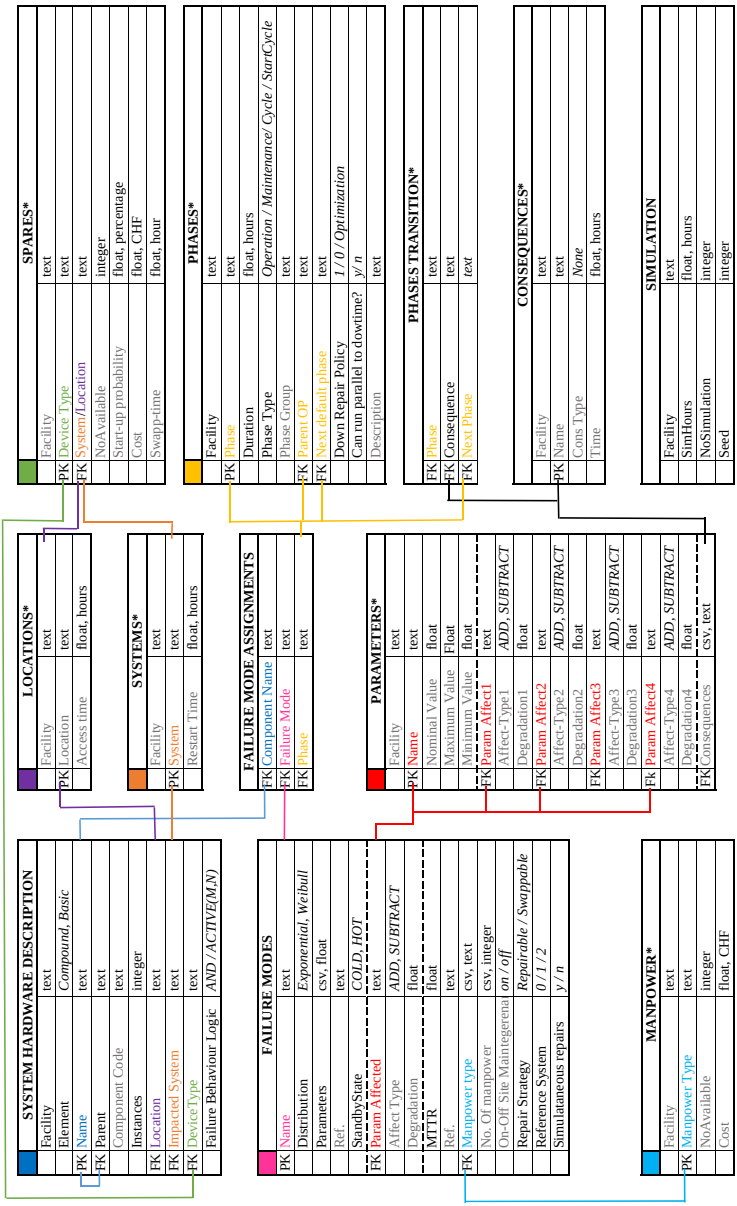


Figure 4.4: Common Input Format Tables relational graphical representation.

field in one table that refers to the Primary key of another table or the same table. The relational graphical representation of the tables is shown in Fig. 4.4.

System Hardware description

This table holds the System hardware and failure logic description. It describes the set of interrelated components, subsystems and systems. For each item, the following attributes should be defined:

Key	Column	Data Type	Null	Description
	Facility	Text	no	Name of the facility the item is part of.
	Element	*Basic / Compound*	no	*Compound*: Item made up of other components. *Basic*: Item in the lowest level of the hierarchical description of the system. Failure modes are assigned only to basic elements.
PK	**Name**	Text	no	Name of the item.
FK	**Parent**	Text	no	Parent of the item in the hierarchical description of the system. The top-level system must have as parent *ROOT*.
	Item Code	Text	yes	Abbreviation used for refering to this item in the model.
	Instances	Int	no	Number of items instantiated in the parent.
FK	**Location**	Text	yes	Defined only for items of *Basic* element type. The location of the item is used to determine how much time is needed to access the item for repair or maintenance. Location related parameters are specified in a dedicated table.
FK	**Impacted System**	FreeText	yes	Defined only for items of *Basic* element type. The set of interrelated items the item is part of is used to determine how much time is needed to restart after repair or maintenance.The interrelated items do not necessary belong to the same parent. The System related parameters are specified in a dedicated table.
FK	**Device Type**	Text	yes	Defined only for items of *Basic* element type. It specifies the type of spare to use for item replacement. Spare parameters are specified in a dedicated table.

Key	Column	Data Type	Null	Description
	System Failure Behavior/Logic	*AND / ACTIVE(M,N)*	no	Defined only for items of *Compound* element type. Refers to the failure behavior of its children. *AND*: all the items the system is parent of, need to be operational for the system to be operational. *ACTIVE(M,N)*: defines an active redundancy wherein at least M of the total N children the element is parent of, need to be operational.

Table 4.1: The Common Input Format *System Hardware description* table.

Failure modes

The table holds the description of failure modes, the effect of these failures on the system parameters, and the repair strategy for each failure.

Key	Column	Data Type	Null	Description
PK	**Failure mode**	Text	no	Name of the failure mode.
	Distribution	*exponential/ weibull*	no	Failure distribution.
	Parameters	Float (hours)	no	For *Exponential* distribution: MTTF, in hours. For *Weibull* distribution: Weibull parameters separated by commas, the first parameter in hours. Note that MTTF does not include repair time, access time or restart time.
	Ref.	Text	yes	Reference or data source of failure distribution parameters (for documentation only).
	Description	Text	yes	Description of the failure mode (for documentation only).
	Standby State	*COLD/ HOT*	no	Define if the item can fail when the system is down due to components failures.
FK	**Parameter affected**	Text	yes	If present, the name of the machine parameter affected by the failure mode.

Key	Column	Data Type	Null	Description
	Affect type	*add/ subtract*	yes	Degradation to be applied to the parameter.
	Degradation	float	yes	The quantum added to, or subtracted from the affected parameter.
	MTTR	Float	no	Time to repair the failure, in hours. Note that MTTR does not account for access time nor restart time.
	Ref.	Text	yes	Reference or data source of the MTTR (for documentation only).
FK	**Manpower Type**	Text	yes	Comma separated list of manpower type needed to repair the item from failure. Manpower type related parameters are specified in a dedicated table.
	No. of Manpower	Int	yes	Comma separated list of corresponding manpower resources needed to repair the item from failure.
	On-Off site maintenance	*on / off*	no	Define if the repair can be done with or without access to the Location.
	Repair Strategy	*Swappable Repairable*	no	The failed item can be replaced by a spare or repaired.
	Reference System	*1 / 0*	no	Defines when corrective maintenance is applied in case the failure occurs during operation. 0=at the moment of failure. 1= only when the facility or system is down.
	Repair	*y / n*	no	Describes if the repairs can be done simultaneously or not, i.e., the MTTR to be used for downtime calculation if the same item failed in several ways due to more than one failure. If simultaneous repairs are allowed, the highest of all the MTTR will be used. If no simultaneous repairs are allowed, the sum of all the MTTR will be used.

Table 4.2: The Common Input Format *System Failure modes* table.

Failure mode assignments

The tables specifies the component failure modes specific for a given phase. Failure modes are only assigned to items of *Basic* element types.

Key	Column	Data Type	Null	Description
FK	**Name**	Text	no	Basic element item name.
FK	**Failure mode**	Text	no	Failure mode of the item.
FK	**Phase**	Text	no	Phase in which the specified failure mode is applicable to the item. Phase related parameters are specified in a dedicated table.

Table 4.3: The Common Input Format *Failure mode assignments* table.

Phases

The table holds the definition of the operation and planned maintenance phases. The following phase types are presented to support the definition of cycling phases:

- Operation: *Operation* phases have fixed duration and cannot be extended. Within an Operation phase there may be periods of downtime caused by a failure consequence.
- Maintenance: *Maintenance* phases have fixed duration. If the repairs take longer that the Maintenance phase duration, the following phase duration is shortened by the remaining repair time.
- Cycle: A Cycle phase has fixed duration and is always a child of an Operation or Maintenance phase, defined through the *Parent Of Phase* column in this table. The total duration of all children of phase type Children of an Operation or Maintenance phase, does not have to match the duration of the Operation or Maintenance phase. *Cycle* phases are repeated cyclically until the duration of the parent phase is reached. The *CycleStart* phase type specifies the initial phase of the cycle and is also a *Cycle* phase type.

The simulation starts in the first declared parent phase until the last one , and is repeated cyclically until the simulation time is reached.

Key	Column	Data Type	Null	Description
	Facility	Text	no	Name of the facility.
PK	**Phase**	Text	no	Name of the phase.
	Duration	Float	no	Duration of the phase, in hours.
	Phase Type	*Operation / Maintenance / Cycle / CycleStart*	no	Phase type.
	Phase Group	Text	yes	Phases may be grouped in named groups, to allow common failure mode declarations for all phases within the phase group.
FK	**Parent phase**	Text	yes	Only for Cycle type phases. Parent phase of the phase.
FK	**Next default phase**	Text	yes	Only for Cycle type phases. Next default phase in the cycle.
	Parallel to downtime	*y /n*	yes	Only for Cycle type phases. Specifies if this phase can continue to run during downtime.
	Down Repair Policy	*1 / 0 / Optimization*	no	Defines how the repairs are made when the system is down due to component failures or due to planned maintenance. 1= Repair all failed components. 0= repair only the last failed components until system is up again. *Optimization*= repair the last failed components until the system is up again plus all the repair that can be done in the shadow of this repairs.
	Description	Text	yes	Description of the phase (for documentation only).

Table 4.4: The Common Input Format *Phases* table.

Phases Transition*

The table defines the transitions between cycling phases in the case that the default cycle, defined in the *Phases* table, is interrupted due to a consequence. If no consequence interrupts the phase during its duration, the specified default phase will follow. Consequences are defined in a separated table.

Key	Column	Data Type	Null	Description
	Facility	Text	no	Name of the facility.
FK	**Phase**	Text	no	The phase.
FK	**Consequence**	Text	no	Consequence name.
FK	**Next Phase**	Text	no	Next phase to jump to when *Consequence* occurs during *Phase*.

Table 4.5: The Common Input Format *Phases Transition* table.

Locations*

The table holds the locations of the Facility and the time needed to access them.

Key	Column	Data Type	Null	Description
	Facility	Text	no	Name of the facility.
PK	**Location**	Text	no	Name of the location.
	Access time	Float	no	Access time to the Location, in hours.

Table 4.6: The Common Input Format *Locations* table.

Systems*

The table holds the systems in the Facility and the time required to restart them after a shut down or a period of downtime.

Key	Column	Data Type	Null	Description
	Facility	Text	no	
PK	**System**	Text	no	Name of the system.
	Restart time	Float	no	Restart time of the system, in hours.

Table 4.7: The Common Input Format *Systems* table.

Spares*

The table holds the definition of spares available during operation.

Key	Column	Data Type	Null	Description
	Facility	Text	no	
PK	**Device Type**	Text	no	Name of the spare. A spare is located thought its device type.
	No. Available	Int	yes	Number of spares of this type available.
	Standby State	*ON / OFF*	no	Standby state of the spare.
	Start-up failure probability	Percentage	yes	The probability that a failure will occur when the component is switching from a non-operational state to an operational state.
	Cost	Float	yes	Cost of the device in arbitrary units.
	Swapp-time	Float	yes	Time needed to replace the failed unit with an spare, in hours.

Table 4.8: The Common Input Format *Spares* table.

Manpower*

The table holds the definition of the number of each manpower type (system expert) available.

Key	Column	Data Type	Null	Description
	Facility	Text	no	
PK	**Manpower Type**	Text	no	Name of the manpower type.
	No. Available	Int	yes	Number of manpower of this type available.
	Cost	Float	yes	Cost of manpower, in arbitrary units per hour.

Table 4.9: The Common Input Format *Manpower* table.

Parameters*

The table holds the definition of machine parameters. A parameter when affected by a failure can affect other parameters and/or trigger consequences when it exceeds one of its threshold values.

Key	Column	Data Type	Null	Description
	Facility	Text	no	
PK	**Name**	Text	no	Name of the machine parameter.
	Nominal Value	Float	no	Nominal Value of the parameter.
	Minimum Value	Float	no	Minimum Value the parameter could have during operation.
	Maximum Value	Float	no	Maximum Value the parameter could have during operation.
FK	**Affect1**	Text	yes	Parameter name. The given parameter might affect other parameters. Defines the first one it affects.
	Affect-Type1	*add/ subtract*	yes	Degradation to be applied to the parameter.
	Degradation1	Float	yes	The quantum added to, or subtracted from the affected parameter.
FK	**Affect2**	Text	yes	Parameter name. The given parameter might affect other parameters. Defines the second one it affects.
	Affect-Type2	*add/ subtract*	yes	Degradation to be applied to the parameter.

Key	Column	Data Type	Null	Description
	Degradation2	Float	yes	The value to affect the parameter with.
FK	**Affect3**	Text	yes	Parameter name. The given parameter might affect other parameters. Defines the third one it affects.
	Affect-Type3	*add/ subtract*	yes	Degradation to be applied to the parameter.
	Degradation3	Float	yes	The value to affect the parameter with.
FK	**Affect4**	Text	yes	Parameter name. The given parameter might affect other parameters. Defines the fourth one it affects.
	Affect-Type4	*add/ subtract*	yes	Degradation to be applied to the parameter.
	Degradation4	Float	yes	The value to affect the parameter with.
FK	**Consequence**	Text	yes	Name of the consequence to occur if the parameter exceeds one of the boundaries.

Table 4.10: The Common Input Format *Parameters* table.

Consequences*

Defines the consequences to occur when a parameters exceed its threshold values and the extra time this consequence needs after repair.

The default consequence, *Beam Off*, is triggered by a parameter when it exceeds one of its threshold values, unless otherwise indicated. It specifies a case in which the system is brought down due to components failures. If the *Beam Off* consequence is triggered, repairs are planned and the corresponding downtime is assigned to the current Operation phase. If a consequence *Beam Off* is triggered during a Cycle phase, the Cycle phase is prematurely terminated before it is due, repairs are performed, the corresponding downtime is assigned to the Operation phase and the machine is brought up again into the next phase defined in the *Phases Transition* table. If the Cycle phase reaches its maximum duration, i.e. no consequence was triggered, the simulation continues with the next default phase.

Key	Column	Data Type	Null	Description
	Facility	Text	no	
PK	**Name**	Text	no	Name of the consequence.
	Time	Float	no	The extra time, in hours, this consequence needs after repairs to restart operation.
	Description	Text	yes	Short description of the consequence (for documentation only).

Table 4.11: The Common Input Format *Consequences* table.

Simulation

Table holds the simulation control parameters.

Key	Column	Data Type	Null	Description
	Facility	Text	no	
	Sim Hours	Float	no	Simulation or mission time, in hours.
	No. of simulations	Int	no	Number of simulation to perform.
	Seed	Int	no	Random number generator seed, for reproducibility of the results.
	Logging	*on /off*	no	Defines if a log file of the simulation should be generated.

Table 4.12: The Common Input Format *Simulation* table.

References*

Table holds references to failure modes and corrective maintenance data sources.

Key	Column	Data Type	Null	Description
	Facility	Text	no	
PK	**Ref.**	Text	no	Reference

Key	Column	Data Type	Null	Description
	Data Source	Text	no	Description or link to the data source

Table 4.13: The Common Input Format *References* table.

The examples presented in Section 4.4 serve as an illustration of the Common Input Format tables implementation.

4.3.3 Availability simulation tools

Several commercial and custom software tools are available for the implementation and simulation of the accelerator performance [37]. This chapter gives an overview of the availability simulation software tools used for availability studies of high energy particle accelerators.

Isograph® Availability Workbench

The AvSim module from the Isograph® Availability Workbench is a commercial tool for the simulation of systems performance in terms of availability [53]. RBDs are used to model the system hardware and failure behavior, as explained in Section 4.3.1. Failure modes are defined together with their maintenance strategy which can be corrective, planned or condition based. In the current version, ten failure mode distributions are supported in addition to the exponential distribution. Each block in the diagram is assigned a previously defined failure mode. Failures can trigger consequences, as defined by the user. A consequence can cause a total outage of the system or a loss in the capacity to operate. Spares and manpower can be assigned to the failure mode maintenance strategies. In addition, simulation phases can be defined, for example, to set components to non-operational during certain time periods. Rules are used to define dependencies between blocks, failure rates, consequences and phases, as needed. A model verification function ensures that the implemented model is valid for simulation. It checks the block diagram logic, missing failure mode assignment in the blocks and rules consistency. In a similar

manner, a simulation watch function displays the simulation status in each time step to allow for model logic validation. For example, one may see the simulation process progress as a sequence of failures and repairs in the system. Results are presented in terms of downtime, availability, number of outages and mean repair times at component and system level together with the simulation statistics representing the accuracy of the results. Custom made reports can also be defined to display results in the desired terms. Additionally, the importance rankings provide a means to identify the main contributors to a certain system parameter, e.g. main contributor to downtime or system outages. Finally, customizable plotting features of the simulation results are also provided in the module.

ELMAS®

Event Logic Modeling and Analysis Software (ELMAS) is a commercial tool, developed by Ramentor [54], for modeling and analysis of logical cause-consequence relations between events, also called event logic. It offers three model implementation paradigms: Fault Tree Analysis, Cause-Consequence Analysis and RBDs. It allows to simulate a wide range of processes, from system failure behavior to production and risk assessment models.

Many accelerator specific functionalities were added into the new version of the software, ELMAS 4.8 [55, 56], in particular the possibility to simulate circular colliders operation schedules including operational modes and cycles. The transitions between accelerator operational states are modeled using semi-Markov Chains [43]. This model defines the next phase to execute in the case of successful or unsuccessful operation. The transition probabilities are defined by the failure probabilities of the Fault Trees, which are used to model the accelerator failure behavior. Individual failure modes are assigned to the Fault Tree nodes, while common-cause failures can be defined by grouping trees together. Failures modes are assigned a failure distribution and a repair strategy.For the accelerator specific case, results can be presented in terms of integrated luminosity production by adding some custom Java code to the model. In addition, the tool can be used for sensitivity analysis of the luminosity production function with respect to component failure

rates.

In general, ELMAS provides a wide spectrum of modeling possibilities that combines Fault Tress, Markov models and production models, making it suitable for the analysis of accelerator systems.

AvailSim

Although commercial software packages provide a broad range of tools and methods for availability modeling and simulation, accelerator specific maintenance strategies and operational modes might be difficult to implement. On the one hand, because the tools are not specific for accelerators, the concepts and terminology employed might become confusing or inadequate. On the other hand, the lack of technical documentation, as well as the difficulties to define big models with a graphical interface, can result in a time-consuming and tedious model implementation process. Based on this considerations, the AvailSim open-source availability simulation software [57], with the Common Input Format Framework, has been adopted for the bottom-up availability studies discussed in Section 4.4.

AvailSim was first developed at SLAC National Laboratory for the International Linear Collider (ILC) availability studies [58]. The simulation code was written in the MATLAB scripting language and contained some accelerator-specific features to account for implemented redundancies, hot spares managements, on-off site maintenance, scheduling of maintenance periods, access time to the accelerator housing and recovery times , etc.. The model was defined in a separate spreadsheet containing all the elements of the ILC accelerator. The results were given in terms of availability and downtime with two main objectives. First, to compare several design choices for the ILC and second, to set downtime limits for the accelerator systems and components.

The second generation of the software was an adaptation of AvailSim for availability studies of the International Fusion Irradiation Facility (IFMIF) [59, 60, 61]. This version included the previous features plus, among others, the possibility to define more than one failure mode (event) per component, grouping of events, different locations (facilities), system parameters and degraded operation. The

model definition was done in separated CSV files containing the events, parameters and simulation data. The results were automatically exported to a spreadsheet containing availability, failure occurrence and downtime figures by facility, event and parameter. Although the idea was to make AvailSim2 as global as possible, the software was still too specific for IFMIF facility.

The third generation of the software, AvailSim3 [57], was initially developed by the European Spallation Source (ESS) [62] and later extended in collaboration with CERN. This last version of the software is tailor-made for particle accelerators, but generic enough to cover the availability modelling requirements for any type of particle accelerator.

AvailSim3 is implemented in Python3 programming language [63]. The availability model is defined in separate csv files containing:

- Definition of the slots (components) of the accelerator by systems and locations
- Access time to the different locations
- Restart time of the systems
- List of the devices operating in the slots of the accelerator system. Devices are physical components placed in the slots.
- Number of available spares
- Failures (time-events) to be simulated on the slots (one entry per slot and per failure)
- Definition of accelerator phases
- Phases transition
- Machine parameter definitions
- Consequence definitions
- Simulation parameters

The significant similarities among the input files of AvailSim3 and the Common Input Format tables arise from the fact that the extensions to AvailSim3 were

developed at CERN in parallel with the Common Input Format, with the aim of defining the Common Input Format as the unique input format of availability models for any simulation tool, including AvailSim3. In particular, as mentioned in Section 4.3.2, a translator has been implemented to generate the corresponding input files for AvailSim from the Common Input Format.

The simulation in discrete time is based on the so called three phased approach [64]. This approach models all changes in the system state as events: timed events (failures, repairs and phase changes) and condition based events (consequences). The system is defined by its components,i.e. the lower level elements in the hierarchical description of the system, and its parameters. These parameters represent real operation parameters as well as reliability parameters such as redundancies or the binary state of the machine (up /down). When a failure event occurs a degradation is applied to each parameter affected by the failure. For example, a klystron failure reduces the power reserve but does not stop the accelerator from operation. If a parameter gets outside its defined threshold values, a consequence event is triggered. Consequences might represent, among others, the powering down of the accelerator to perform repairs or the need for tuning the accelerator. In the event that the accelerator is turned off, based on the defined repair strategy, downtime is planned to perform the necessary repairs. Specific maintenance strategies are defined for each failure mode that range from immediate repair to repair requiring access to the accelerator housing. For example, a klystron modulator that is not in the accelerator tunnel can be replaced without causing any downtime but on the contrary, repair of a magnet power supply can only be done when the accelerator is down. The repair events cause an upgrade in machine parameters ultimately bringing the accelerator back into operation. For the particular case of cycling machines, consequences might also trigger phase change events. For instance, a failure during luminosity production phase terminates this phase and brings the system into a ramp-down phase.

The results of the simulation are exported to a separate spreadsheet containing the availability, downtime and failure occurrence for each component, system and facility as well as the parameter mean values per phase. Plots are generated to show the evolution of the parameters, availability and available spares over time.

In addition, a log file of the entire simulation is also generated for model validation.

4.4 Examples of availability prediction for particle accelerators

The examples follow the availability modelling guide presented in 4.2 to fill the Common Input Format tables, perform the simulations and analyze the results.

4.4.1 LHC cycles availability model

The example of the Large Hadron Collider (LHC) availability model is used to illustrate the definition and simulation of cycling phases. The LHC availability model is completely defined in the framework of the Common Input Format with the following seven tables. The failure modes and phase data is based on the LHC 2017 performance data [32, 33].

The LHC model System Hardware description table is shown in Table 4.14. Only the main subsystems of LHC are considered for the simulation.

The repair times and failure rates, shown in Table 4.15, are calculated directly from the 2017 operational data [32] and thus, the repair times already include access and restart time for each subsystem. As a consequence, the following simplifications can be made: a) the tunnel can be accessed immediately for repairs, i.e. no additional access time is needed, and b) the LHC is ready to operate after the repairs, i.e. no restart time is needed. If any of the defined failures occur, the LHC operation is interrupted and repairs are done immediately. However, not all failures can occur in all LHC cycle phases. For instance, Injectors failures only occur during the Injection phase. LHC cycle phases and their average duration used for simulation are defined in Table 4.16. For simplicity, neither failures during downtime nor failures that occur parallel in time are simulated.

Failure modes and cycle phases are linked together in Table 4.18 to define phase dependent failures.

If the nominal cycle is interrupted due to a consequence, the transitions between cycling phases are defined in Table 4.19.

Facility	Element	Name	Parent	Component Code	Instances	Location	Impacted System	Device Type	Failure Behaviour Logic
LHC	Compound	LHC	ROOT	LHC	1				AND
LHC	Basic	Accelerator Controls	LHC	CO	1	Tunnel	LHC	Accelerator Controls	
LHC	Basic	Access Management	LHC	ACM	1	Tunnel	LHC	Access Management	
LHC	Basic	Access System	LHC	ACC	1	Tunnel	LHC	Access System	
LHC	Basic	Beam Dumping System	LHC	LBDS	1	Tunnel	LHC	Beam Dumping System	
LHC	Basic	Beam Exciters	LHC	BEX	1	Tunnel	LHC	Beam Exciters	
LHC	Basic	Beam Instrumentation	LHC	BI	1	Tunnel	LHC	Beam Instrumentation	
LHC	Basic	Beam Losses	LHC	LOSS	1	Tunnel	LHC	Beam Losses	
LHC	Basic	Collimation	LHC	COLL	1	Tunnel	LHC	Collimation	
LHC	Basic	Cooling & Ventilation	LHC	CV	1	Tunnel	LHC	Cooling & Ventilation	
LHC	Basic	Cryogenics	LHC	CRYO	1	Tunnel	LHC	Cryogenics	
LHC	Basic	Electrical Network	LHC	EL	1	Tunnel	LHC	Electrical Network	
LHC	Basic	Operational Settings	LHC	OP	1	Tunnel	LHC	Error, Settings	
LHC	Basic	Experiments	LHC	EXP	1	Tunnel	LHC	Experiments	
LHC	Basic	Induced Quench	LHC	BIQ	1	Tunnel	LHC	Induced Quench	
LHC	Basic	Beam Injection	LHC	INJ	1	Tunnel	LHC	Injection	
LHC	Basic	Injection Systems	LHC	INJS	1	Tunnel	LHC	Injection Systems	
LHC	Basic	Injector Complex	LHC	INJC	1	Tunnel	LHC	Injector Complex	
LHC	Basic	IT Services	LHC	IT	1	Tunnel	LHC	IT Services	
LHC	Basic	Machine Interlocks	LHC	MI	1	Tunnel	LHC	Machine Interlocks	
LHC	Basic	Magnet Circuits	LHC	MC	1	Tunnel	LHC	Magnet Circuits	
LHC	Basic	Orbit Control	LHC	OC	1	Tunnel	LHC	Orbit Control	
LHC	Basic	Other	LHC	OT	1	Tunnel	LHC	Other	
LHC	Basic	Power Converters	LHC	PC	1	Tunnel	LHC	Power Converters	
LHC	Basic	Quench Protection	LHC	QPS	1	Tunnel	LHC	Quench Protection	
LHC	Basic	Radio Frequency	LHC	RF	1	Tunnel	LHC	Radio Frequency	
LHC	Basic	Software Interlocks	LHC	SIS	1	Tunnel	LHC	Software Interlocks	
LHC	Basic	Transverse Damper	LHC	ADT	1	Tunnel	LHC	Transverse Damper	
LHC	Basic	Vacuum	LHC	VSC	1	Tunnel	LHC	Vacuum	
LHC	Basic	Ventilation Door	LHC	VD	1	Tunnel	LHC	Ventilation Door	

Table 4.14: LHC availability model definition in the Common Input Format: System Hardware description table.

Failure Mode Name	Distribution	Parameters	Standby State	Corrective Maintenance MTTR	On-Off Site Maintenance	Repair Strategy	Reference System	Simultaneous repairs? (y/n)
Accelerator Controls Failure	exponential	140	COLD	0.62	on	repairable	0	y
Access Management Scheduled	exponential	140	COLD	1.29	on	repairable	0	y
Access System Failure	exponential	336	COLD	1.85	on	repairable	0	y
Beam Dumping System Failure	exponential	74	COLD	2.75	on	repairable	0	y
Beam Exciters Failure	exponential	3362	COLD	0.49	on	repairable	0	y
Beam Instrumentation Failure	exponential	153	COLD	1.46	on	repairable	0	y
Beam Losses Occurrence	exponential	25	COLD	0.18	on	repairable	0	y
Collimation Failure	exponential	336	COLD	0.17	on	repairable	0	y
Cooling & Ventilation Failure	exponential	480	COLD	7.63	on	repairable	0	y
Cryogenics Failure	exponential	52	COLD	3.47	on	repairable	0	y
Electrical Network Failure	exponential	224	COLD	2.52	on	repairable	0	y
Operational Settings Error	exponential	146	COLD	0.08	on	repairable	0	y
Experiments Failure	exponential	120	COLD	0.55	on	repairable	0	y
Induced Quench Occurrence	exponential	1×10^6	COLD	0.00	on	repairable	0	y
Injection Failure	exponential	127	COLD	0.29	on	repairable	0	y
Injection Systems Failure	exponential	57	COLD	1.08	on	repairable	0	y
Injector Complex Failure	exponential	11	COLD	1.46	on	repairable	0	y
IT Services Failure	exponential	3362	COLD	0.00	on	repairable	0	y
Machine Interlocks Failure	exponential	672	COLD	1.15	on	repairable	0	y
Magnet circuits Failure	exponential	96	COLD	0.06	on	repairable	0	y
Orbit Control Failure	exponential	3362	COLD	0.02	on	repairable	0	y
Other Failure	exponential	160	COLD	0.94	on	repairable	0	y
Power Converters Failure	exponential	19	COLD	1.18	on	repairable	0	y
Quench Protection Failure	exponential	30	COLD	1.16	on	repairable	0	y
Radio Frequency Failure	exponential	51	COLD	1.42	on	repairable	0	y
Software Interlocks Failure	exponential	3362	COLD	0.02	on	repairable	0	y
Transverse Damper Failure	exponential	840	COLD	0.52	on	repairable	0	y
Vacuum Failure	exponential	1681	COLD	1.50	on	repairable	0	y
Ventilation Door Failure	exponential	509	COLD	0.98	on	repairable	0	y

Table 4.15: LHC availability model definition in the Common Input Format: Failure modes table, based on 2017 LHC performance[32]. Empty columns are not displayed.

Facility	Phase	Duration	Phase Type	Phase Group	Parent OP Phase	Next Default Phase	Down Repair Policy	Can run parallel to donwtime?
LHC	Operation	3362	Operation				1	
LHC	Injection	0.91	CycleStart		Operation	Ramp	1	n
LHC	Ramp	0.85	Cycle		Operation	Stable Beams	1	n
LHC	Stable Beams	10.70[1]	Cycle		Operation	Ramp-down	1	n
LHC	Ramp-down	0.97	Cycle		Operation	Injection	1	y

Table 4.16: LHC availability model definition in the Common Input Format: Phases table. LHC cycle phases average duration in 2017 [33] assumed for the simulation.

Lastly, The Common Input Format Simulation table, Table 4.20, defines the parameters for simulation of LHC cycles in AvailSim 3.0.

These tables completely define the high level LHC availability model.

Analysis of the simulation results as shown in Fig. 4.5, indicate that, in the interval considered, approximately 50% of the time was spent in *Stable Beams*, i.e. with colliding beams. *Operations* encompasses all cycles carried out between *Stable Beam* phases. This is, all the cycles when the machine is not in *Stable Beams* or fault. The average length of each cycling phase is shown in Table 4.21. *Stable Beams* phases interrupted by a failure have an average length of 3.29 hours.

In general, according to the simulations the LHC suffered from 532 faults and achieved a machine availability of 79.3%.

The simulations reproduce fairly well the actual performance of the LHC in 2017, as shown in [32]. The assumptions taken into consideration and the statistical significance of the input data are the main causes of the differences in the outcome. The simulation results would likely improve, and be closer to actual performance, by taking as input not only the 2017 LHC performance data, but by including all the LHC operation data. However, the frequent change in the LHC operation parameters, even during the same run, makes the statistical analysis of the performance data a complex tasks. Further efforts are being invested to improve data

Component Name	Failure Mode	(Operational)Phase
Accelerator Controls	Accelerator Controls Failure	Operation
Access Management	Access Management Scheduled	Injection
Access System	Access System Failure	Operation
Beam Dumping System	Beam Dumping System Failure	Stable Beams
Beam Exciters	Beam Exciters Failure	Operation
Beam Instrumentation	Beam Instrumentation Failure	Operation
Beam Losses	Beam Losses Occurrence	Stable Beams
Collimation	Collimation Failure	Operation
Cooling & Ventilation	Cooling & Ventilation Failure	Operation
Cryogenics	Cryogenics Failure	Stable Beams
Electrical Network	Electrical Network Failure	Operation
Operational Settings	Operational Settings Error	Operation
Experiments	Experiments Failure	Operation
Induced Quench	Induced Quench Occurrence	Stable Beams
Beam Injection	Injection Failure	Injection
Injection Systems	Injection Systems Failure	Injection
Injector Complex	Injector Complex Failure	Injection
IT Services	IT Services Failure	Operation
Machine Interlocks	Machine Interlocks Failure	Operation
Magnet Circuits	Magnet Circuits Failure	Stable Beams
Orbit Control	Orbit Control Failure	Operation
Other	Other Failure	Operation
Power Converters	Power Converters Failure	Stable Beams
Quench Protection	Quench Protection Failure	Stable Beams
Radio Frequency	Radio Frequency Failure	Stable Beams
Software Interlocks	Software Interlocks Failure	Operation
Transverse Damper	Transverse Damper Failure	Operation
Vacuum	Vacuum Failure	Operation
Ventilation Door	Ventilation Door Failure	Injection

Table 4.18: LHC availability model definition in the Common Input Format: Failure mode assignments.

Facility	Phase	Consequence	Next Phase
LHC	Injection	BeamOff	Injection
LHC	Ramp	BeamOff	Ramp-down
LHC	Stable Beams	BeamOff	Ramp-down
LHC	Ramp-down	BeamOff	Ramp-down

Table 4.19: LHC Availability model definition in the Common Input Format: Phases transition.

Facility	SimHours	No. Of Simulations	Seed	Logging
LHC	3362	1000	1	OFF

Table 4.20: LHC availability model in the Common Input Format: Simulation table.

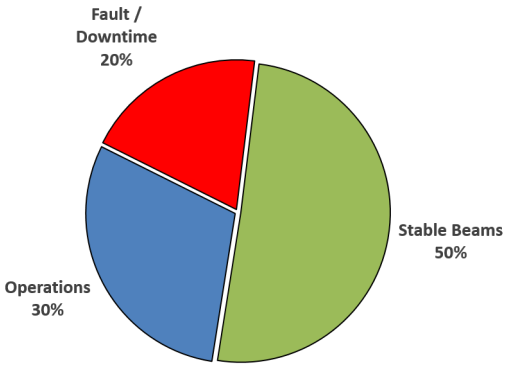


Figure 4.5: LHC cycles duration breakdown from simulations.

Phase	Total average duration	Average duration (end of cycle)	Average duration (ended by fault)
Injection	0.83	0.91	0.37
Ramp	0.83	0.85	0.42
Stable Beams	3.84	10.64	3.27
Ramp-down	0.22	0.97	0.00

Table 4.21: LHC cycles average duration, in hours, from simulations.

collection and analysis.

4.4.2 Availability studies for CLIC

In this section, the bottom up availability studies of two critical CLIC systems are discussed in detail. The first study examines the powering system of the Drive Beam magnets. The second study compares two alternative options for the Main Beam RF powering of the low-energy stage of CLIC.

Main Beam powering system at 380 GeV

For low collision energies, the RF power for the Main Beam acceleration can be extracted from the Drive Beam or alternatively, produced by klystrons [65, 13]. The viability of the two alternatives for RF powering generation in terms of machine availability is studied below [66]. It is important to note that the study of the Klystron based RF powering design also includes the acceleration structures of the Main Beam, while the study of the Drive Beam based RF powering design does not. That is, the Two Beam Modules, where the Drive Beam is decelerated and the Main Beam accelerated, are not included in the analysis of the Drive Beam based design. For this reason, the Two Beam Modules should be included in the Drive Beam based powering system availability model to be able to compare the systems in terms of availability.

The availability simulations are posed on the following assumptions:

- The simulation period corresponds to the yearly scheduled operation time of CLIC: 175 days.
- Components failure behaviour follows an exponential distribution.
- Failed components are repaired only when the system is down due to components failures, unless otherwise defined.
- All repairs must be finished before restarting operation, including spare part repairs.
- The implemented hot-standby spares are again available every time operation (re-starts).

The main parameters used for availability predictions, are based on experts' estimates and operational experience. These are Mean Time to Fail (MTTF) and Mean Time to Repair (MTTR). The same failure modes are considered for the components in both designs, except for the Modulator in the Klystron based design, which has an additional failure mode. The failure modes used in this study represent generic failure modes of the components. Once the final design of the system is available and operation tests have been performed, a more exhaustive failure mode and effect analysis of each component should be done, which may then serve as more detailed input of the present availability models.

As for the LHC model, the AvailSim availability simulation software has been adopted to study the failure behaviour of the Main Beam powering schemes.

Drive Beam based design

The Drive Beam of the Drive Beam powering option is accelerated in travelling wave RF structures, powered by L-band klystrons [65]. A simplified layout of a full accelerating unit is shown in Fig. 4.6. The baseline design has 472 acceleration units, with in addition 2.5% hot-standby spares allowing for a failure tolerant operation. The assumption is that hot-standby spares are installed and running, with a different timing so they don't affect the beam. When a failure occurs and a spare needs to be used, the trigger is switched to be in time with

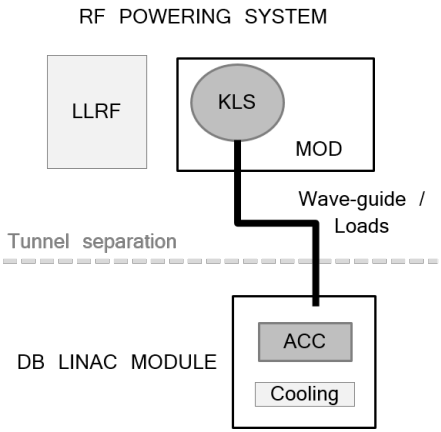


Figure 4.6: Simplified layout of the Drive Beam based powering design.

the beam. The hot-standby spares are strategically placed along the machine to ensure such a model. Klystrons and Modulators in this case are located on the surface with no access restrictions, failing units can be replaced without causing downtime.

The hardware description of the Drive Beam based powering option for the CLIC Main Beam is shown in Table 4.22. Failure mode parameters are shown in Table 4.23. Each component in the system is assigned a failure mode, as shown in Table 4.24. Note that every time an immediately repairable component fails, it is replaced by a hot-standby spare until it is repaired and brought back to operation. In this process, a spare unit is in use only for the duration of the repair.

No cycling phases are defined, only an *Operation* phase that corresponds to the CLIC scheduled operation time, as shown in Table 4.25. The access time and restart time for each subsystem are defined in Tables 4.26 and 4.27, respectively.

Table 4.28 defines the hot-standby spares available in the tunnel, while the Simulation table shown in Table 4.29 sets the simulation parameters.

Facility	Element	Name	Parent	Component Code	Instances	Location	Impacted System	Device Type	Failure Behaviour Logic
CLIC	Compound	Drive Beam	ROOT	CLIC-DB	1				AND
CLIC	Compound	RF Module	Drive Beam	RF	472				AND
CLIC	Compound	RF Powering System kls	RF Module	PS	1				AND
CLIC	Basic	Klystron	RF Powering System kls	Kls	1	SurfaceBld	RF Powering System	DB Linac Module	
CLIC	Basic	Modulator	RF Powering System kls	Mod	1	SurfaceBld	RF Powering System	DB Linac Module	
CLIC	Basic	Wave-guides	RF Powering System kls	WG	1	SurfaceBld	RF Powering System	DB Linac Module	
CLIC	Basic	LLRF	RF Powering System kls	LLRF	1	SurfaceBld	RF Powering System	DB Linac Module	
CLIC	Compound	DB Linac Module	RF Module	Mod	1				AND
CLIC	Basic	RF Cavity	DB Linac Module	C	1	Tunnel	LINAC cavity	DB Linac Module	
CLIC	Basic	Cooling System	DB Linac Module	CS	1	Tunnel	DB Linac Module	DB Linac Module	

Table 4.22: Model definition in the Common Input Format of the Drive Beam based powering option for the CLIC Main Beam: System Hardware description table.

Tables from 4.22 to 4.29 completely define the Drive Beam based powering system availability model.

Analysis of the simulation results performed by AvailSim software package, shows that the baseline powering system can operate for around 822 hours without seeing a system failure due to a shortage of hot-standby spares. Overall, the Drive Beam based powering system is available 98.2% of the total operating time. Table 4.30 summarizes the system performance.

In 175 days of operation, we expect to observe around 5 failures of the system followed by an average of 15 hours of downtime.

Failure Mode Name	Distribution	Parameters	Standby State	Corrective Maintenance MTTR	On-Off Site Maintenance	Repair Strategy	Reference System	Simultaneous repairs? (y/n)
RF Breakdown	exponential	15000	COLD	0.03	off	Repairable	0	y
Cooling System failure	exponential	43800	COLD	6.00	on	Swappable	1	y
Klystron failure	exponential	50000	COLD	12.00	off	Swappable	0	y
Modulator failure	exponential	100000	COLD	12.00	off	Swappable	0	y
Wave-guides failure	exponential	100000	COLD	3.00	on	Swappable	1	y
LLRF failure	exponential	26300	COLD	3.00	off	Swappable	0	y

Table 4.23: Model definition in the Common Input Format of the Drive Beam based powering option for the CLIC Main Beam: Failure modes table. Empty columns are not displayed.

Component Name	Failure mode	(Operational)Phase
RF Cavity	RF Breakdown	Operation
RF Cooling System	Cooling System failure	Operation
Klystron	Klystron failure	Operation
Modulator	Modulator failure	Operation
Wave-guides	Wave-guides failure	Operation
LLRF	LLRF failure	Operation

Table 4.24: Model definition in the Common Input Format of the Drive Beam based powering option for the CLIC Main Beam: Failure mode assignments.

Facility	Phase	Duration	PhaseType	PhaseGroup	DownRepairPolicy
CLIC	Operation	4200	Operation	1	1

Table 4.25: Model definition in the Common Input Format of the Drive Beam based powering option for the CLIC Main Beam: Phases. Empty columns are omitted.

Facility	Location	Access Time
CLIC	Tunnel	8
CLIC	SurfaceBld	0

Table 4.26: Model definition in the Common Input Format of the Drive Beam based powering option for the CLIC Main Beam: Locations.

Facility	System	Restart Time
CLIC	LINAC cavity	0
CLIC	DB LINAC Module	1
CLIC	RF Powering System	1

Table 4.27: Model definition in the Common Input Format of the Drive Beam based powering option for the CLIC Main Beam: Systems.

Facility	Device Type	System/Location	NoAvailable	StandbyState
CLIC	DB LINAC Module	Tunnel	12	ON

Table 4.28: Model definition in the Common Input Format of the Drive Beam based powering option for the CLIC Main Beam: Spares. Empty columns are omitted.

Facility	SimHours	No.ofSimulations	Seed	Logging
CLIC	4200	100	1	off

Table 4.29: Model definition in the Common Input Format of the Drive Beam based powering option for the CLIC Main Beam: Simulation.

Availability	Times Down	Downtime (h)	Standard deviation (Availability)	MTTR (h)	MTTF (h)
98.2%	5	75	0.003	15	822

Table 4.30: CLIC Drive Beam based powering availability predictions.

Analysis of the components failures and downtime contributors, as shown in Fig.4.7 , indicate that the Klystrons, Wave-guides and Cooling Systems dominate the Drive Beam based powering system downtime.

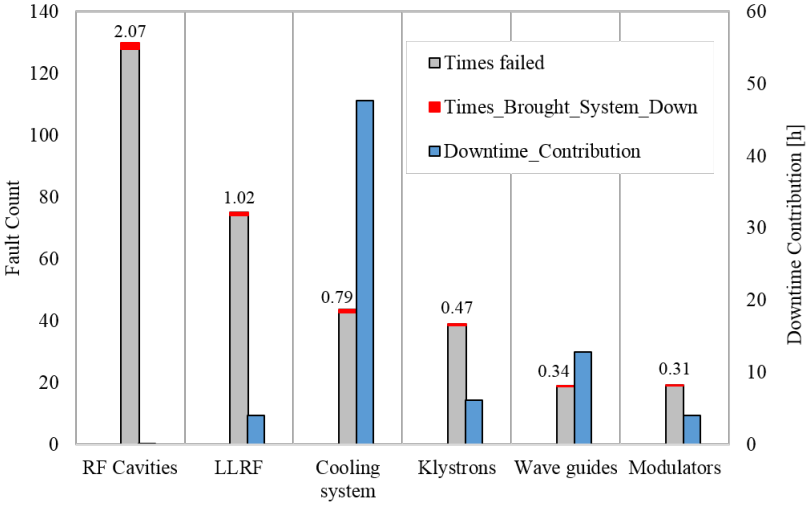


Figure 4.7: Components failure number and downtime contribution in 175 days of operation for the Drive Beam based powering system.

If planned maintenance is done after every 6 days of operation, simulations ensure continuous operation of the system during the 6 days , i.e. 100 % of availability, with a maximum of 2 hot-standby spares in use before planned maintenance. Moreover, in this context, the amount of hot-standby spares could be reduced to 7 to ensure continuous operation for 6 days. The system will probably start suffering from failures if maintenance is done after 3 weeks of operation.

At 3TeV, the baseline design has instead two linacs with 526 acceleration units each and 2.5% additional hot-standby spares in each linac to allow for failure tolerant operation. Simulations show a similar availability for the 3TeV scheme of around 98%. The powering system can operate for around 697 hours with-

out seeing a system failure. In 175 days of schedules operation, we expect to observe 6 failures followed by an average 15 hours of downtime. However, during this downtime, the amount of components to be repaired in parallel at 3TeV scales proportionally with the amount of components present in the system.

Klystron based design

The Klystron based accelerator unit layout is based on two klystrons powered by a single modulator and followed by an RF distribution network delivering power to 8 accelerating structures [13]. A simplified schema of the Klystron based powering unit is shown in Fig. 4.8. This alternative design has 1500 accelerating units per linac with in addition 10% hot-standby spares implemented for failure tolerant operation. The hot-standby spares are, as in the previous case, installed and running and can replace a failed unit immediately. However, Klystrons and Modulators in this case are located in the accelerator tunnel with no access during operation, hence failing units can be replaced on scheduled maintenance days only.

The CLIC Main Beam Klystron based powering system Hardware description table is shown in Table 4.31. The failure modes, shown in Table 4.32, are largely identical to the failure modes of the Drive Beam based design, with the following exceptions: the added Alignment and Vacuum failures, an additional failure mode of the Modulator, and the higher lifetime of the X-band Klystrons. Each component in the system is assigned a failure mode,as shown in Table 4.33. As for the Drive Beam based model, only an Operation phase is defined, see Table 4.25.

The access time and restart time for each subsystem are defined in Tables 4.34 and 4.35, respectively. Table 4.36 defines the hot-standby spares available by location.

The simulation parameters are defined as for the Drive Beam based design in Table 4.29.

According to the simulation results in Table 4.37, the alternative powering

Facility	Element	Name	Parent	Component Code	Instances	Location	Impacted System	Device Type	Failure Behaviour Logic
CLIC	Compound	Main Beam	ROOT	CLIC-MB	1				**AND**
CLIC	Compound	RF Module L1	Main Beam	RF-1	1500				AND
CLIC	Compound	RF Powering System Kls L1	RF Module L1	PS	1				AND
CLIC	Basic	Klystron	RF Powering System Kls L1	Kls	2	Tunnel L1	RF Powering System	LINAC Module	
CLIC	Basic	Modulator	RF Powering System Kls L1	Mod	1	Tunnel L1	RF Powering System	LINAC Module	
CLIC	Basic	Wave Guide	RF Powering System Kls L1	WG	1	Tunnel L1	RF Powering System	LINAC Module	
CLIC	Basic	LLRF	RF Powering System Kls L1	LLRF	1	Tunnel L1	RF Powering System	LINAC Module	
CLIC	Compound	LINAC Module L1	RF Module L1	Mod	1				AND
CLIC	Basic	Accelerating Structure	LINAC Module L1	AS	1	Tunnel L1	RF System	LINAC Module	
CLIC	Basic	RF Cooling System	LINAC Module L1	CS	1	Tunnel L1	LINAC Module	LINAC Module	
CLIC	Basic	Alignment system	LINAC Module L1	AL	1	Tunnel L1	LINAC Module	LINAC Module	
CLIC	Basic	Vacuum System	LINAC Module L1	Vac	1	Tunnel L1	Vacuum	Vacuum	
CLIC	Compound	RF Module L2	Main Beam	RF-2	1500				AND
CLIC	Compound	RF Powering System Kls L2	RF Module L2	PS	1				AND
CLIC	Basic	Klystron	RF Powering System Kls L2	Kls	2	Tunnel L2	RF Powering System	LINAC Module	
CLIC	Basic	Modulator	RF Powering System Kls L2	Mod	1	Tunnel L2	RF Powering System	LINAC Module	
CLIC	Basic	Wave Guide	RF Powering System Kls L2	WG	1	Tunnel L2	RF Powering System	LINAC Module	
CLIC	Basic	LLRF	RF Powering System Kls L2	LLRF	1	Tunnel L2	RF Powering System	LINAC Module	
CLIC	Compound	LINAC Module L2	RF Module L2	Mod	1				AND
CLIC	Basic	Accelerating Structure	LINAC Module L2	AS	1	Tunnel L2	RF System	LINAC Module	
CLIC	Basic	RF Cooling System	LINAC Module L2	CS	1	Tunnel L2	LINAC Module	LINAC Module	
CLIC	Basic	Alignment System	LINAC Module L2	AL	1	Tunnel L2	LINAC Module	LINAC Module	
CLIC	Basic	Vacuum System	LINAC Module L2	Vac	1	Tunnel L2	Vacuum	Vacuum	

Table 4.31: Model definition in the Common Input Format of the Klystron based powering option for the CLIC Main Beam: System Hardware description.

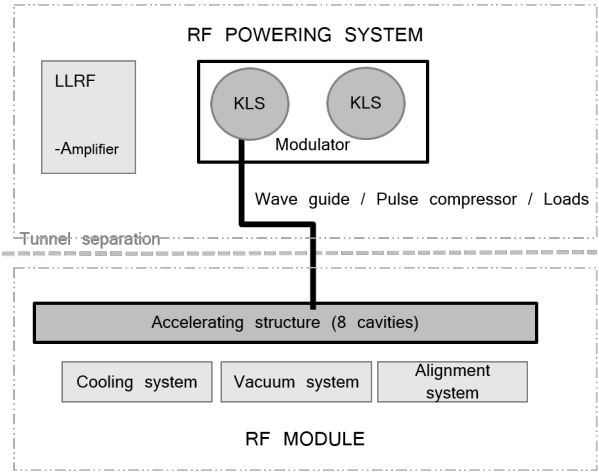


Figure 4.8: Simplified layout of the Klystron based powering design.

Failure Mode Name	Distribution	Parameters	Standby State	Corrective Maintenance MTTR	On-Off Site Maintenance	Repair Strategy	Reference System	Simultaneous repairs? (y/n)
RF Breakdown	exponential	15000	COLD	0.03	off	Repairable	0	y
Cooling System failure	exponential	43800	COLD	6.00	on	Swappable	1	y
Klystron failure	exponential	60000	COLD	24.00	on	Swappable	1	y
Modulator failure	exponential	100000	COLD	12.00	on	Swappable	1	y
Modulator failure 2	exponential	10000	COLD	1.00	off	Repairable	0	y
Wave-guides failure	exponential	100000	COLD	3.00	on	Swappable	1	y
LLRF failure	exponential	26300	COLD	3.00	off	Swappable	1	y
Alignment failure	exponential	100000	COLD	3.00	off	Swappable	1	y
Vacuum failure	exponential	3264000	COLD	24.00	on	Swappable	1	y

Table 4.32: Model definition in the Common Input Format of the Klystron based powering option for the CLIC Main Beam: Failure modes. Empty columns are not displayed.

Component Name	Failure mode	(Operational)Phase
Klystron	Klystron failure	Operation
Modulator	Modulator failure	Operation
Modulator	Modulator failure 2	Operation
Wave Guide	Wave-guides failure	Operation
LLRF	LLRF failure	Operation
Accelerating Structure	RF breakdown	Operation
RF Cooling System	Cooling System failure	Operation
Alignment System	Alignment failure	Operation
Vacuum System	Vacuum failure	Operation

Table 4.33: Model definition in the Common Input Format of the Klystron based powering option for the CLIC Main Beam: Failure mode assignments.

Facility	Location	Access Time
CLIC	Tunnel L1	8
CLIC	Tunnel L2	8

Table 4.34: Model definition in the Common Input Format of the Klystron based powering option for the CLIC Main Beam: Locations.

Facility	System	Restart Time
CLIC	RF Powering System	8
CLIC	LINAC Module	8
CLIC	Vacuum	8
CLIC	RF System	0

Table 4.35: Model definition in the Common Input Format of the Klystron based powering option for the CLIC Main Beam: Systems.

Facility	Device Type	System/Location	NoAvailable	StandbyState
CLIC	DB LINAC Module	Tunnel L1	150	ON
CLIC	DB LINAC Module	Tunnel L2	150	ON

Table 4.36: Model definition in the Common Input Format of the Klystron based powering option for the CLIC Main Beam: Spares. Empty columns are omitted.

Availability	Times Down	Downtime (h)	Standard deviation (Availability)	MTTR (h)	MTTF (h)
93.5%	6.8	167.7	0.007	40	577.7

Table 4.37: Availability predictions for the Klystron based powering option of the CLIC Main Beam.

system can operate for around 577.7 hours without seeing a system failure due to the implemented hot-standby spares. The Klystron based powering system is available 93.5% of the scheduled operation time. During this period, we expect to observe around 7 system failures which interrupt operation for around 40 hours.

The results in Fig 4.9 show that the Vacuum System is the most critical component of the system as the major contributor to the downtime and failure of the overall system. Note that a failure in the Vacuum System will immediately bring the machine down for 24 hours. As the second major contributor, the Klystrons contribute 24% of the overall powering system downtime.

According to simulations, if planned maintenance is done after every 6 days of operation, the system is available 96.75 % of the time, with a probability of 12% to suffer from a Vacuum failure before the Planned Maintenance. A maximum of 4 hot-standby spares are in use per linac before entering the maintenance period. Moreover, in this context, the amount of hot-standby spares could be reduced to 26 to ensure the same availability for the 6 days of operation.

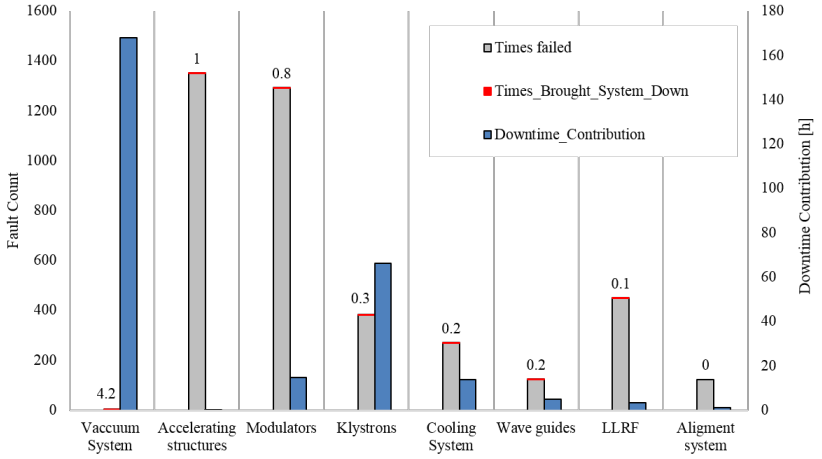


Figure 4.9: Components failure number and downtime contribution in 175 days of operation for the Klystron based powering system.

Drive Beam Quadrupoles powering system

A major concern regarding reliability and availability in CLIC was related to the Drive Beam Decelerators, which contains around 45000 quadrupole magnets. Individual powering of the magnets by highly reliable power converters still gives on average a prediction of one failure every 7 hours. Moreover, a large number of very long cables would be needed in the tunnel to power the magnets individually. To overcome these problems, in the proposed powering strategy [67, 68], one big converter supplies the current for several magnets in series (between 10 and 60), while small by-pass trimmers located close to the magnet reduce the current to the desired values. A schematic of the proposed powering strategy is shown in Fig 4.10. The main linac is divided in 48 accelerating sectors. In each sector, 20 out of 830 trimmers can fail without affecting the beam parameters. On the other hand, the power converters are implemented with identical redundant modules to

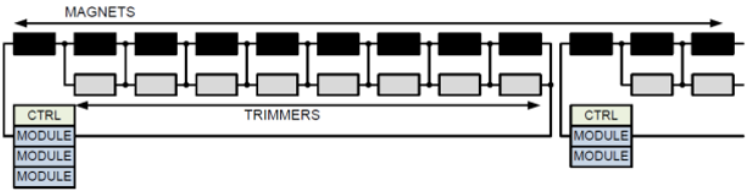


Figure 4.10: Powering strategy of the Drive Beam Quadrupoles.

allow for failure tolerant operation and eventual replacement during scheduled maintenance days. Specifically, there are power converters of 4, 3 and 2 modules designed with an $M+1$ redundancy, where M is the number of needed operating modules. In each sector, there are twelve power converters of 4 modules, sixteen of 3 modules and two of 2 modules. The main parameters of the design are shown in the system Hardware description table, Table 4.38.

The availability simulations are based on the same assumptions as for the Main Beam RF powering, except that the tunnel can be accessed immediately in this case. This is due to the fact that the power converters are installed in separated room close to the tunnel that remain accessible during beam operation.

The main parameters used for availability predictions, estimated based on previous experience [68], are show in Table 4.39 together with the failure modes description. Failure modes are assigned to the components in Table 4.40.

As for the previous models, an Operation phase of 175 days is defined. In this case, however, no access time and no restart time is required for repairs. The simulation parameters are defined as in the previous models.

Analysis of the simulation results shown in Table 4.41, give an average prediction of one failure each 1575 hours in contrast to the individual powering with an average of one failure every 7 hours. The proposed powering solution is available 99.7% of the scheduled operation time. During this period, we expect to observe on average 3 system outages followed by a downtime of 4 hours.

The failure contribution of each component is shown in Fig. 4.11. Failure of the

Facility	Element	Name	Parent	Component Code	Instances	Location	Impacted System	Device Type	Failure Behaviour Logic
CLIC	Compound	DB QD powering	ROOT	DB-QD	1				AND
CLIC	Compound	Sector	DB QD powering	Sector	48				AND
CLIC	Compound	Power Converters	Sector	PC	1				AND
CLIC	Compound	4-modules PC	Power Converters	4mod	12				AND
CLIC	Compound	4module	4-modules PC	4mod	1				AND
CLIC	Basic	Module	4module	M	4	Tunnel	Power Converters	PC Module	
CLIC	Basic	Controls	4-modules PC	Controls	1	Tunnel	Power Converters	Controls	
CLIC	Compound	3-modules PC	Power Converters	3mod	16				AND
CLIC	Compound	3module	3-modules PC	3mod	1				AND
CLIC	Basic	Module	3module	M	3	Tunnel	Power Converters	PC Module	
CLIC	Basic	Controls	3-modules PC	Controls	1	Tunnel	Power Converters	Controls	
CLIC	Compound	2-modules PC	Power Converters	2mod	2				AND
CLIC	Compound	2module	2-modules PC	2mod	1				AND
CLIC	Basic	Module	2module	M	2	Tunnel	Power Converters	PC Module	
CLIC	Basic	Controls	2-modules PC	Controls	1	Tunnel	Power Converters	Controls	
CLIC	Compound	Trimmers	Power Converters	T	1				ACTIVE(810,830)
CLIC	Basic	Trimmer	Trimmers	Trimmer	830	Tunnel	Power Converters	Trimmer	

Table 4.38: CLIC Drive Beam Quadrupoles powering system model definition in the Common Input Format: System Hardware description table.

Failure Mode Name	Distribution	Parameters	Standby State	Corrective Maintenance MTTR	On-Off Site Maintenance	Repair Strategy	Reference System	Simultaneous repairs? (y/n)
Controls failure	exponential	3000000	COLD	4.00	on	Repairable	1	y
Trimmer failure	exponential	300000	COLD	4.00	on	Repairable	1	y
Converter Module failure	exponential	300000	COLD	4.00	on	Repairable	1	y

Table 4.39: CLIC Drive Beam Quadrupoles powering system model definition in the Common Input Format: Failure modes table. Empty columns are not displayed.

Component Name	Failure mode	(Operational)Phase
Controls	Controls failure	OP
Trimmer	Trimmer failure	OP
Modules	Converter Module failure	OP

Table 4.40: CLIC Drive Beam Quadrupoles powering system model definition in the Common Input Format: Failure mode assignments.

Availability	Times Down	Downtime (h)	Standard deviation (Availability)	MTTR (h)	MTTF (h)
99.7%	2.7	10.6	0.001	4	1575

Table 4.41: CLIC Drive Beam Quadrupoles availability predictions.

powering system is mainly caused by the power converter module failures. This is not unexpected, considering the large number of power converters and their limit in reliability. Despite the fact that many more trimmers fail during operation, they barely contribute to the system failure due to their redundancy.

Given the high availability of the proposed solution, the failure tolerance on the trimmers could be relaxed. A sensitivity analysis shows that changing the trimmers

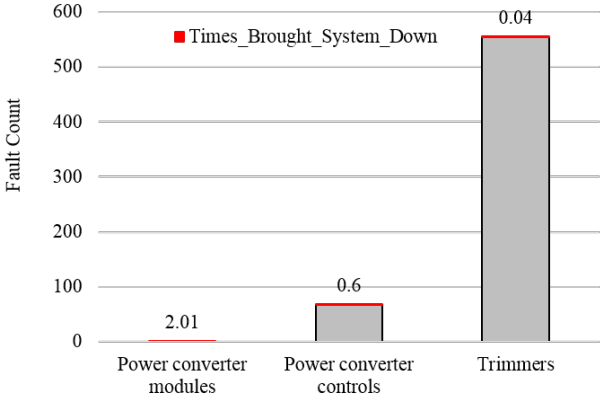


Figure 4.11: Components failure contribution in 175 days of operation for the Drive Beam Quadrupoles powering system

redundancy requirement from 20 down to 10 failing trimmers by sector, leads to a tolerable increase in downtime of 4 hours. Moreover, if a maintenance period is scheduled after each 6 days of operation, a failure tolerance of 2 trimmers per sector would be sufficient not to suffer from any trimmers failure, while maintaining the high availability of the system.

Finally, the study demonstrates the important role of the redundant power converters: if no redundant power converters were implemented, the availability of the magnet powering system would be decreased by 6% and the system would fail on average every 61.5 hours, which is 62 more times than in the baseline design.

5 Availability tracking and performance evaluation

For already operating particle accelerators the ultimate goal is to boost machine performance to its limits. To this end, adequate procedures need to be first established to properly evaluate the current performance of the accelerator and its evolution over time. As a fist step, this procedures should include the compilation of accelerator operation and failure data, which provides the essential input for the performance evaluation of the accelerator. The present chapter explains the importance of tools for collecting accelerator operation and failure data. In particular, it will discuss the relevance of the Accelerator Fault Tracking system implemented at CERN, a tool that was used for Linac4 failure tracking during a dedicated Reliability Run to assess the availability of the linear accelerator.

A conclusive evaluation of the accelerator performance could be done by comparing the results, obtained from the subsequent analysis of the gathered operation data, with an objective performance target. Objective performance targets could be set by comparison with other similar accelerators, provided a sufficient number of accelerators is available, with comparable complexity and compiled fault data. Since this is not the case for the high energy accelerators discussed in this thesis, the availability allocation method introduced in Chapter 3 is proposed instead as a baseline reference to evaluate the accelerator systems in operation and to identify subsystems with major improvement potential. This other application of the availability allocation method is illustrated by the examples of Linac4 and LHC, during the Reliability Run and the LHC 2017 run, respectively.

5.1 Importance of availability tracking tools

Assessing the performance of a complex machine like an accelerator is far from obvious. A true understanding of the machine performance can only be developed by the systematic and reliable tracking of relevant quantities affecting the operation.

These quantities range from failure occurrence and repair times to operational modes and beam parameters of the accelerator. The storage of these data in a relational database allows for a complete and clear overview of the accelerator performance. However, a procedure for a regular follow-up of the faults should be established involving system experts to ensure the data quality and consistency.

The information derived from the subsequent analysis of the captured data is essential for machine availability optimization. It not only helps in the identification of the major contributors to failure and downtime, it also provides a tool to reveal patterns between failures of systems, accelerator modes and beam parameters. Furthermore, it provides a solid basis for decision making, by identifying the weak areas with high improvement potential, that will ultimately optimize the overall availability of the accelerator. For this reason, efforts should also be invested in drawing meaningful statistics from the analysis of the data.

The lack of data regarding accelerator subsystem availability is one of the major problems encountered when performing availability studies, as discussed in Section 4.2. A system that continuously tracks accelerator performance, can also serve as a database for future machines availability studies.

5.1.1 The Accelerator Fault Tracker at CERN

The Accelerator Fault Tracker (AFT)[69] was deployed at CERN at the beginning of 2015 to systematically track LHC faults and other events affecting LHC operation [70]. Until then, failure tracking at CERN was done by experts using diverse and ill adapted systems such as spread sheets. Consequently, it was difficult to obtain a clear overview of the accelerator performance and the impact of the faults on it. After the successful experience with the ATF of the LHC, The AFT was extended in 2017 to cover the fault tracking of the whole CERN Injector Complex.

The AFT is a database with a web interface which allows to browse, edit and analyze fault data collected from the CERN Electronic Logbook, a tool that contains basic fault data entered by operators. A predefined fault tree, defined in concordance with the accelerator hardware failure mode analysis, is used to classify the faults. This serves as the primary base for the fault data capture. The accelerator

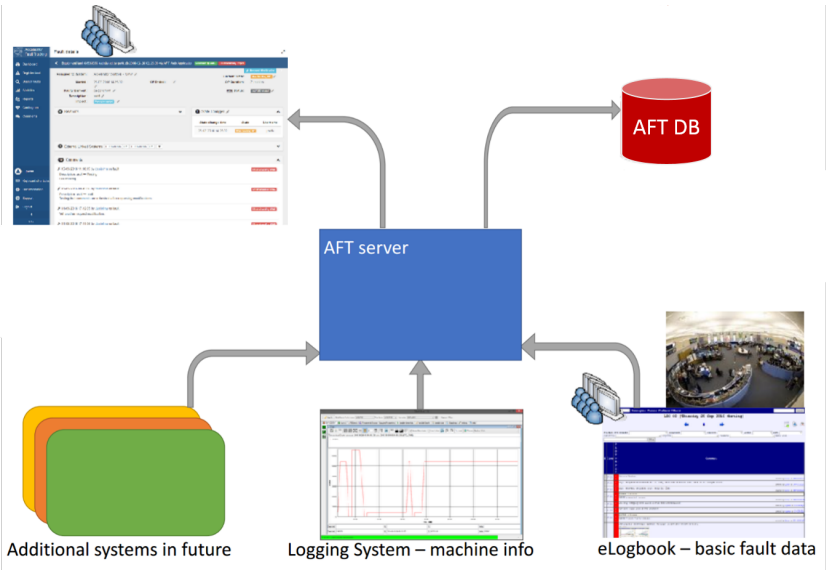


Figure 5.1: The AFT basic architecture

operational modes and beam parameters are then extracted from the Accelerator Logging System [71] and combined with the AFT fault data, to give a better insight of the impact of faults on the machine performance. The AFT System architecture is shown in Fig 5.1.

System experts are notified when a fault enters the database and can complete the information provided by the operators or propose changes to the classification, if relevant. In order to ensure reliable data capture, weekly reviews of the faults are also organized by the member of the availability working group, involving machine supervisors and a responsible for the infrastructure. In addition, the AFT also allows for the definition of dependencies among faults. The most common case of dependency is the case in which a primary ('parent or primary') failure causes other secondary ('child or secondary') failures. This is the so-called 'parent/child failure relation'. For example, a fault in the Electrical Network might induce long recovery

times in other subsystems even though the Electrical fault has been already solved.

The AFT can provide a wide range of fault and availability statistics at a selected accelerator or subsystem level, for a selected time period. For example, the frequently used 'Cardiogram' shows the LHC subsystems faults and associated downtimes, together with the accelerator mode and beam parameters (i.e. beam intensity and energy) over time. This view can help to identify trends among failures and operational modes. An example of the LHC cardiogram is shown in Fig. 5.2.

The consistent tracking and objective reporting on accelerator performance allows to prioritize consolidation activities according to their impact on availability, which ultimately lead to the optimization of the availability and luminosity production of the accelerator. The successful exploitation of the AFT at CERN demonstrates the need of systematic fault data capture in a unified manner.

5.1.2 Linac4 Reliability Run

The Linac4 Reliability Run was intended as a smooth transition between commissioning and final integration of Linac4 into the rest of the CERN accelerator complex [72]. It provided a unique opportunity to identify weak points, improve operational procedures and, for the first time at CERN, assess its availability before actual exploitation. The goal was to reach an availability above its requirement, set at 95%, during the Reliability Run.

The Linac4 Reliability Run immediately followed its commissioning and was divided into three phases to allow for scheduled Technical Stops. The first phase was from mid-July 2017 to the end of September 2017. A second phase took place from the end of October 2017 to the end of December 2017, and the last phase took place from mid-April to mid-May 2018. The Reliability Run schedule is shown in Fig.5.3. While the first phase was composed of short periods of operation followed by repairs and optimization, the next two phases were composed of longer periods of operation followed by technical interventions, hence getting closer to realistic operating conditions. In total, 23 weeks were dedicated to the Linac4 Reliability Run, from which 8 weeks were used for specific studies and machine development

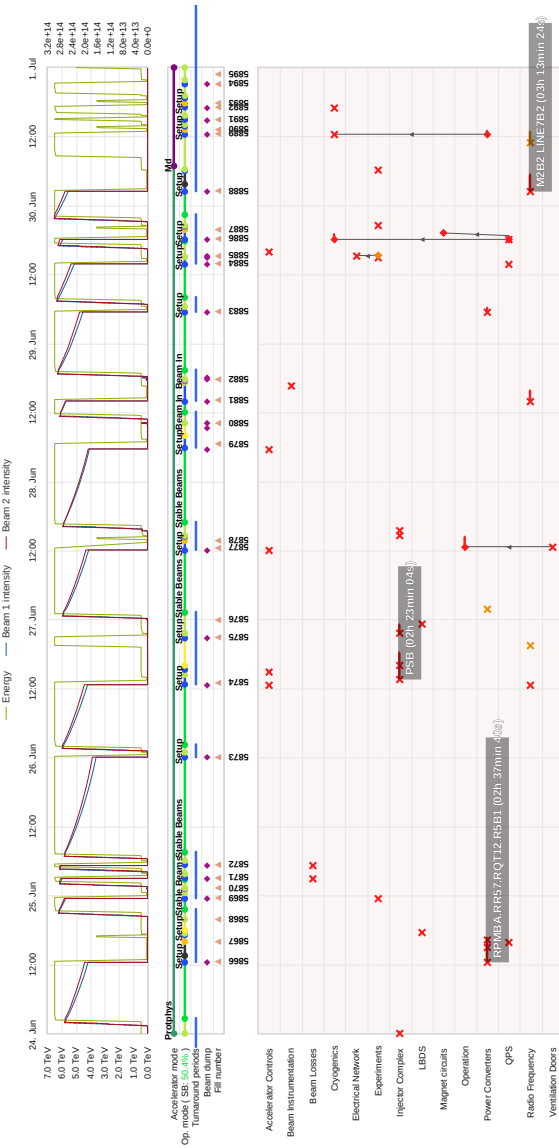


Figure 5.2: Example of the Cardiogram of LHC operation during the last week of June 2017

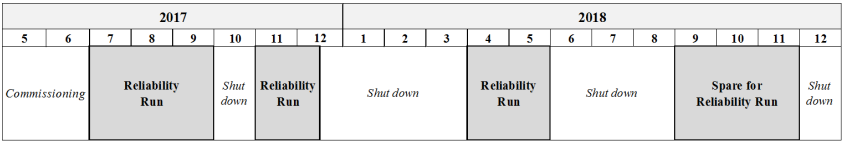


Figure 5.3: Linac4 Reliability Run Schedule.

periods. Linac4 was operated from the CERN Main Control Room 24/7 with expert assistance only during working hours.

The Accelerator Fault Tracker (AFT) was used for systematic Linac4 failure tracking throughout the Reliability Run. A predefined fault tree was implemented in the AFT to precisely classify the faults. In order to assure reliable data capture and correct availability assessments, weekly reviews of the faults were done by the Linac4 team in collaboration with system experts. These reviews included the identification of periods to be excluded from the operational time due to: measurements, dedicated studies and failures extended in time due to the absence of assistance during non working hours. Analysis of the gathered data allowed for the identification of weak points and recurrent failures that affected availability. The Resolution of the majority of the identified failures, by an in-depth analysis of their cause, ultimately led to the improvement of the Linac4 performance.

Table 5.1 summarizes the main Linac4 performance figures for the 23 weeks of the Reliability Run. Of these 23 weeks, an equivalent of 8 weeks were excluded due to reasons outlined above. Linac4 was operational 91.5% of the effective operation time. A total of 449 faults were observed, each of them took on average 29 minutes to detect, understand and repair.

Effective Operation	Availability	Fault Count	Fault Mean Time To Repair
15 weeks	91.5 %	449	29 min

Table 5.1: Linac4 Availability during the Reliability Run.

The analysis of the weekly availability as shown in Fig.5.4 indicates a weekly

availability in line with the target of 95%, except for some weeks, where long faults and recurrent short faults were observed. In Week 29, a Pre-Chopper failure caused a downtime of almost 12 hours. In Week 36, three long failures, a controls timing issue, a Radio Frequency (RF) cavity cooling trip and a High Voltage (HV) Modulator Internal fault in the Power Converters, caused a downtime of over 16 hours. Similarly, five long faults caused a downtime of more than 30 hours in Week 47: another three recurrent HV Modulator Internal failures, a Chopper failure and a Pre-Chopper failure. In particular, a HV connector of the Pre-Chopper had to be exchanged. On the other hand, the operating time was only one day in week 37 due to a planned source replacement, and two days in week 47 due to consecutive machine development periods.

Apart from the specific long faults that took longer to understand, Linac4 also suffered from the following short but recurrent faults:

- Power Supply and HV Modulator trips in the RF Systems: 133 faults with an average repair time of 27 minutes per fault.
- Power Converter trips in the Correctors, Quadrupoles and Source High Voltage: 66 faults lasting 6 minutes per fault.
- 82 stops due to Beam Losses lasting on average 19 minutes per fault.

In general, RF Systems, Power Converters and Modulators, Pre-Chopper and the Source were the main contributors to Linac4 downtime as shown in Fig. 5.5. The notable difference between root cause and raw fault time in the Power Converters and Radio Frequency is due to the large amount of these systems failures occurring in parallel. On the other hand, Accelerator Controls and Operation have slightly higher root cause fault time than raw fault time because of the downtime caused to other systems.

As illustrated in Fig. 5.6, the following teething problems were either resolved during the Technical Stop in October 2017 or during the End-of-Year-Technical-Stop, or addressed during the Technical Stop in summer 2018:

- Power supply of a klystron vacuum pump in the RF Systems, resolved during the first Technical Stop.

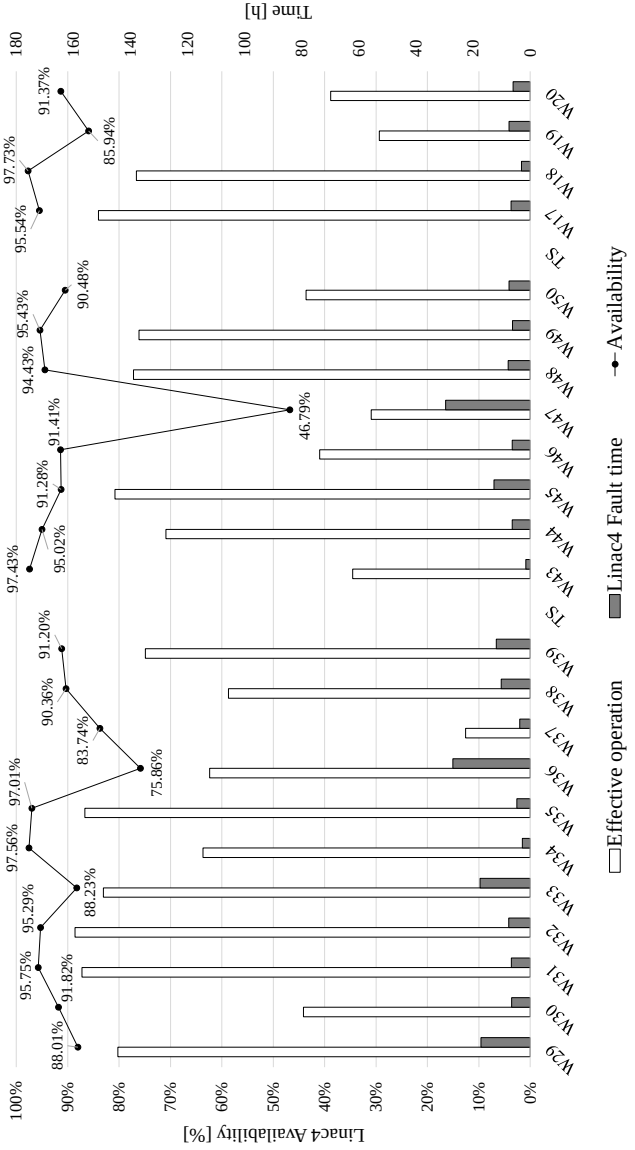


Figure 5.4: Linac4 Weekly availability during the Reliability Run.

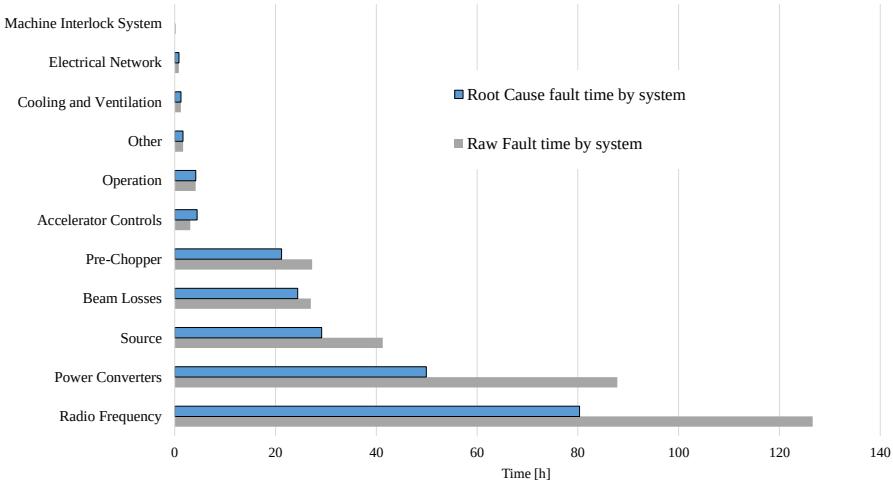


Figure 5.5: Linac4 systems fault times during three phases of the Reliability Run.

- Defective flow meter on one RF System Cooling system, resolved during the first Technical Stop.
- Insufficient radiation hardness of arc beam-loss detector electronics that originally was not designed to be installed in the Linac4 tunnel, addressed during the summer Technical Stop.
- Source Optimization application. This application regulates and optimizes source parameters, but could end up compromising beam stability. During the third phase of the Reliability Run the application was off and as expected, no related faults were observed. In the future, the application will be improved.

The identification and resolution of these teething problems yielded an availability improvement of about 3%, towards the project goal of 95%. In fact, while the average Linac4 availability during the first two phases of the Reliability Run was 91%, the availability in the third phase increased up to 94.3%. Finally, clearer

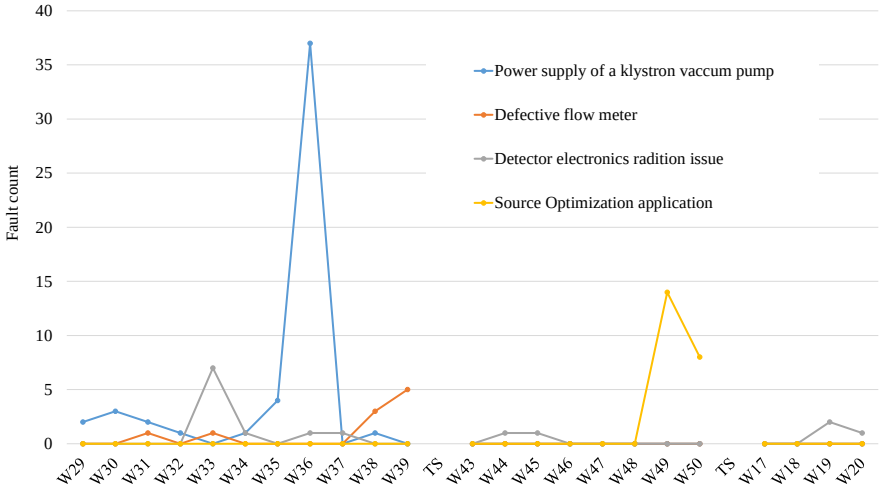


Figure 5.6: Linac4 teething problems fault occurrence by weeks.

procedures will be defined for the optimization of routine operation, specially for the Source.

Overall, the Reliability Run was a successful experience, allowing the identification of issues beyond the possibilities offered in a commissioning phase. The strategy adopted during the Reliability Run was to accept increased downtime in favor of fully understanding and identifying the root cause of faults.

Implementation of the Accelerator Fault tracking system is a crucial step towards future operation, allowing for identification of recurrent faults and providing a deep insight of the actual operation of Linac4 and accelerators in general.

5.2 Performance evaluation based on complexity criteria

The performance of an already operating particle accelerator could be assessed by comparing the results, obtained from the analysis of the gathered operation data,

with an objective performance target. Objective performance targets could be set from other similar accelerators. The principal impediment is that accelerators with comparable complexity and compiled fault data as the high energy particle accelerators discussed in this thesis are currently not available. To overcome this problem, the method described in Chapter 3 is proposed to evaluate the performance of the machine by comparing the observed availability with the availability allocated according to complexity criteria. This is particularly useful for cases in which objective performance targets are not available for comparison purposes. In addition, this comparison allows for the identification of subsystems with high improvement potential.

For a given machine of n subsystems in series, let A_i be the observed availability of the i-th subsystem, for $i = 1, ..., n$ and A_S the achieved accelerator availability over a given period defined as:

$$A_S = \prod_{i=1}^{n} A_i \tag{5.1}$$

Using assessed complexity C_i, the allocated availability for the i-th subsystem, $\tilde{A_i}$, can be calculated following Eq. 3.16 and setting the availability target to A_S:

$$\tilde{A_i} = A_S^{C_i} \tag{5.2}$$

Note that the product of the allocated availability of the subsystems is the observed machine availability, i.e.:

$$A_S = \prod A_i = \prod \tilde{A_i} \tag{5.3}$$

Hence, this method provides a tool to evaluate if the accelerator subsystems performed better or worse than required by complexity criteria.

- If $A_i < \tilde{A_i}$, the subsystem performed worse that the requirement based on its complexity. In other words, the assessed complexity indicates that the subsystem still has potential for improvement in terms of availability. The bigger the difference between the allocated availability and the achieved

availability, the more potential for improvement the subsystem has.

- If $A_i = \tilde{A}_i$, the subsystem performed as expected based on complexity criteria, i.e. the subsystem offers little to no potential to improve the availability.
- If $A_i > \tilde{A}_i$, the subsystem performed better than the requirement based on its complexity.

The comparison between allocated and achieved availability only makes sense when the DEMATEL procedure is included in the complexity allocation and the root cause downtime is used for the achieved availability calculation. Under these two premises, the effects between subsystems are included in the evaluation and thus, both quantities are comparable. Only when the effects between subsystems are negligible, the complexity allocation could be done without considering the DEMATEL procedure. Furthermore, in such case, the root cause and raw downtime are almost equal.

5.2.1 Linac4 performance evaluation during the Reliability Run

The Linac4 performance during the Reliability Run, reported in 5.1.2, is used to illustrate the proposed application of the availability allocation method.

Based on the results of system engineering and expert evaluation, the complexity factor score and the initial direct-relation matrix Z for the Linac4 subsystems are shown in Table 5.2 and Table 5.3, respectively. Note that only the Linac4 physical subsystems are considered in the evaluation, i.e. Operation and Beam Losses are not listed here, and that Chopper and Pre-Chopper systems are included as part of the RF Systems.

The normalized direct relation matrix, X, and the total relation matrix, T, of the DEMATEL procedure are calculated by Eq. 3.8 and Eq. 3.9 and shown in Table 5.4 and Table 5.5, respectively.

Following Equations 3.10 to 3.14, the outcome for the DEMATEL implementation for Linac4 subsystems is shown in Table 5.6, columns 1 to 6. The $r - d$ values of the DEMATEL procedure allow for the grouping of Linac4 subsystems into the causer and net receiver groups. Unfortunately little can be done to reduce the

CLIC subsystem	Repair time	Criticality	Intricacy	State of art	Performance time	Environment
Accelerator Controls	2	8	1	3.3	10.0	3.3
Access System	3	2	2	3.3	10.0	3.3
Beam Instrumentation	5	6	5	10.0	6.7	3.3
Cooling and Ventilation	7	2	3	3.3	10.0	3.3
Dumps and Absorbers	7	6	3	6.7	6.7	3.3
Electrical Network	7	10	3	3.3	10.0	3.3
IT Services	2	1	1	3.3	10.0	3.3
Machine Interlocks	3	2	2	6.7	6.7	3.3
Magnets	7	2	2	6.7	6.7	3.3
Power Converters	3	4	2	6.7	6.7	3.3
Radiation Protection	1	1	1	3.3	10.0	3.3
Radio Frequency	5	8	7	10.0	6.7	3.3
Source	7	4	7	10.0	6.7	3.3
Vacuum	5	6	2	3.3	6.7	3.3

Table 5.2: Availability allocation factors scoring for Linac4 subsystems.

effect of the Electrical Network, the system causing more downtime to others, since it provides power to practically the entire accelerator. The next larger causers are the Accelerator Controls, Cooling and Ventilation and IT Services, while Radio Frequency and Vacuum system are the systems that are caused more downtime by others.

Table 5.8 further shows the subsystems complexity weights, obtained as explained in Section 3.1, w^G: calculated by the Geometric Average Weighting method , $w^G + D$: idem but in addition adjusted by the DEMATEL procedure. Through normalization of the $w^G + D$ values (Eq. 3.23), the assessed complexity figures, displayed in column C, are obtained. Finally, setting the availability goal to the

	j	1	2	3	4	5	6	7	8	9	10	11	12	13	14
i	Z_{ij} 0: No influence 1: Low influence 2: High influence 3: Very high influence	Accelerator Controls	Access System	Beam Instrumentation	Cooling and Ventilation	Dumps and Absorbers	Electrical Network	IT Services	Machine Interlocks	Magnets	Power Converters	Radiation Protection	Radio Frequency	Source	Vacuum
1	Accelerator Controls	0	1	3	1	1	1	1	2	0	2	1	3	3	2
2	Access System	0	0	0	0	0	0	0	2	0	0	0	0	3	0
3	Beam Instrumentation	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Cooling and Ventilation	0	0	1	0	3	0	0	0	3	3	0	3	3	2
5	Dumps and Absorbers	0	0	0	0	0	0	0	0	0	0	0	0	0	2
6	Electrical Network	1	3	3	3	0	0	3	3	0	3	3	3	3	3
7	IT Services	3	1	1	1	0	1	0	1	0	1	1	1	1	1
8	Machine Interlocks	0	0	0	0	3	0	0	0	2	2	0	0	3	0
9	Magnets	0	0	0	0	2	0	0	0	0	0	0	0	0	2
10	Power Converters	0	0	0	0	0	0	0	1	3	0	0	0	0	0
11	Radiation Protection	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	Radio Frequency	0	0	0	0	0	0	0	0	0	0	0	0	0	3
13	Source	0	0	0	0	0	0	0	0	0	0	0	2	0	2
14	Vacuum	0	0	0	0	0	0	0	0	1	0	0	3	0	0

Table 5.3: The indirect relation matrix Z of the DEMATEL procedure for the Linac4 subsystems.

achieved availability, $A_T = 91.2\%$, the assessed availability figures for Linac4 subsystems are calculated (Eq. 3.16) shown in column $\tilde{A}_i$)

Figure 5.7 presents the comparison between the achieved availability and allocated availability by complexity criteria, in terms of unavailability.

The RF System and Power Converters, which are also the main contributors to Linac4 downtime, achieved a lower availability than demanded in accordance to their complexity. This can be explained by the fact that both systems suffered from

0	0.032	0.097	0.032	0.032	0.032	0.032	0.065	0	0.065	0.032	0.097	0.097	0.065
0	0	0	0	0	0	0	0.065	0	0	0	0	0.097	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0.032	0	0.097	0	0	0	0.097	0.097	0	0.097	0.097	0.065
0	0	0	0	0	0	0	0	0	0.000	0	0	0	0.065
0.032	0.097	0.097	0.097	0	0	0.097	0.097	0	0.097	0.097	0.097	0.097	0.097
0.097	0.032	0.032	0.032	0	0.032	0	0.032	0	0.032	0.032	0.032	0.032	0.032
0	0	0	0	0.097	0	0	0	0.065	0.065	0	0	0.097	0
0	0	0	0	0.065	0	0	0	0.000	0	0	0	0	0.065
0	0	0	0	0	0	0	0.032	0.097	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0.097
0	0	0	0	0	0	0	0	0	0	0	0.065	0	0.065
0	0	0	0	0	0	0	0	0.032	0	0	0.097	0	0

Table 5.4: Corresponding normalized direct relation matrix, X, of Linac4 subsystems with $s = 31$.

0.005	0.037	0.103	0.037	0.044	0.034	0.036	0.074	0.019	0.078	0.037	0.122	0.116	0.095
0	0	0	0	0.007	0	0	0.065	0.005	0.004	0	0.007	0.103	0.008
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0.032	0	0.104	0	0	0.003	0.109	0.097	0	0.112	0.097	0.095
0	0	0	0	0.000	0	0	0	0.002	0	0	0.006	0	0.065
0.042	0.102	0.108	0.102	0.024	0.005	0.099	0.114	0.033	0.120	0.102	0.136	0.135	0.135
0.099	0.039	0.047	0.039	0.012	0.036	0.007	0.046	0.013	0.049	0.039	0.058	0.058	0.056
0	0	0	0	0.102	0	0	0.002	0.071	0.065	0	0.008	0.097	0.018
0	0	0	0	0.065	0	0	0	0.002	0	0	0.007	0	0.069
0	0	0	0	0.010	0	0	0.032	0.099	0.002	0	0.001	0.003	0.007
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0.000	0	0	0	0.003	0	0	0.009	0	0.098
0	0	0	0	0.000	0	0	0	0.002	0	0	0.071	0	0.072
0	0	0	0	0.002	0	0	0	0.033	0	0	0.098	0	0.012

Table 5.5: Corresponding total direct relation matrix, T, of Linac4 subsystems.

L4 subsystem	R	D	r	d	$r-d$	w_i^G	w_i^{G+D}	C_i	$\tilde{A}_i$ (%)
Accelerator Controls	0.834	0.145	0.179	0.031	0.148	1742	1999	0.010	99.90
Access System	0.199	0.178	0.043	0.038	0.005	1307	1313	0.007	99.94
Beam Instrumentation	0	0.290	0	0.062	−0.062	33 165	31 110	0.161	98.53
Cooling and Ventilation	0.651	0.178	0.139	0.038	0.101	4574	5037	0.026	99.76
Dumps and Absorbers	0.074	0.370	0.016	0.079	−0.063	18 665	17 482	0.091	99.17
Electrical Network	1.256	0.074	0.269	0.016	0.253	22 869	28 654	0.149	98.64
IT Services	0.598	0.141	0.128	0.030	0.098	218	239	0.001	99.99
Machine Interlocks	0.363	0.336	0.078	0.072	0.006	1778	1788	0.009	99.91
Magnets	0.143	0.393	0.031	0.084	−0.053	4148	3926	0.020	99.81
Power Converters	0.155	0.415	0.033	0.089	−0.056	3555	3357	0.017	99.84
Radiation Protection	0	0.178	0	0.038	−0.038	109	105	0.001	99.99
Radio Frequency	0.111	0.637	0.024	0.136	−0.113	61 908	54 938	0.285	97.41
Source	0.145	0.609	0.031	0.130	−0.099	43 336	39 039	0.202	98.15
Vacuum	0.144	0.731	0.031	0.156	−0.126	4378	3828	0.020	99.82

Table 5.6: $r-d$ values of the DEMATEL procedure and allocated availability values by the Geometric Average Weighting method for the Linac4 subsystems.

unexpected long and recurrent failures as well as teething problems during the Reliability Run, as described in Section 5.1.2. Hence, one can expect that the RF system and the Power Converters will achieve an availability closer to the allocated availability after the End-Of-Year-Technical-Stop. The Source instead, performed better than required according to complexity. However, it has to be noted that during the Reliability Run the Source operated at half the nominal current and did not suffer from the intrinsically long recovery times required after a failure, leading to a too optimistic availability figure for the Source. In like manner, the Electrical Network showed better performance than estimated by the availability allocation method. This can be explained by the fact that no electrical glitches occurred

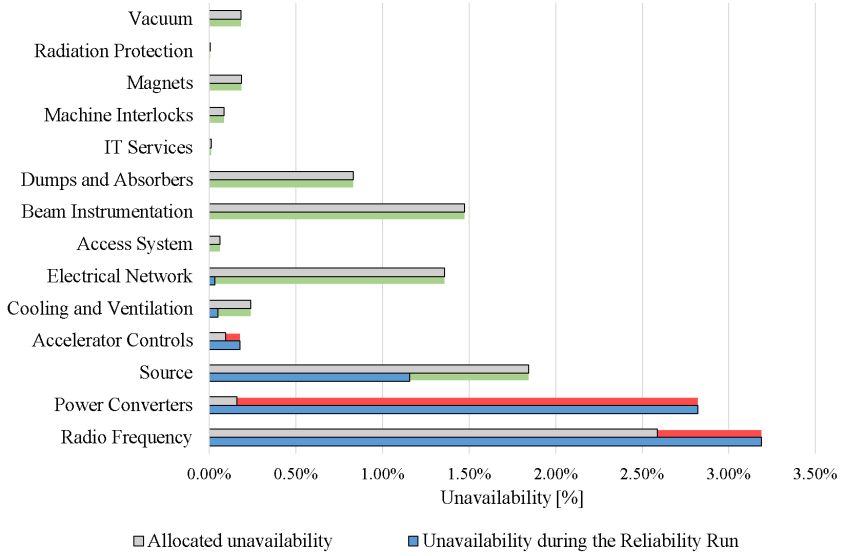


Figure 5.7: Comparison of the allocated availability based on complexity criteria, with $A_T = 91.2\%$, and achieved availability during the Reliability Run for the Linac4 subsystems. The difference between allocated availability and achieved availability is shown in green for positive difference and in red for negative difference.

during the Reliability Run, which usually cause long stops with potentially long recovery times.

An important outcome of this comparison is the identification of systems that still have some margin for failure, such as the Source and Electrical Network, and systems which performance could be improved according to their assessed complexity, such as the Power Converters and RF System.

In order to investigate what really needs to be improved to attain the initial goal of 95% set for the Reliability Run, one can also envisage the possibility to set the availability target to 95%. Fig 5.8 shows the comparison between the observed availability during the Reliability Run and the allocated availability based

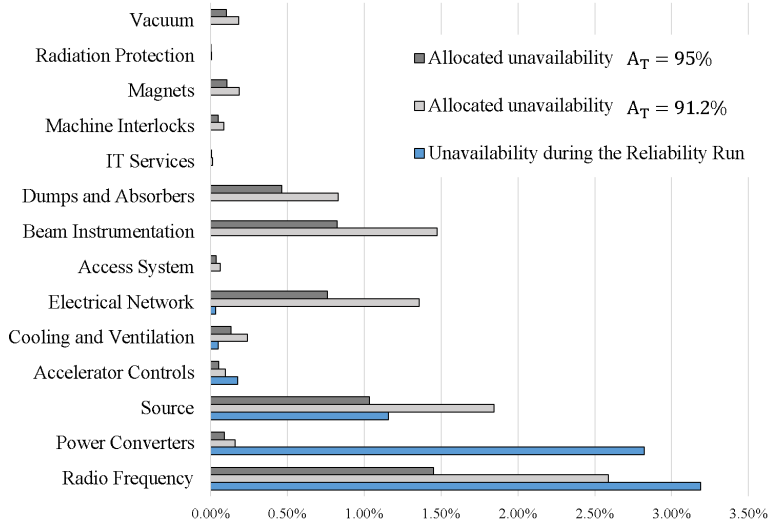


Figure 5.8: Comparison of the allocated availability based on complexity criteria and achieved availability during the Reliability Run for the Linac4 subsystems. Availability is allocated based on complexity criteria for two different availability targets: $A_T = 91.2\%$ and $A_T = 95\%$.

on complexity criteria by setting two different availability targets: $A_T = 91.2\%$, the observed availability during the Reliability Run, and $A_T = 95\%$, the availability goal for the Reliability Run.

In order to reach the Linac4 availability goal of 95%, the Source, in this case, does not have any margin for failure anymore. Instead, it's performance is required to be similar to the one observed during the Reliability Run. The Electrical Network still has some margin for failure, but less than in the previous case. The Power Converters and Radio Frequency systems instead, are required even tighter availability requirements according to the allocation method.

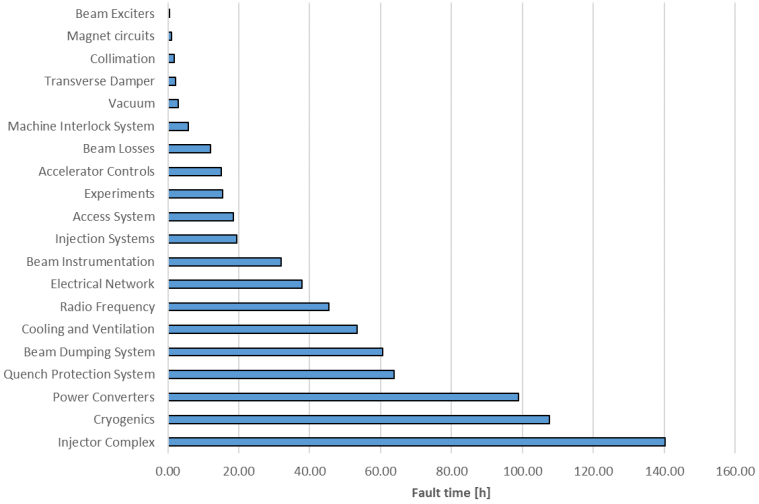


Figure 5.9: Root cause downtime by LHC system.

5.2.2 LHC performance evaluation during the 2017 run

The Large Hadron Collider (LHC) 2017 performance data [32] is used as a second example to illustrate the proposed application of the availability allocation method. In this case, the complexity was assessed by five different experts and the comparison of the different outcomes is presented.

The availability of the LHC in 2017 was about 86%. Fig. 5.9 shows the corresponding root cause downtime contributions by system.

The complexity of LHC subsystems is determined by the evaluation of all the influential factors presented in Section3.2.2 apart from the *Performance time*, since all the LHC subsystems are required to be operational during the whole scheduled operation time. In order to prevent subjectivity and bias, the influential factors are evaluated by five LHC experts, as shown in Table 5.7. For sake of simplicity, the DEMATEL procedure is not included in the complexity assessment. Note that

two categories of Beam Interlocks have been distinguished for the complexity assessment: interlocked and not-interlocked. This is largely due to the fact that the 90% of the root cause downtime of Beam Instrumentation in 5.9 is estimated to be caused by interlocked Beam Instrumentation.

The complexity weights for the LHC subsystems are calculated by the Geometric Average Weighting method. Availability allocation is done based on each expert complexity assessment, according to Equations 3.23 and 3.16 and setting the availability goal as the achieved availability, $A_T = 86\%$.

The allocated availability values based on each expert complexity assessment are compared in Fig 5.10. A considerable amount of consistency can be discerned among experts, with the exception of some outliers. These are the availability values allocated to *Collimation* by Expert 5, *Experiments* by Expert 2 and *Magnets Circuits* by Expert 4. The outliers in the allocated availability are caused by outliers in the factor score, highlighted in red in Table 5.7. In order to avoid a significant affect on the average complexity assessment, the highlighted subsystem factor scores are replaced by the average factor score of the other four experts:

- Experiments Repair time is scored very high by Expert 2 in comparison to the average score of 5.5 of the other four experts.
- Experiment criticality is scored very high by Expert 2 in comparison to the average score of 4 of the other four experts.
- Magnets Circuits is scored too high by Expert 4 in comparison to the average score of 5.75 of the other four experts.
- Collimation Repair time is scored to high by Expert 5 in comparison to the average score of 3.5 of the other four experts.

By replacing the outstanding factor scores by the average, the average complexity assessment is less subject to the influence of outliers and therefore, the allocated unavailability is also more consistent over different outcomes as shown in Figure 5.11.

Table 5.8 shows per LHC subsystem: the geometric average of the complexity weight (w_i), the assessed average complexity (C_i), and the allocated availability

Subsystem	Repair time	Criticality	Intricacy	State of the Art	Environment	Aging	Designed for Reliability
Accelerator Controls	2- 2- 2 1- 1	4- 10- 5 8- 2	4- 5- 6 2- 2	6- 3- 7 1- 7	1- 1- 1 5- 1	2- 5- 4 5- 7	6- 2- 9 5- 4
Access Infrastructure	6- 5- 3 1- 2	2- 7- 5 1- 3	2- 1- 3 2- 1	1- 1- 2 1- 3	1- 1- 1 1- 1	10- 10- 3 10- 3	8- 1- 6 5- 7
Access System	4- 4- 5 1- 2	7- 7- 9 10- 3	3- 3- 4 2- 1	1- 1- 5 1- 3	1- 1- 2 1- 1	5- 8- 5 5- 7	1- 1- 1 5- 5
Beam Exciters	5- 6- 5 1- 3	2- 6- 3 5- 3	3- 3- 8 5- 3	3- 3- 8 5- 5	4- 4- 5 5- 6	5- 5- 4- 5- 7	8- 4- 7 5- 7
Beam Instrumentation - Interlocked	3- 3- 5 1- 3	4- 6- 7 5- 5	4- 3- 9 5- 3	5- 5- 8 5- 6	4- 4- 5 10- 7	5- 5- 3 5- 7	6- 5- 6 5- 7
Beam Instrumentation - not Interlocked	5- 4- 5 1- 3	10- 10- 10 10- 7	8- 4- 8 5- 7	8- 6- 8 5- 6	7- 4- 5 5- 7	5- 6- 3 5- 7	1- 2- 2 5- 5
Collimation	4- 4- 5 1- 7	8- 8- 8 5- 7	5- 5- 8 5- 4	8- 8- 7 5- 7	8- 8- 9 10- 9	5- 2- 3 5- 7	8- 2- 5- 5- 7
Cooling and Ventilation	7- 5- 5 1- 5	8- 4- 5 5- 5	3- 3- 3 2- 5	1- 2- 3- 1- 3	1- 1- 1 1- 5	10- 5- 5 5- 10	8- 1- 3- 10- 7
Cryogenics	10- 10- 10 10- 10	10- 10- 8 10- 4	8- 8- 8 8- 8	8- 7- 7 8- 7	5- 2- 2 5- 5	7- 4- 4 5- 5	4- 1- 5 1- 6
Electrical Network	8- 8- 6 8- 4	10- 10- 9 10- 7	4- 4- 6 2- 4	1- 3- 4 1- 3	1- 1- 1 1- 2	8- 2- 8 10- 9	4- 2- 6 5- 7
Experiments	7-10- 7 1- 7	5- 8- 5 1- 5	10- 10- 10 10- 5	10- 10- 9 8- 7	8- 8- 8 10- 7	5- 3- 3 5- 7	3- 7- 5 5- 7
IT Services	2- 4- 2 1- 2	5- 4- 5- 5- 5	4- 4- 7 2- 2	3- 3- 7 1- 3	1- 1- 1 1- 2	7- 7- 3 1- 9	9- 3- 5 10- 7
Injection Systems	6- 6- 5 1- 5	5- 5- 7 2- 7	6- 7- 8 8- 3	6- 6- 8 5- 5	6- 7- 5 5- 7	5- 4- 3 5- 9	7- 4- 5 5- 7
Injector Complex	7- 8- 8 5- 5	8- 5- 7 2- 7	10- 9- 10 8- 3	7- 8- 9 5- 5	2- 4- 5 5- 7	10- 5- 3 5- 9	8- 6- 5 5- 7
Beam Dumping System	7- 10- 7 1- 4	10- 8- 10 10- 4	8- 5- 9 8- 3	8- 5- 8 8- 3	9- 9- 6 5- 5	5- 4- 3 5- 7	1- 2- 1 1- 7
Machine Interlocks System	4- 5- 5 1- 4	10- 8- 10 10-8	4- 5- 7 5- 3	5- 3- 6 1- 7	5- 1- 3 5- 2	5- 5- 4 5- 7	1- 2- 1 1- 4
Magnet circuits	8- 8- 8 10- 7	10- 8- 8 10- 7	8- 4- 7 2- 3	8- 4- 8 5-7	7- 5- 6 10- 5	5- 5- 5 5- 7	4- 3- 6 5- 7
Power Converters	4- 4- 3 1- 5	8- 8- 5 5- 7	6- 4- 7 3- 3	6- 5- 7 5- 7	7- 3- 5 5- 5	5- 5- 4 5- 7	2- 2- 2 5- 4
Quench Protection System	4- 4- 3 1- 5	8- 8- 8 10- 8	6- 5- 8 5- 3	7- 6- 8 5- 7	7- 4- 5 5- 7	5- 3- 3 5- 7	3- 3- 2 5- 4
Radio Frequency	4- 4- 4 1- 7	8- 7- 5 10- 8	6- 6- 8 5- 2	5- 6- 9 5- 6	4- 6- 5 1- 6	5- 5- 4 5- 7	7- 4- 7 5- 7
Transverse Damper	3- 4- 3 1- 4	3- 5- 8 1- 4	5- 4- 9 3- 3	7- 3- 9 5- 5	4- 6- 2 5- 5	5- 5- 3 5- 7	7- 4-6 10- 7
Vacuum	5- 7- 7 1- 7	9- 9- 9 10- 7	5- 6- 6 5- 3	5- 7- 7 5- 6	3- 3- 3 5- 6	5- 4- 4 5- 7	7- 5- 5 5- 7
Ventilation Doors	3- 5- 1 1- 3	2- 3- 8 1- 3	1- 2- 1 1- 1	1- 1- 1 1- 2	1- 1- 2 1- 1	10- 10- 5 10- 9	10- 1- 9 10- 7

Table 5.7: Scoring of the factors for availability allocation of the LHC subsystems determined by five different system experts. Outliers marked in red.

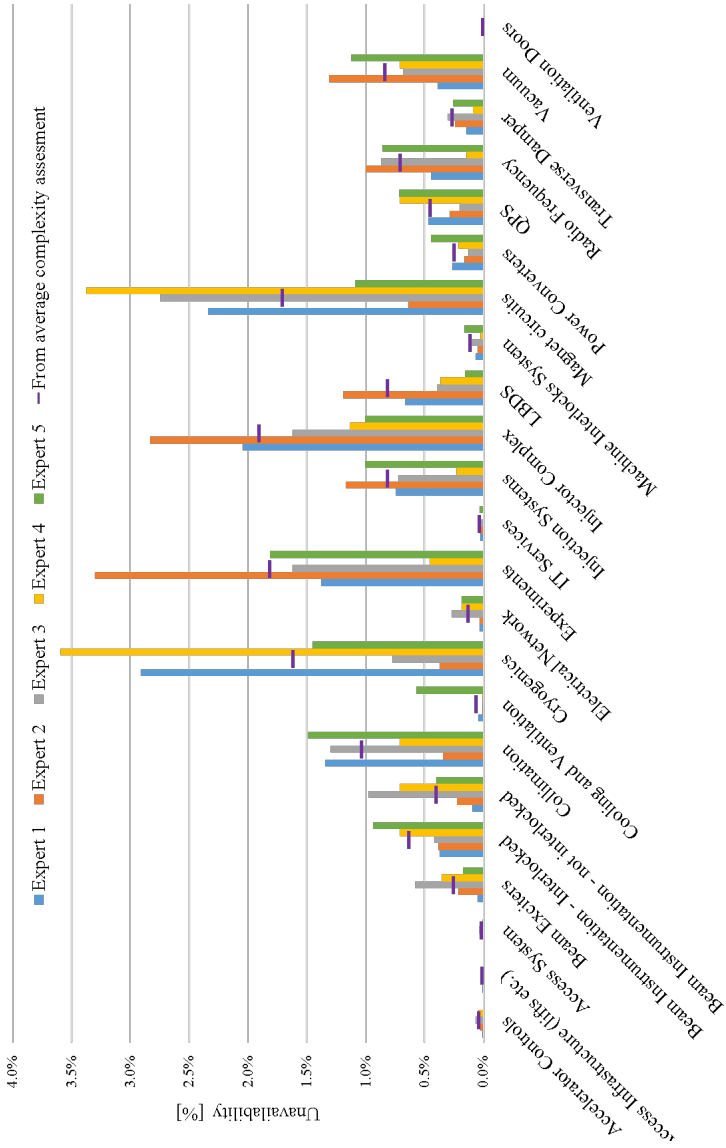


Figure 5.10: Comparison of the allocated unavailability to the LHC subsystems based on five experts complexity assessment.

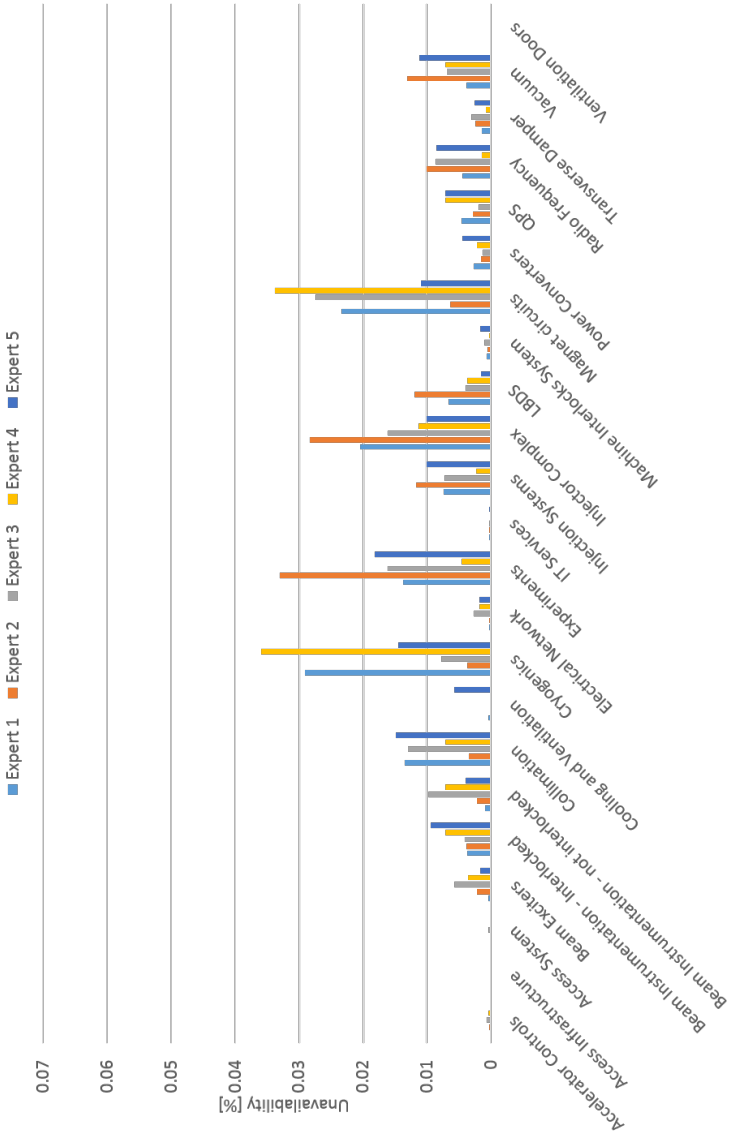


Figure 5.11: Comparison of the allocated availability to the LHC subsystems based on five experts complexity assessment and corrected for outliers.

LHC subsystems	w_i	C_i (%)	$\tilde{A}_i$	A_i	2017 Difference $(A_i - \tilde{A}_i)$
Accelerator Controls	7288	0.26	0.9996	0.9971	-2.50×10^{-3}
Access Infrastructure	1371	0.05	0.9999	1.0000	0.07×10^{-3}
Access System	2467	0.09	0.9999	0.9965	-3.41×10^{-3}
Beam Exciters	49679	1.80	0.9975	0.9999	2.42×10^{-3}
Beam Instrumentation- Interlocked	78475	2.85	0.9937	0.9999	6.22×10^{-3}
Beam Instrumentation- not Interlocked	124872	4.53	0.9960	1.0000	3.96×10^{-3}
Collimation	204859	7.44	0.9897	0.9997	1.00×10^{-2}
Cooling and Ventilation	11618	0.42	0.9994	0.9898	-9.62×10^{-3}
Cryogenics	321243	11.66	0.9839	0.9794	-4.44×10^{-3}
Electrical Network	25599	0.93	0.9987	0.9928	-5.93×10^{-3}
Experiments	361359	13.12	0.9819	0.9971	15.2×10^{-3}
IT Services	6012	0.22	0.9997	1.0000	0.30×10^{-3}
Injection Systems	160485	5.83	0.9919	0.9963	4.39×10^{-3}
Injector Complex	380102	13.80	0.9809	0.9732	-7.73×10^{-3}
Beam Dumping System	161210	5.85	0.9919	0.9884	-3.45×10^{-3}
Machine Interlocks System	22115	0.80	0.9989	0.9989	0.03×10^{-3}
Magnet Circuits	339254	12.32	0.9830	0.9998	16.8×10^{-3}
Power Converters	48309	1.75	0.9976	0.9811	-16.5×10^{-3}
Quench Protection System	89150	3.24	0.9955	0.9878	-7.69×10^{-3}
Radio Frequency	139722	5.07	0.9929	0.9913	-1.64×10^{-3}
Transverse Damper	52477	1.91	0.9973	0.9996	2.25×10^{-3}
Vacuum	165369	6.00	0.9917	0.9994	7.77×10^{-3}

Table 5.8: Per LHC subsystem: complexity values calculated by the Geometric Average Weighting method and the corresponding allocated availability values, compared to the achieved availability in 2017.

based on the average complexity ($\tilde{A}_i$). For comparison, the table also shows the achieved availability (A_i) per subsystem during 2017. In Fig. 5.12 the allocated availability is compared to the achieved availability in 2017, in terms of the difference $A_i - \tilde{A}_i$.

Cryogenics, despite being one of the major contributors to the LHC downtime, only showed a slightly worse performance than required according to complexity. Actually, only few long stops of the Cryogenics system were observed during 2017.

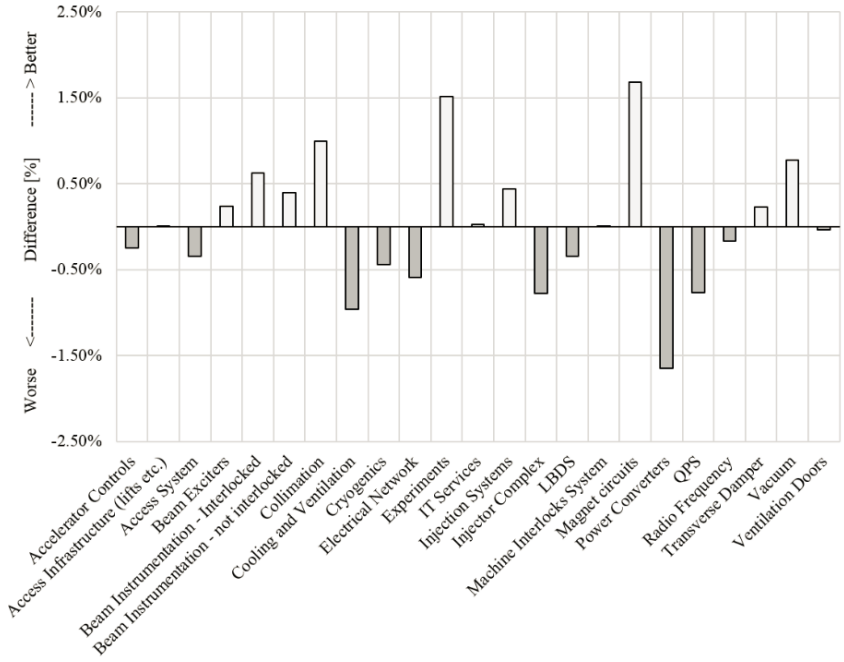


Figure 5.12: Comparison of the allocated availability based on the average complexity criteria and achieved availability during 2017 run for the LHC subsystems.

The Magnet Circuits showed a better performance than expected; during 2017 no quenches nor electrical faults of the Magnet Circuits were observed. In contrast, the Power Converters and Cooling and Ventilation systems performed worse than required according to the allocation method and contributed significantly to the unavailability of the LHC. Although the Injector Complex performance was better than expected during 2017 in comparison with previous years, according to the availability allocation method the performance of the Injector Complex should still improve. This can be explained by the fact that the Injector Complex is made up of several accelerators that are all required to operate during LHC injection, a

configuration that cannot be adequately taken into account by the procedure. To solve this, the individual accelerators of the Injector Complex should be considered individually in the allocation process.

In general terms, the results obtained allow for the identification of the systems in which more effort could be invested to improve the overall LHC availability. These systems are not always the ones contributing more to downtime, but the ones with more improvement potential according to their complexity. Of course, the cost of improvement should be considered at this stage. The best would be to invest in systems that give the biggest gain at lower cost.

For this particular run, experts should focus on the improvement of the Power Converts, Cooling and Ventilation system and Electrical Network performance. When it is not possible to avoid the system fault, as in the case of the Electrical Network, one should focus on the reduction of the induced downtime to other systems to improve its availability. However, in order to be able to draw more general and realistic conclusions, this analysis should be done over the years, including in some way the running conditions (beam parameters) of the LHC.

The methodology outlined in this section has been adopted for the performance evaluation of the LHC subsystems in the coming physics runs.

6 Availability optimization and sensitivity analysis

The ultimate goal of accelerator availability studies is to determine the system designs and operation modes that leads to the best performance of the accelerator or, in other words, to identify the critical components and their failures that compromise significantly the optimal performance of the accelerator. Since not all the components contribute in the same way to the accelerator performance, Importance Measures are chosen to account also for the "position" of the component in the system and not only for their availability parameters, i.e. repair and failure rates. "Position" refers here to the arrangement of the components in the system to fulfill its function. For example, a component with a redundant function will likely have less importance than a component that does not profit from any redundancy in the system.

In this section, the Differential Importance Measures (DIM)[73] are proposed as a basis for:

- Sensitivity analysis of availability models with the following objectives:
  - → analyze the impact of a limited input parameter knowledge on the output results
  - → identify the critical components with high impact on system performance
  - → identify combinations of failures that could significantly compromise the system performance and for which common causes should be avoided
- Optimization of the accelerator system performance by identifying the component upgrades that would lead to the best system availability improvement at lowest cost.
- Assess impact of planned accelerator upgrades on machine availability.

The availability models presented in Section 4.4 are used to illustrate the proposed sensitivity analysis and availability optimization processes based on Importance Measures. In addition, the Importance Measures are also suggested to assess the impact of planned accelerators upgrades on machine availability.

6.1 Differential Importance Measures

Since risks Importance Measures were introduced by Birnbaum [74], several component Importance Measures have been developed in the reliability and availability domain [75, 76]. The main advantage of the Importance Measures is that they not only consider the input parameters of the model, but also the "position" of the components in the system. In particular, the first order Differential Importance Measures (DIM)[77] allow for the ranking of components according to the impact of a small variation in one of their availability related parameters (e.g. repair rate, failure rate, availability or any other parameter affecting availability), on the output of the availability model, taken one at a time. The components with the larger Importance Measures have the biggest effect on the system availability.

A limitation of the first order Importance Measures is that the interactions between individual components are not included. This is, the effect of simultaneous variations in more than one input parameter on the overall system are not considered. These variations might represent for example, the improvement of more than one component at the same time, the improvement of one component at the expense of reducing the availability of another, or the degradation of more than one component at the same time. The latter case, in particular, might be induced by common cause failures, i.e. failures occurring at the same time due to shared causes. These failures can potentially compromise the optimal machine operation, but as they are hard to predict and even more difficult to quantify, these failures are rarely considered in the availability studies. The second order Differential Importance Measure is proposed here to account for these interactions [78]. The second order DIM, in the context of availability models serve to identify the common cause failures that could significantly compromise optimal machine performance and that need to be taken into consideration. Further, in the availability optimization

process, second order DIM may help in deciding which simultaneous component improvements lead to the greatest benefit or which component performance may be compromised in favor of improving others.

In order to have information on the interactions between more than two components of the system, Differential Importance Measures of higher order can be defined. However, the estimation of a higher order Importance Measure generally requires an extremely high number of model evaluations. An exception is the total order DIM, which can be evaluated by a finite variations of the individual variables [79, 80]. In this thesis, the total order DIM is proposed to analyze the change in system availability associated with the change in the unavailability of an individual component i, single and in any combination with the change in the availability of the remaining components. It gives a measure of the importance of the individual component in its interaction with the remaining components of the system.

The calculation of Importance Measures is posed on the following assumptions:

- The system consists of n independent repairable components, $i = 1, ..., n$. Components can range from subsystems to individual failure modes of the system.
- Component availability is known, i.e., component failure rates λ_i and repair rates μ_i are known.
- Components are 'as good as new' after repair.
- Components have two states: working and failed.

Let A_s be the measure of system performance, availability in this case, as a function of its components availability. Let A_i be the availability of component i with an exponential failure and repair distribution. A_i as a function of the failure rate λ_i and the repair rate μ_i is given by:

$$A_i = \frac{\mu_i}{\mu_i + \lambda_i} \tag{6.1}$$

Based on the above assumptions, the following Availability Importance Measures are considered.

Birnbaum Importance Measure

The Birnbaum Importance Measure of component i based on availability is defined as:

$$B_i = \frac{\partial A_s}{\partial A_i} \tag{6.2}$$

and it represents the effect of a variation in A_i on the overall system availability. The component with the largest Birhaum Importance Measure has the greatest impact on the overall system availability.

In order to perform the analysis also at component level, Availability Important Measures can be defined based on the failure rate and the repair rate.

The Birnbaum Importance Measure of component i based on the failure rate is defined as:

$$B_{\lambda_i} = -\frac{\partial A_s}{\partial \lambda_i} = -\frac{\partial A_s}{\partial A_i} \cdot \frac{\partial A_i}{\partial \lambda_i} \tag{6.3}$$

and represents the impact of a variation in the failure rate λ_i, of component i, on the overall system availability. Note that the minus sign corresponds to the improvement of the failure rate by a decrease in λ_i.

Likewise, the Birnbaum Importance Measure of component i based on the repair rate is defined as:

$$B_{\mu_i} = \frac{\partial A_s}{\partial \mu_i} = \frac{\partial A_s}{\partial A_i} \cdot \frac{\partial A_i}{\partial \mu_i} \tag{6.4}$$

representing the impact of a variation in the repair rate μ_i, of component i, on the overall system availability. Note that the sign corresponds to the improvement of the repair rate by an increase in μ_i.

As for the availability, the component parameter with the largest Birhaum Importance Measure has the greatest effect on the overall system availability. The

Birnbaum Importance Measure gives an indication on the sensitivity to variations in the component availability parameters. However, it does not allow to compare the Importance Measures as there is no prescription on how to set the scale for the variations in the component availability parameters. The first order Differential Importance Measure is a first tentative to mediate this.

First order Differential Importance Measure

The first order Differential Importance Measure (DIM) represents the total change in the result due to a small change in the input variables, taken one at a time. The component with larger DIM will have the total greater impact on the overall system availability. As for the Birnbaum Importance Measures, the DIM can be defined based on the component availability, failure rate or repair rate.

The first order DIM of component i based on its availability is defined as:

$$DIM_i = \frac{dA_{s_{A_i}}}{dA_s} = \frac{(\partial A_s/\partial A_i)\cdot dA_i}{\sum_{j=1}^{n}(\partial A_s/\partial A_j)\cdot dA_j} = \frac{B_i \cdot \Delta A_i}{\sum_{j=1}^{n} B_j \cdot \Delta A_j} \tag{6.5}$$

where ΔA_i represents the variation in the availability of component i, which can be either positive (availability improvement) or negative (availability decrease). In particular, in order to compare the effects on the system availability of each component, choose either $\Delta A_j = \Delta A_i$ for uniform changes in the components availability for all i, j or choose $\Delta A_i = \alpha \cdot (1 - A_i)$ for uniform percentage changes in the components availability, $\alpha \in (0, 1]$ and for all i.

Note that DIM is an additive measure, DIM for a group of parameters is the sum of the DIM of the parameters, and that the sum of all DIM is equal to one, this is:

$$\sum_{i=1}^{n} DIM_i = 1 \tag{6.6}$$

As for the Birnbaum measure, DIM can be also expressed as a function of the underlying failure and repair rates. Let $\Delta\lambda_i$ depict a small variation in the

failure rate of component i and $\Delta\mu_i$ depict a small variation in its repair rate. Uniform variations in the components failure and repair rates are defined by setting $\Delta\lambda_j = \Delta\lambda_i$ and $\Delta\mu_j = \Delta\mu_i$, respectively, for all i, j. For uniform percentage changes instead, the variations in the components failure and repair rates are defined as $\Delta\lambda_j/\lambda_j = \Delta\lambda_i/\lambda_i$ and $\Delta\mu_j/\mu_j = \Delta\mu_i/\mu_i$, respectively, for all i, j.

The fist order DIM of component i based on the failure rate represents the total importance of component i failure rate on the overall system availability and is given by Eq. 6.7.

$$DIM_{\lambda_i} = \frac{dA_{s_{\lambda_i}}}{dA_s} = \frac{\frac{\partial A_s}{\partial \lambda_i} \cdot d\lambda_i}{\sum_{j=1}^{n} (\frac{\partial A_s}{\partial \lambda_j} \cdot d\lambda_j + \frac{\partial A_s}{\partial \mu_j} \cdot d\mu_j)}$$

$$= \frac{\frac{\partial A_s}{\partial A_i} \cdot \frac{\partial A_i}{\partial \lambda_i} \cdot \Delta\lambda_i}{\sum_{j=1}^{n} \frac{\partial A_s}{\partial A_j} \cdot (\frac{\partial A_j}{\partial \lambda_j} \cdot \Delta\lambda_j + \frac{\partial A_j}{\partial \mu_j} \cdot \Delta\mu_j)} \tag{6.7}$$

In the same way, the first order DIM of component i based on the repair rate is defined by Eq. 6.8 and represents the total availability importance of the repair rate of component i on the overall system availability.

$$DIM_{\mu_i} = \frac{dA_{s_{\mu_i}}}{dA_s} = \frac{\frac{\partial A_s}{\partial \mu_i} \cdot d\mu_i}{\sum_{j=1}^{n} (\frac{\partial A_s}{\partial \lambda_j} \cdot d\lambda_j + \frac{\partial A_s}{\partial \mu_j} \cdot d\mu_j)}$$

$$= \frac{\frac{\partial A_s}{\partial A_i} \cdot \frac{\partial A_i}{\partial \mu_i} \cdot \Delta\mu_i}{\sum_{j=1}^{n} \frac{\partial A_s}{\partial A_j} \cdot (\frac{\partial A_j}{\partial \lambda_j} \cdot \Delta\lambda_j + \frac{\partial A_j}{\partial \mu_j} \cdot \Delta\mu_j)} \tag{6.8}$$

Second order Differential Importance Measure

The second order Differential Importance Measure (DIM^{II}), which accounts also for the effects of simultaneous variations in the availability of components i and component j , is defined as:

$$DIM_{ij}^{II} = \frac{\frac{\partial A_s}{\partial A_i} \cdot \Delta A_i + \frac{\partial A_s}{\partial A_j} \cdot \Delta A_j + \frac{\partial^2 A_s}{\partial A_i \partial A_j} \cdot \Delta A_i \cdot \Delta A_j}{\sum_{k=1}^{n} \frac{\partial A_s}{\partial A_k} \cdot \Delta A_k + \sum_{k=1}^{n-1} \sum_{l=k+1}^{n} \frac{\partial^2 A_s}{\partial A_k \partial A_l} \cdot \Delta A_k \cdot \Delta A_l} \tag{6.9}$$

where ΔA_i and ΔA_j represent the variation in availability of components i and j, respectively. The numerator is the total variation of the output (availability) due to the single and simultaneous variation of the inputs (availability of the two components). The denominator instead describes the total variation in the availability due to the variations of each component availability and simultaneous to each pair. The pair of components with higher DIM^{II} will have the highest effect on the overall system availability.

The second order DIM with respect to failure and repair rate can be derived in a similar manner and represents the effect on the system availability of simultaneous variations in the repair or failure rate of component i and repair or failure rate of component j. Let $x = (\lambda_1, ..., \lambda_n, \mu_1, ..., \mu_n)$, then the second order DIM with respect to x_i and x_j for all $i, j \in 1, ..., 2n$ and $i \neq j$ is defined as:

$$DIM_{x_i x_j}^{II} = \frac{\frac{\partial A_s}{\partial x_i} \cdot \Delta x_i + \frac{\partial A_s}{\partial x_j} \cdot \Delta x_j + \frac{\partial^2 A_s}{\partial x_i \partial x_j} \cdot \Delta x_i \cdot \Delta x_j}{\sum_{k=1}^{2n} \frac{\partial A_s}{\partial x_k} \cdot \Delta x_k + \sum_{k=1}^{2n-1} \sum_{l=k+1}^{2n} \frac{\partial^2 A_s}{\partial x_k \partial x_l} \cdot \Delta x_k \cdot \Delta x_l} \tag{6.10}$$

The combination of parameters (x_i, x_j) with higher DIM^{II} will have the highest effect on the overall system availability.

Unlike DIM, DIM^{II} is not an additive measure and the sum of all DIM^{II} is not equal to one.

Total order Differential Importance Measure

The total order Differential Importance Measure (DIM^T) of component i represents the total change in the output due to the change in the unavailability of the individual component i, single and in any combination with the change in the availability of the remaining $n-1$ components. It gives a measures of the influence of the component as a result of its individual effect and of all its possible interactions with the other components. Thus, it combines in a single measure the information obtained by the differential importance measures of any order. The limitation of the total order DIM is that when the changes become small the interaction between components is lighter and thus, the total order DIM is very similar to the first order DIM.

The total order DIM of component i based on availability is defined as [80]:

$$DIM_i^T = \frac{B_i * \Delta A_i + \sum_{k=2}^{n} \sum_{\substack{j_1<\ldots<j_k \\ i\in j_1,\ldots,j_k}} \frac{\partial^k A_S}{\partial A_{j_1}\ldots\partial A_{j_k}} \cdot \prod_{s=1}^{k} \Delta A_{x_{j_s}}}{\sum_{l=1}^{n} B_l * \Delta A_l + \sum_{k=2}^{n} \sum_{j_1<\ldots<j_k} \frac{\partial^k A_S}{\partial A_{j_1}\ldots\partial A_{j_k}} \cdot \prod_{s=1}^{k} \Delta A_{x_{j_s}}} \tag{6.11}$$

In order to avoid the extremely high number of derivatives to evaluate, it is possible to evaluate the total Importance Differential Measure by making finite variations of the variables [73, 79] as shown in Equation 6.12.

$$DIM_i^T = \frac{A_f - A_i}{A_f - A_0} \tag{6.12}$$

where:

- $A_0 = A_S(A_1^0, \ldots, A_n^0)$, the system availability when all the components assume their initial availability value,
- $A_f = A_S(A_1^f, \ldots, A_n^f)$, the system availability when all the components assume their final availability value,

- $A_i = A_S(A_1^f, ..., A_i^0, ..., A_n^f)$, the system availability when all the components assume their final availability value except for component i that takes its initial availability value.

The total order DIM with respect to failure and repair rate can be calculated in the same way. The system final and initial availability correspond to the value of availability assuming the final and initial values in the component failure or repair rates, respectively. A_i, instead, corresponds to the system availability when all the components assume their final availability except for the component i failure or repair rate.

6.2 Sensitivity analysis and identification of critical components

Once the system availability model has been completed and verified, a sensitivity analysis is particularly useful to understand the effect of small variations in the availability parameters of the components on the output availability results. Furthermore, such analysis allows to identify critical components and failures with high impact on the system performance. The identification of these critical events might ultimately lead to the implementation of actions that mitigate the effects of those events. While first order DIM are useful to identify the critical components with high impact on machine availability, second order DIM allows for the identification of potential common cause failures that could significantly compromise system performance.

The sensitivity analysis of availability models based on Availability Importance Measures can be implemented following these steps:

- Define the availability of the system as a function of its component availability parameters, failure and repair rate, where possible. This function can be derived directly from the availability model of the system and the basic formulas for parallel (i.e. redundant) and series systems (i.e. non-redundant) described in Equations 6.13, 6.14 and 6.15.

  When the components in the system are arranged in series, the availability of the system is expressed as:

$$A_S = \prod A_i \tag{6.13}$$

When the components in the system are arranged in parallel, then the availability of the system is expressed as:

$$A_S = 1 - \prod (1 - A_i) \tag{6.14}$$

If the system consist of N parallel identical components wherein at least M of the total N items must be operational for the system to be operational (M out of N redundancy), the availability of the system is given by:

$$A_S = \sum_{k=M}^{N} \binom{N}{k} \cdot A_i^k \cdot (1 - A_i)^{N-k} \tag{6.15}$$

For a system consisting of both series and parallel arrangement of components, the availability of the system can be expressed as a combination of the above formulas.

- Set $\alpha \in (0, 1]$ and for all $i \in \{1, \ldots n\}$ define:

$$\Delta A_i = \alpha \cdot (1 - A_i) \tag{6.16}$$

In this thesis, the change in the failure rate is defined as the change that would lead to the same availability improvement as ΔA_i. The same applies for the definition of the change in the repair rate. Thus, the decrease in the failure rate that would lead to the same availability improvement as ΔA_i for each i is given by:

$$\Delta \lambda_i = -\lambda_i \cdot \frac{\Delta A_i}{(1 - A_i) \cdot (A_i + \Delta A_i)} \tag{6.17}$$

The increase in the repair rate that would lead to the same availability

improvement as ΔA_i for each i is given by:

$$\Delta\mu_i = \mu_i \cdot \frac{\Delta A_i}{A_i \cdot (1 - A_i - \Delta A_i)} \tag{6.18}$$

- Calculate first, second and total order Availability Importance Measures for all components, as explained in Section 6.1, by setting ΔA_i, $\Delta\lambda_i$ and $\Delta\mu_i$ as in 6.16, 6.17 and 6.18, respectively.

  Values for the Importance Measures presented in this thesis have been calculated analytically with a custom-software developed in MATLAB [81]. The custom-made code takes as input the system availability function, initial availability values of the components and the small variations to be considered.

- Identify critical components with higher first order and total order DIM. These components have the greatest impact on machine performance. The improvement of their availability leads to the best improvement on the overall system availability. Moreover, errors on the availability parameters of these critical components will have a more significant impact on the simulation results. Hence, additional efforts should be invested to improve the accuracy of the availability parameters for those systems in order to produce more reliable and meaningful results.

- Identification of the pair of components with higher second order DIM. A simultaneous failure of such pairs of components would have a significant impact on machine operation. Thus, studies should be performed to investigate if these pairs of components could fail simultaneously due to common causes and if so, implement preventive measures.

The proposed sensitivity analysis can also be used to assess the impact of accelerator upgrades on the overall machine availability. Accelerator upgrades aim to increase the physics reach through the upgrades of particular systems. Due to the added complexity, these upgraded systems might become less reliable or more difficult to repair. The first order Importance Measures allow to analyze how

these changes might affect the overall machine availability. The degradation in the availability of system i due to its upgrade can be expressed as $\Delta A_i < 0$ and thus, the effect of these change in the overall availability can be calculated with Equation 6.5. The same applies if the degradation occurs in the failure rate of component i, expressed as $\Delta\lambda_i > 0$, or in the repair rate, $\Delta\mu_i < 0$.

In order to illustrate the method proposed, such sensitivity analysis is applied to the CLIC availability models presented in Section 4.4.2.

6.3 Sensitivity analysis and optimization of CLIC availability models

The basic concept and advantages of the use of Importance Measures for sensitivity analysis of availability models is explained with an an example of the powering system for the CLIC Drive Beam Quadrupoles. Then, a more complex example of the Importance Measures is given using the CLIC Main Beam RF powering system. Both studies are presented on the basis of the availability models presented in Section 4.4.2.

Drive Beam Quadrupoles powering system

Let A_c be the availability of the Power Converter Controls, A_{mod} the availability of the Power Converter Module and A_t the availability of the Trimmer as a function of its failure and repair rates, this is,

$$A_i = \frac{\mu_i}{\mu_i + \lambda_i} \tag{6.19}$$

The availability parameters of each component are given in Table 6.1 together with the variation in the parameters value considered for the calculation of Importance Measures, with $\alpha = 0.5$.

The availability of the Drive Beam Quadrupoles powering system as a function of its component availability parameters can be derived as detailed below.

The availability function of a power converter consisting of $M + 1$ modules, with

Component	$\lambda_i[h^{-1}]$	$\mu_i[h^{-1}]$	A_i^0	ΔA_i	$\Delta\lambda_i$	$\Delta\mu_i$	A_i^f
PC module	3.33×10^{-6}	0.25	0.999 986	6.66×10^{-6}	1.66×10^{-6}	0.25	0.999 993
Controls	3.33×10^{-7}	0.25	0.999 998	6.66×10^{-7}	1.66×10^{-7}	0.25	0.999 999
Trimmer	3.33×10^{-6}	0.25	0.999 986	6.66×10^{-6}	1.66×10^{-6}	0.25	0.999 993

Table 6.1: Availability parameters and variations considered for the calculation of Importance Measures, with $\alpha = 0.5$, of the CLIC Drive Beam Quadrupoles powering components.

a redundancy of M out of $M+1$, is given by Equation 6.20.

$$A_{pc_{M+1}} = A_{mod}^{M+1} + (M+1)\cdot A_{mod}^{M}\cdot(1-A_{mod}) \tag{6.20}$$

For the trimmers, where 20 out of 830 trimmers in a powering sector can be tolerated to fail, the availability function, A_{tr}, is expressed as:

$$A_{tr} = \sum_{i=810}^{830}\binom{830}{i}\cdot A_t^i\cdot(1-A_t)^{830-i} \tag{6.21}$$

Then, the availability function of one powering sector, A_{sec}, with twelve 4-module Power Converters,sixteen 3-module Power Converter and two 2-module Power Converters with corresponding Controls and Trimmers is given by:

$$A_{sec} = (A_c\cdot A_{pc_4})^{12}\cdot(A_c\cdot A_{pc_3})^{16}\cdot(A_c\cdot A_{pc_2})^{2}\cdot A_{tr} \tag{6.22}$$

With 48 powering sectors, the availability of the full Drive Beam Quadrupoles powering system can be expressed by Equation 6.20.

$$A_S = A_{sec}^{48} \tag{6.23}$$

Based on Equations 6.5, 6.9 and 6.12, the Availability Importance Measures for the components of one powering sector of the Drive Beam Quadrupoles are calculated and shown in Table 6.2. The three Availability Importance Measures show that the Controls component has the greatest influence on the availability of the whole system and therefore, also any simultaneous improvement of two

i	Component	DIM_i	(i,j)	DIM_{ij}^{II}	DIM_i^T
1	PC module	3.25×10^{-3}	**(1, 2)**	1	8.13×10^{-4}
2	Controls	0.998916	**(1, 3)**	1.08×10^{-3}	0.999187
3	Trimmer	6.61×10^{-56}	**(2, 3)**	0.998916	0

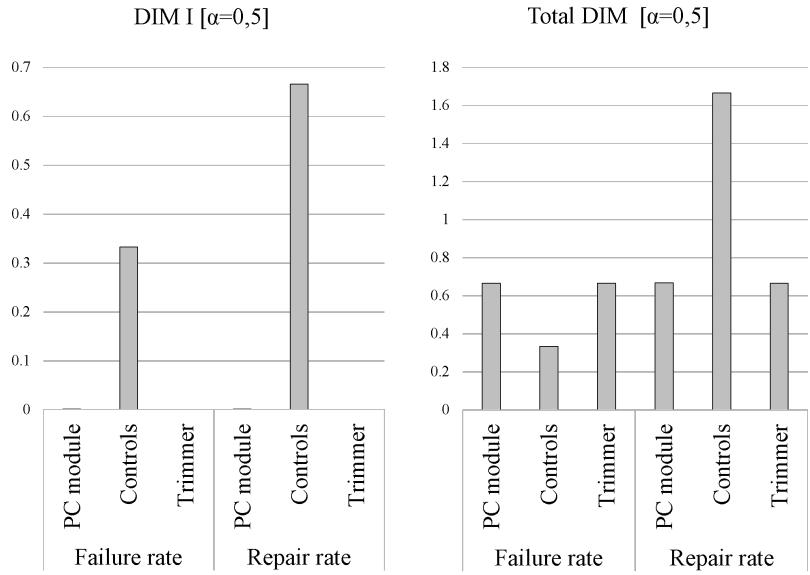
Table 6.2: Values of DIM and DIM^T for the components of one powering sector of the Drive Beam Quadrupoles and values of DIM^{II} for all the pair of components, with respect to availability.

components that includes the improvement of the Controls component has a dominating effect on the overall system availability. The information given here by the Importance Measures with respect to availability is not directly obvious, as Controls is the component with the highest availability out of the three components. Regarding the availability models, the Importance Measures indicate that while uncertainties in the input parameters of Power Converter Modules and Trimmers will not have a significant impact on the simulation results, uncertainties in the input parameters of the Controls failure may produce unreliable results. Also the second order DIM is basically dominated by the Controls first order DIM, which means that no major interactions are observed between the pairs of components.

Similar conclusions can be derived for the first order DIM based on failure and repair rate shown Fig. 6.1a. The availability parameters of the Controls component have the greatest first order effects on the overall system availability.

The second order DIM with respect to the failure and repair rate determines the pair of parameters with greater impact on system availability, that is, the pair of parameters with greatest first and second order effects on system availability. As might be expected, all the combinations that include the Controls failure or repair rate have a higher impact on system availability. However, as shown in Fig. 6.2, not all the configurations contribute in the same way. In particular, the Controls repair rate combined with any other availability parameter of the PC module or Trimmer has 2 times greater effect on the overall system availability than the combination with the Controls failure rate.

This effect becomes more relevant by analyzing the Total DIM presented in



(a) First order DIM

(b) Total Order DIM

Figure 6.1: First and total order Differential Importance Measures, with respect to failure and repair rate, for the components of one powering sector of the CLIC Drive Beam Quadrupoles.

Fig. 6.1b. The Controls repair rate is the availability parameter with strongest impact including all its interaction effects. Moreover, an analysis of the third order interactions showed that interactions not including the controls failure rate prevail over the interactions that include the failure rate.

Thus, including all interaction effects of first, second and third order, if the availability of the system needs to be improved, one should focus on the improvement of the Controls repair time. This could be accomplished by the implementation of remotely repairable controls, faster failure detection or periodic preventive maintenance actions. If for some technological or budget constraint the Controls

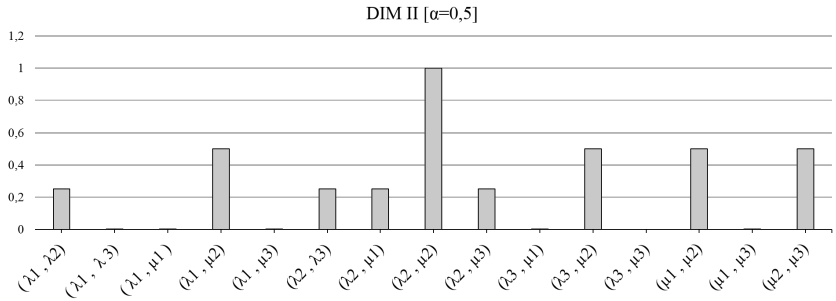


Figure 6.2: Second order Differential Importance Measures, with respect to failure and repair rate, for the components of one powering sector of the CLIC Drive Beam Quadrupoles. The indexes 1, 2 and 3 refer to the PC Module, Controls and Trimmer component, respectively.

component repair time cannot be improved, then, one should invest in improving the availability of the one of the remaining components over the improvement of the Controls failure rate.

Since the 48 powering sectors are connected in series, identical Importance Measures are obtained for the entire system. Thus, the same conclusions apply to the whole CLIC Drive Beam Quadrupoles powering system.

Main Beam RF powering system at 380 GeV: Drive Beam based system

The Drive Beam based RF powering system described in 4.4.2 is studied here to illustrate the use of Importance Measures for sensitivity analysis and optimization of availability models. The same exercise can be done with the alternative Klystron based RF powering system.

Let A_i be the availability of the components of the Drive Beam based RF powering system, for $i = 1, .., 6$, expressed as a function of their failure and repair rates, as in Equation 6.1. In each accelerating unit, the components are connected in series and thus, the availability of an accelerating unit, A_{Acc}, is given by:

i	**Component**	$\lambda_i[h^{-1}]$	$\mu_i[h^{-1}]$	A_i^0	ΔA_i	$\Delta\lambda_i$	$\Delta\mu_i$	A_i^f
1	RF Cavity	6.67×10^{-5}	33.3	0.999998	1.0×10^{-6}	3.33×10^{-5}	33.33	0.999999
2	Cooling System	2.28×10^{-5}	0.17	0.999863	6.8×10^{-5}	1.1×10^{-5}	0.17	0.999931
3	Klystron	2.00×10^{-5}	0.08	0.999760	1.2×10^{-4}	1.0×10^{-5}	0.08	0.999880
4	Modulator	1.00×10^{-5}	0.08	0.999880	6.0×10^{-5}	5.0×10^{-6}	0.08	0.999940
5	Wave-guides	1.00×10^{-5}	0.33	0.999970	1.5×10^{-5}	5.0×10^{-6}	0.33	0.999985
6	LLRF	3.80×10^{-5}	0.33	0.999885	5.7×10^{-5}	1.9×10^{-5}	0.33	0.999943

Table 6.3: Availability parameters and variations considered for the calculation of Importance Measures, with $\alpha = 0.5$, of the CLIC Drive Beam based Main Beam RF powering system components.

$$A_{Acc} = \prod_{i=1}^{6} A_i \tag{6.24}$$

To include the 12 hot-standby spares that are installed in the tunnel into the analysis, the system is considered as a 472 out of 484 active redundant system. Therefore, the availability of the Drive Beam based RF powering system as a function of its components' availability can be expressed as:

$$A_S = \sum_{i=472}^{484} \binom{484}{i} \cdot A_{Acc}^i \cdot (1 - A_{Acc})^{484-i} \tag{6.25}$$

Table 6.3 provides availability values and input data for the calculation of Importance Measures, with $\alpha = 0.5$.

To facilitate comprehension, first, the Importance Measures for one accelerating unit are analyzed, and then, the ones for the entire system are introduced.

The first and total order DIM of one accelerating unit are tabulated in Table 6.4. Since all the components are connected in series, the interactions between components of second or higher order become negligible and thus, first and total order DIM are almost equal. The values in Table 6.4 show that the components with lower availability have the largest influence in the overall system availability. In particular, the Klystrons, which are the components with highest impact on the accelerating unit, followed by the Cooling System, Modulators and LLRF

i	Component	DIM_i	DIM_i^T
1	RF Cavity	0.003	0.002
2	Cooling System	0.213	0.203
3	Klystron	0.373	0.356
4	Modulator	0.187	0.178
5	Wave-guides	0.047	0.044
6	LLRF	0.177	0.169

Table 6.4: Values of DIM and DIM^T for the components of one accelerating unit of the CLIC Drive Beam based Main Beam RF powering system.

components. For the same reason, errors associated to the availability parameters of these components will have a significant impact on the precision of the simulation results.

The second order DIMs with respect to availability for one accelerating unit are shown in Fig. 6.3. As one could expect from the previous conclusion, the ranking produced by DIM^{II} suggests that increasing simultaneously the availability of the Klystrons and the Cooling system, Modulator or LLRF has the greater impact on the system availability. Furthermore, in the event that any of these pair of components have a common cause failure, the availability of the system would be considerably affected. For example, the common cause failures of the Klystrons and Modulators should be investigated, as well as the ones affecting the Klystrons and LLRF systems.

Additional information can be obtained by introducing the Importance Measures with respect to the failure and repair rate. As shown in Fig. 6.4, the repair time of the Klytrons is the parameter with highest influence on the availability of 1 accelerating unit, followed by the repair times of the Cooling System and LLRF and the failure rate of the Klystrons. If the availability of one unit needs to be improved, one should focus on decreasing the repair time of the klystrons to obtain the greatest availability increase.

The second order DIM with respect to failure and repair rate is calculated by 6.10 for 66 pair of combinations. The obtained DIM^{II} values for 1 accelerating

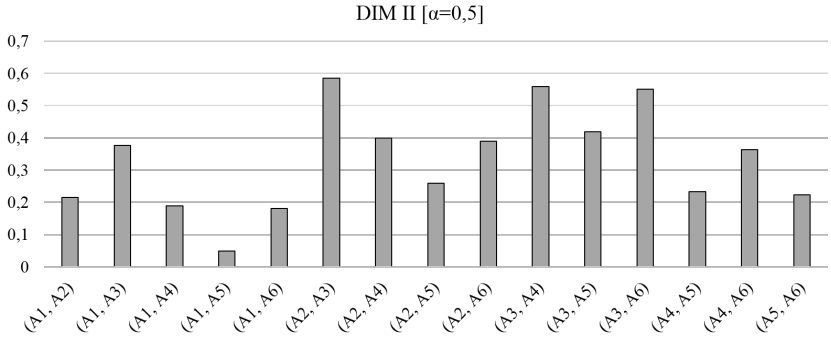


Figure 6.3: Second order Differential Importance Measures, with respect to availability, for the components of 1 accelerating unit of the CLIC Drive Beam based Main Beam RF powering system.

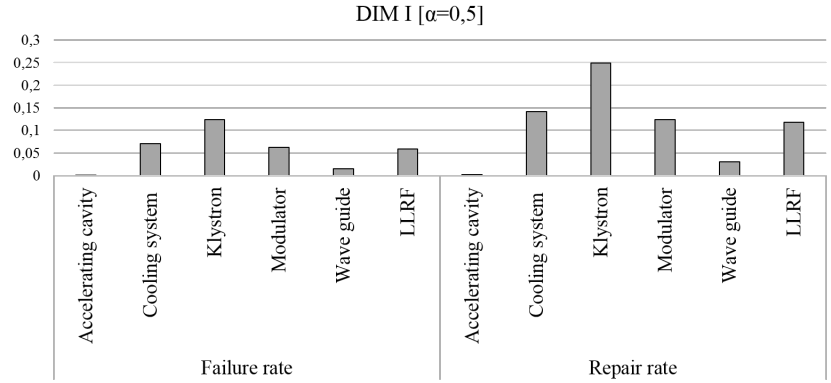


Figure 6.4: First order Differential Importance Measures, with respect to failure and repair rate, for the components of 1 accelerating unit of the CLIC Drive Beam based Main Beam RF powering system.

unit and for the entire Drive Beam based RF powering system are compared in Fig. 6.5. The improvement of any pair of parameters has always greater impact on the availability of the individual accelerating unit than in the overall system. As can be inferred from the previous results, the simultaneous improvement of the failure and repair rate of the Klystrons has the greatest impact on system availability. Although the klystrons are hence the major contributors to the system availability, it is not completely dominating the system availability and other systems also substantially influence the system availability. The values of DIM^{II} suggests the following pair of availability parameters to be improved to get the largest improvement in the overall system performance:

- Failure rate of the Cooling System and repair rate of Klystrons.
- Failure rate of Modulators and repair rate of Klystrons.
- Failure rate of Klystrons and repair rate of Cooling Systems.
- Failure rate of LLRF and repair rate of Klystrons.

The Total order DIM values, with respect to failure and repair rate, for one accelerating unit and for the entire Drive Beam based RF powering system are compared in Fig. 6.6. When including the interactions of all orders, for one accelerating unit, the impact on the overall availability of all the components is similar. However, the Klystron repair rate remains to be the most important. For the entire RF powering system instead, the total order effects of the failure rates are negligible, while the repair rates have a relevant impact on the overall system availability. Overall, the availability parameters with higher total impact on the overall system availability are the repair rates of Klystrons, Cooling System, Modulators and LLRF components. Note that the importance of all availability parameters is higher for one accelerating unit than for the entire RF powering system, but for the Klystron repair rate. First and second order effects of the Klystrons repair rate are already relevant and as indicated by its DIM^{T} value, also higher order interactions with the other parameters have a large impact on the overall system availability.

In conclusion, the improvement of the Klystron repair rate would lead to the

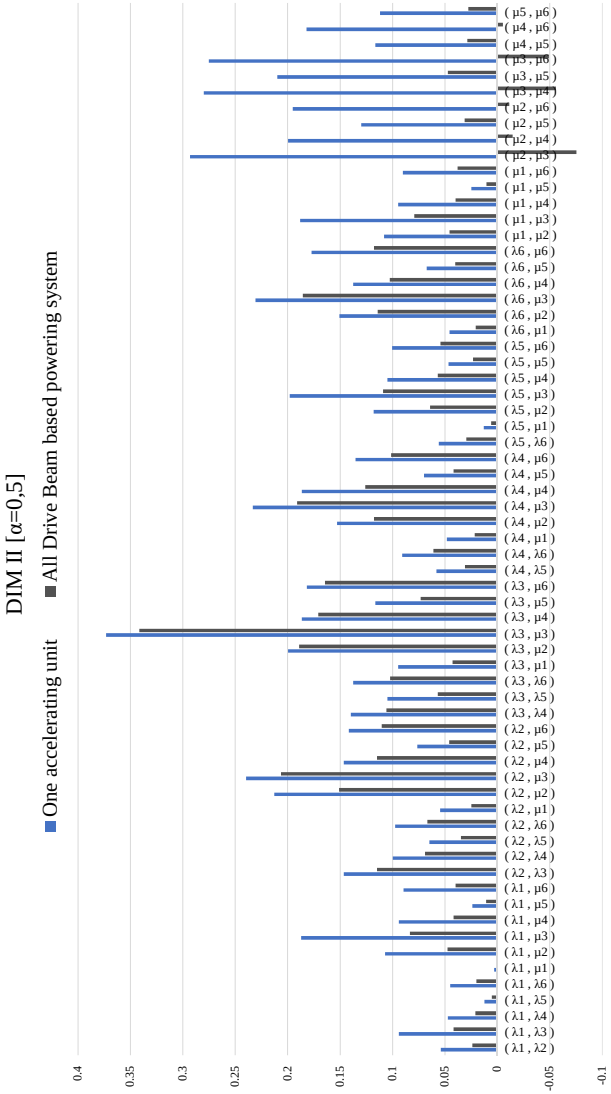


Figure 6.5: Second order DIM, with respect to failure and repair rate, for the components of 1 accelerating unit and the entire CLIC Drive Beam based Main Beam RF powering system.

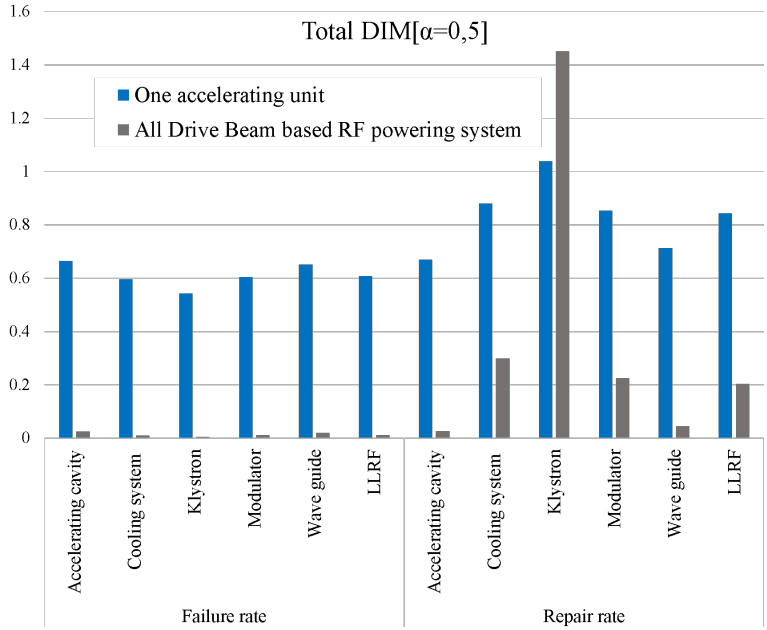


Figure 6.6: Total order Differential Importance Measures, with respect to failure and repair rate, for the components of 1 accelerating unit and of the entire CLIC Drive Beam based RF powering system.

greatest availability improvement of the Drive Beam based RF powering system. Together with the Klystron repair rate improvement, one could consider to improve also the failure rate of the Cooling system, Modulator or LLRF. If for any technological constraint, the Klystron availability cannot be improved, one should focus on the improvement of the repair rate of the Cooling System, Modulator or LLRF.

6.4 Cost driven availability optimization based on Importance Measures

The result of applying the Importance Measures concept to accelerator systems is used to define an availability optimization strategy that prioritizes actions with higher improvement potential at lower cost. In [82], J. Barabady proposes an availability optimization strategy based on defining the cost of the system as a function of its components availability. In this thesis, the strategy is derived instead by defining the availability of the component as the function of its cost.

Let $A_i(C)$ be the availability of component i as a function of its cost, C, $i = 1, ..., n$. Then, the achievable change in availability of component i, for a certain investment, ΔC_i, can be expressed as:

$$\Delta A_i = \frac{\partial A_i}{\partial C} \cdot \Delta C_i \tag{6.26}$$

The corresponding variation in the overall system availability, ΔA_S, due to the change in the availability of component i is given by:

$$\Delta A_S = \frac{\partial A_s}{\partial A_i} \cdot \Delta A_i = B_i \cdot \frac{\partial A_i}{\partial C} \cdot \Delta C_i \tag{6.27}$$

where B_i equals the Birnbaum Importance Measure given by 6.3.

The availability of a repairable component can be improved by either improving the component failure rate or improving its repair rate. To determine which of the two options is the most cost effective, the effect of improvements on the system availability is expressed also as a function of the repair and failure rates.

Let $\lambda_i(C)$ and $\mu_i(C)$ be the failure rate and repair rate of component i as a function of their cost. Following the same procedure as described above, the variations on the overall system availability due to a change in the failure or repair rate of component i for a certain investment, are given by 6.28 and 6.29.

$$\Delta A_{S_{\lambda_i}} = B_{\lambda_i} \cdot \frac{\partial \lambda_i}{\partial C} \cdot \Delta C_{\lambda_i} \tag{6.28}$$

$$\Delta A_{S_{\mu_i}} = B_{\mu_i} \cdot \frac{\partial \mu_i}{\mu C} \cdot \Delta C_{\mu_i} \tag{6.29}$$

The relative effect in availability due to the improvement of component i availability, failure or repair rate, for a certain investment, normalized to the total achievable improvements can be expressed as:

$$\Delta^r A_{S_{x_i}} = \frac{B_{x_i} \cdot \frac{\partial x_i}{\partial C} \cdot \Delta C_{x_i}}{\sum_{j=1}^{n} B_{x_j} \cdot \frac{\partial x_j}{\partial C} \cdot \Delta C_{x_j}} \quad \text{where} \quad x = A,\ \lambda \ \text{ or } \ \mu \tag{6.30}$$

Let K be the budget available to spent in improvements of the components. Now with equal cost budgets for all components, i.e. $\Delta C_{x_j} = \Delta C_{x_i} = K$, the relative effect in availability is given by:

$$\Delta^r A_{S_{x_i}} = \frac{B_{x_i} \cdot \frac{\partial x_i}{\partial C}}{\sum_{j=1}^{n} B_{x_j} \cdot \frac{\partial x_j}{\partial C}} \tag{6.31}$$

The relative value enables the identification of the improvement that would lead to the largest variation in availability among all the possible improvements.

The achievable availability expressed as an explicit function of cost, $A(C)$, might often be difficult to provide. However, often the change in availability per unit cost can be more readily expressed relative to a reference component, ref (example, given the same budget, the availability improvement of component X will be about 30 per cent of the availability improvement achievable in the reference component). That is, the relative change in availability of component i can be defined as:

$$r_{A_i} := \frac{\partial A_i / \partial C}{\partial A_{ref} / \partial C} \tag{6.32}$$

The same applies for defining the change in the failure rate and repair rate of component i, with respect to a change in the failure or repair rate of component ref.

Therefore, the relative effect in availability due to a change in the availability, failure rate or repair rate of component i can be defined as:

$$\Delta^r A_{S_{x_i}} = \frac{B_{x_i} \cdot r_{x_i} \cdot \frac{\partial A_{x_{ref}}}{\partial C} \cdot K}{\sum_{j=1}^{n} B_{x_j} \cdot r_{x_j} \cdot \frac{\partial A_{x_{ref}}}{\partial C} \cdot K} = \frac{B_{x_i} \cdot r_{x_i}}{\sum_{j=1}^{n} B_{x_j} \cdot r_{x_j}} \quad \text{where} \quad x = A,\ \lambda \text{ or } \mu \qquad (6.33)$$

Thus, the decision making for availability optimization can be based on the following steps:

- Define the availability of the system: 1) as a function of its components' availability parameters and 2) as the function of its components' availability cost. In absence of the second, define the change in availability per unit cost relative to a reference component, as described by Equation 6.32.
- Calculate the relative change in availability due to changes in the availability parameters of component i for a certain investment as given by Equation 6.33.
- Prioritize the improvements of components on the basis of their effects on system availability. These can be either general improvements in the components availability, or explicit improvements in their repair and failure rates.

Nevertheless, it could be sometimes an advantage to invest the budget in the improvement of more than one component. In this case, a fraction f_i of the budget, K, is invested in improving component i with $\sum_{i=1}^{n} f_i = 1$. For shake of simplicity, consider f the fraction of the budget invested in the improvement of component i and the remaining fraction $1-f$ invested in the improvement of component j. Then the relative variation on the overall system availability can be expressed as:

$$\Delta A_{x_i,x_j} = B_{x_i} \cdot \frac{\partial A_{x_i}}{\partial C} \cdot f\ K\ +\ B_{x_j} \cdot \frac{\partial A_{x_j}}{\partial C} \cdot (1-f)\, K$$

$$+\ \frac{\partial^2 A_s}{\partial A_{x_i} \partial A_{x_j}} \cdot \frac{\partial A_{x_i}}{\partial C} \cdot f\ K \cdot \frac{\partial A_{x_j}}{\partial C} \cdot (1-f)\, K \tag{6.34}$$

where $x = A$, λ or μ. The calculation of the above value for all pair combinations can be tedious in many cases. In order to overcome this problem, the second order DIM can be used in the decision making process instead. Once the improvements with higher relative impact have been identified, the second order DIM indicates which combinations of the identified improvements lead to the best availability improvement. The drawback of this solution is that the cost of simultaneous improvements is not considered in the calculation.

Illustrative numerical example

The proposed availability optimization strategy is illustrated with the example system of Fig 6.7. The system consists of two redundant systems. While one line has two redundant components, the other line has two components connected in series. The components' availability parameters and the achievable availability improvement for an certain investment with respect to component 1 are given in Table 6.5. For example, for a certain investment, the achievable availability improvement of Component 2 is about 80% of the achievable availability improvement of Component 1. In principle, the line with two redundant components will be the most available, but at the same time it is also the most expensive to improve in terms of availability.

The system availability function can be expressed as:

$$A_S = 1-(1-A_1 \cdot A_2) \cdot (1-A_3) \cdot (1-A_4) \tag{6.35}$$

Table 6.6 provides the first order DIM and the relative effect in availability for

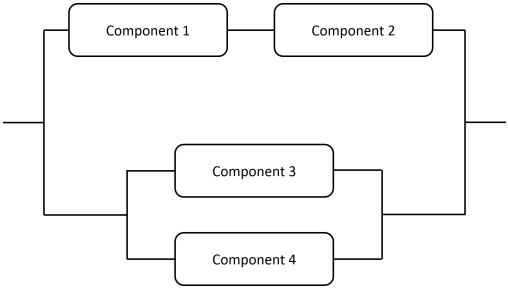


Figure 6.7: System reliability block diagram.

	$\lambda[h^{-1}]$	$\mu[h^{-1}]$	A_i^0	$\frac{\partial A_i/\partial C}{\partial A_{ref}/\partial C}$	$\frac{\partial A_i/\partial \lambda_i \cdot \partial \lambda_i/\partial C}{\partial A_{ref}/\partial C}$	$\frac{\partial A_i/\partial \mu_i \cdot \partial \mu_i/\partial C}{\partial A_{ref}/\partial C}$
Component 1	0.0025	0.04	0.94	1	0.6	0.8
Component 2	0.01	0.1	0.91	0.8	0.9	0.7
Component 3	0.02	0.04	0.67	0.2	0.2	0.3
Component 4	0.05	0.2	0.80	0.4	0.25	0.1

Table 6.5: Components' availability parameters and achievable availability improvement at a unit cost with respect to the reference component (Component 1).

equal cost budgets and for all the components, calculated based on Eq. 6.33.

As a general observation, the values in Table 6.6 suggest that the best results are always achieved by the improvement of repair rates. As expected, the first order DIM with respect to availability indicates that Component 3 and 4 have

	DIM_i	DIM_{λ_i}	DIM_{μ_i}	$\Delta^r A_{S_{A_i}}$	$\Delta^r A_{S_{\lambda_i}}$	$\Delta^r A_{S_{\mu_i}}$
Component 1	0.12	0.04	0.09	0.26	0.06	0.18
Component 2	0.20	0.07	0.14	0.33	0.15	0.25
Component 3	0.34	0.09	0.23	0.14	0.05	0.18
Component 4	0.34	0.10	0.23	0.28	0.07	0.06

Table 6.6: First order Differential Importance Measures and relative effect in availability for equal budgets and for all the components of the system.

a better effect on the overall system availability. In particular, the improvement in the repair rates of those components leads to the best increase in the overall system availability. However, if one needs to prioritize actions that lead to the best availability improvement for a given budget, then it is more cost effective to focus on the improvement of Component 2, as suggested by $\Delta^r A_{S_{A_i}}$ values. Indeed, higher availability increase is achieved by investing in the improvement of the repair rate of Component 2 . This behaviour can be explained by the fact that for a fixed budget, the achievable increase in the availability of Components 1 and 2 is larger and thus, the series configuration becomes more available than the parallel line.

Values of DIM^{II} in Fig 6.8 are used as an aid in decision making, if the main interest is to identify the pair of components to be improved to get the biggest improvement in the system performance. One might focus in the improvement of parameters that have high second order DIM but also, high relative effect in availability. An assessment purely based on DIM^{II}, suggests that the improvement efforts should be devoted to the pair of components (3,4). However, these are not the components with higher relative effect in availability for a fixed budget. For example, although the pair of parameters (λ_4, μ_3) have the largest effect in the system performance, the relative effect in availability of Component 3 failure rate for a fixed budget is one of the lowest. On the contrary, the pair of parameters (λ_2, μ_3) have a high relative effect in the system availability and also, a large DIM^{II} value. Thus, at a fixed budget, it is better to invest the resources in the simultaneous improvement of (λ_2, μ_3).

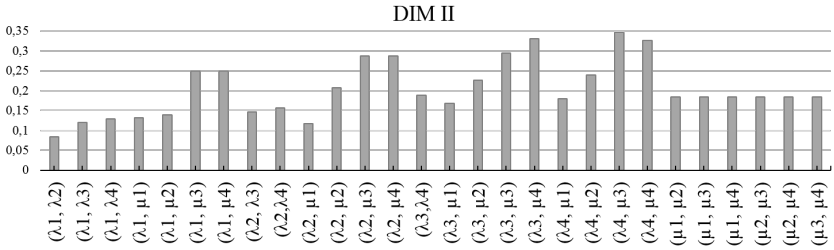


Figure 6.8: Second order DIM for all pair combinations of the availability parameters of the system components.

7 Conclusions and Outlook

The increasingly challenging objectives of the current and future particle accelerators pose strong requirements on their performance. One of the indicators of accelerators performance that is taking a major role in accelerator engineering is machine availability. Availability is the time that the particle accelerator is in operational state without failure. The longer the particle accelerator is available, the more particles interactions can be studied. Availability requirements are typically set at the beginning of a project and should be achieved during the operation phase. This thesis presents a methodology to study and optimize the availability of high energy particle accelerators throughout its life-cycle, from its conceptual design to its exploitation and upgrade.

In the early stages of an accelerator, the novel availability allocation method presented in this thesis, translates the overall accelerator availability target into availability requirements for each subsystem based on their complexity. The usefulness of the DEMATEL procedure has been demonstrated in cases where the root cause fault time and raw fault time of the systems differ significantly. Although a more objective complexity assessment would be preferred, the examples presented show successful results in-line with expectations. The example of the LHC demonstrated that if complexity assessment is conducted by more than one expert the subjectivity in the results is considerably reduced. Applying this methodology to CLIC and assuming an availability target of 75% for CLIC, the availability requirements for its subsystems have been allocated. The Two Beam Modules system is the most complex and therefore, dedicated studies should be performed to assess the availability of this system. Additionally, special attention should be paid also to less complex systems with high availability requirements such as the Technical Network, Post Decelerators and Machine Interlocks. As another example, the allocated availability to FCC subsystems have been compared to the observed

availability of LHC subsystems during the 2017 run, to give an insight of the feasibility to reach the availability requirements for the FCC subsystems.

The availability of a particular system can be studied further by the implementation of an availability model. Availability models use component reliability data to estimate the overall system availability. This is of crucial importance for availability-critical accelerators, from the late design phase to exploitation, and has several objectives: demonstrate the practical applicability of the accelerator, understand its failure behaviour and identify the components impacting availability, among others. The step-wise methodology for the definition of availability models of particle accelerators presented in this thesis ensures the completeness and consistency of availability models. Additionally, the advantages and disadvantages of several modelling and simulation tools have been discussed. The Common Input Format has been proposed for the definition of availability models in a user-friendly and intuitive manner. The AvailSim availability simulation tool, considered the most appropriate tool for the simulation of particle accelerators, has been adopted for the simulation of LHC and CLIC availability models. The conclusions derived from CLIC availability models are very instructive, despite that the acceleration structures of the Main Beam were not yet included in the Drive Beam based powering scheme. Hence, no comparison could be made yet of the two powering schemes for the Main Beam in terms of availability.

A limitation of availability modelling is often the limited reliable failure data of accelerator components. However, there are two ways to get around this limitation. First, through systematic and reliable procedures to track failures. The growing interest for availability studies in the particle accelerators community has increased awareness of the importance of failure tracking tools and thus, such tools are increasingly being implemented. An example is the Accelerator Fault Tracking system implemented at CERN that was used for the failure tracking of Linac4 during a dedicated Reliability Run. The results demonstrate that the tracking system is crucial for the identification of recurrent faults, the understanding of the actual operation and the identification of weak areas with high improvement potential. The availability allocation method is proposed to evaluate the performance of a subsystem by comparing its tracked availability with the availability allocated

according to complexity criteria. The introduced methodology showed realistic results, in line with experts judgment, and has been adopted for the performance evaluation of the LHC subsystems in the coming physics runs. In the case of Linac4, systems were identified whose performance could be improved according to their assessed complexity, such as the Power Converters and RF System. Also systems that still have some margin for failure were identified, such as the Proton Source and the Electrical Network.

The ultimate goal of accelerator availability studies is to determine the system designs and operation modes that would lead to the best performance of the accelerator. To this end and also as the second way to overcome the lack of reliable failure data for availability models, Availability Differential Importance Measures (DIM) are introduced. Firstly, Importance Measures are presented as a basis for sensitivity analysis of availability models. The sensitivity analysis based on DIM has been applied to CLIC and showed interesting, and not always obvious, results. For example, in the Drive Beam Quadrupoles powering system, whilst the Controls component is the component with higher availability, it is also the component with greatest influence on the system performance. Finally, an availability optimization strategy that prioritizes actions with higher improvement potential at lower cost is proposed based on Importance Measures. The described strategy is illustrated with a numerical example. The results show that it is not necessarily the best to invest in the improvement of components with greater impact on the overall system performance (specifically when these improvements turn out to be very costly).

High availability is also a key requirement for many systems in other domains, such as military systems. Availability studies are therefore essential not only in the particle accelerators domain, but also in many other fields. Availability modelling, and more in particular reliability modelling, is a fairly common method used in industry for the prediction of machine performance. In contrast, the availability allocation method based on complexity criteria and the applications of differential importance measures were defined for a particular purpose in the accelerators domain. In particular, the availability allocation method based on complexity criteria has been first described here and is specific for particle acccelerators.

However, the complete methodology presented in this thesis for the study of machine availability is applicable to general cases. Furthermore, this methodology demonstrated usefulness as well as potential for further development.

The availability allocation method based on complexity is particularly relevant to establish availability targets already during the design of a system and thus, ultimately ensure that the overall goal can be met. The complexity of each subsystem is assessed based on several factors affecting the availability. Because these factors can be rarely exactly quantified, specially in case of very large machines, prototypes or innovative systems, the complexity assessment is generally not objective. The complexity apportionment techniques are combined with the DEMATEL procedure to account also for the interactions between subsystems. In the proposed allocation method, only the definition of complexity and the characterization of the effect between subsystems in the DEMATEL procedure are specific for particle accelerator systems. The definition of complexity can be easily adapted by considering additional factors that affect the availability of the system under study. This is, the influential factors can be considered depending on the application and information available. Moreover, for less complex systems, the influential factors might be exactly measurable making the availability allocation less subjective. Likewise, in the DEMATEL procedure, the effect between subsystems can be expressed in terms of other relevant aspect affecting the availability of the system. In many industrial fields, requirements are often set in terms of reliability. The proposed complexity criteria and assessment method can be also used to allocate reliability requirements based on complexity, by considering the final reliability goal instead of the availability goal.

This thesis aimed at providing a general and common basis for the modelling and simulation of availability models of high-energy particle accelerators, but could be applicable to any other field. The step-wise methodology, that ensures the completeness and consistency of availability models, is easily adaptable to specific requirements of any availability or reliability study. Furthermore, the Common Input Format Framework although it was defined as a general modelling language for particle accelerators, can be easily extended to include additional features specific to the application domain.

Although failure catalogues are available for reliability studies of military systems, this is not the case for other applications. The lack of reliable failure data is also a limitation of availability models in other fields. The advantages of systematic and reliable procedures to track machine failure and operation data are many. First, the stored data serves as input for availability models. Second, the tracking system is crucial to understand the actual operation of the machine and its evolution over time. And finally, from the subsequent analysis of the stored failure data, one can evaluate the performance of the machine and identify needs for improvements. Evaluating the performance of the subsystems by comparing their availability, however, might not be fair, since some subsystems might be more complex than others and thus, their availability performance potential might be limited. Another option is to compare their performance with similar reference systems. When the system under study is new or poorly used in other fields, this references might be unavailable. The performance evaluation procedure proposed in this thesis provides an excellent tool to overcome this limitation. In the proposed method the performance of a subsystem is evaluated by comparing its observed availability with the availability allocated according to complexity criteria.

For all types of availability-critical systems, the ultimate goal of availability studies is to boost machine performance to its limits. To this end and also as the second way to overcome the lack of reliable failure data for availability models, Availability Differential Importance Measures (DIM) have been introduced. The proposed applications of Differential Importance Measures demonstrated to be an excellent tool for the identification of critical components and failures that compromise significantly the optimal performance of the machine. Firstly, Importance Measures are presented as a basis for sensitivity analysis of availability models. Differential Importance Measures have been defined based on the availability parameters. However, they could also be defined based on any other parameter as long as the availability function of the system can be defined as a function of those. DIM is a first order sensitivity measure that determines the impact of uncertainties in the input parameters on the simulation results and identifies the component parameters with greatest impact on machine performance. Hence, improvement of these parameters would lead to the best improvement on the overall system

availability. The ranking produced by the second order DIM instead considers the interactions of coupled changes to system design and ranks the pair of components or availability parameters with greatest impact on machine availability. This means that, while a simultaneous upgrade of such pair of components leads to the greatest overall improvement, a simultaneous failure of those could significantly compromise machine performance. Thus, dedicated studies should be performed to investigate if these pairs of components could fail simultaneously due to common causes and if so, implement preventive measures. In the second order DIM the effect of simultaneous improvements is often hidden by the sum of individual improvements. The second order derivatives should be examined to get a better insight in the effects of those simultaneous changes. One of the disadvantages of the second order DIM is that the amount of values to be computed and analyzed increases with the number of components of the system. For example, for a system of 8 components, 136 second order DIM values with respect to failure and repair rate need to be computed. The total order DIM combines in a unique measure the information obtained by the differential importance measures of any order. The limitation of total order DIM is that it tends to the DIM values when the considered availability changes are small. Often bigger availability changes cannot be considered due to the intrinsically high availability of the components. A criticism of importance measures in its present form is that it ignores maintenance strategies. Often, when permitted by component redundancy, actual repair is deferred until the next planned maintenance period. Hence, the effective repair time of such a component is increased and the component will remain in a failed state until the next maintenance period, decreasing its experienced availability. To take periodic maintenance strategies into account, one could increase the repair time of these components. A more general solution would be to include relevant parameters, such as the planned maintenance frequency, in the availability equations of the system.

Finally, the availability optimization strategy based on Importance Measures, that is used to prioritize actions with higher improvement potential at lower cost, is proposed. For a given investment, the improvement of components with smaller overall impact in machine performance but greater availability increase

might be preferred. The described strategy demonstrated to be ideal for the identification of actions that lead to the best ratio of performance improvement over cost. Nevertheless, often cost function are not know or difficult to obtain even relative to a reference component. In this case, the optimization strategy could be defined based on the assessed complexity of the components.

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170	J. Gölz	Manschettendichtringe aus PTFE-Compounds, Funktionsmechanismus von PTFE-Manschettendichtungen und Entwicklung von Rückförderstrukturen für beidseitig drehende Wellen
171	J. Kümmel	Schmutzabdichtung mittels Fettgefüllter Berührungsfreier Wellendichtungen
172	S. Bader	Gehäusedichtungen unter korrosiver Last
173	J. Juskowiak	Beanspruchungsgerechte Bestimmung des Weibull-Formparameters für Zuverlässigkeitsprognosen
174	F. Jakob	Nutzung von Vorkenntnissen und Raffungsmodellen für die Zuverlässigkeitsbestimmung
175	N. P. Tonius	Klauenschaltelemente in Stufenautomatgetrieben
176	V. Schweizer	Berücksichtigung und Bewertung streuender Einflussgrößen in der Zuverlässigkeitssimulation
177	F. Bosch	Abdichtung trockener Stäube mit fettgefüllten berührungsfreien Wellendichtungen
178	M. Botzler	Präventive Diagnose abnutzungsabhängiger Komponentenausfälle
179	C. Fehrenbacher	Förderverhalten im Dichtsystem Radial-Wellendichtung

Nr.	Verfasser	Titel
180	B. Heumesser	Optimierung des Klapper- und Rasselgeräuschverhaltens bei Doppelkupplungsgetrieben
181	A. Eipper	Einfluss transienter Betriebsbedingungen auf den RWDR im System Radial-Wellendichtung
182	Alexander Buck	Einfluss der Oberflächenrauheit auf den Verschleiß an Hydraulikstangendichtungen
183	Andrea Buck	Simulation und Optimierung der Instandhaltung unter Berücksichtigung sich ändernder Belastungen mittels Petrinetzen
184	St. Kemmler	Integrale Methodik zur Entwicklung von robusten, zuverlässigen Produkten
185	T. Rieker	Modellierung der Zuverlässigkeit technischer Systeme mit stochastischen Netzverfahren
186	M. Bartholdt	Kunden- und kostenorientierte Zuverlässigkeitszielermittlung
187	V.Warth	Systematische Synthese und Bewertung von Stufenlosgetrieben
188	N. Nowizki	Funktionale Sicherheit und Zuverlässigkeit in frühen Phasen der Produktentwicklung
189	F. Schiefer	Additive Fertigung von Radial-Wellendichtringen
190	M. Dazer	Zuverlässigkeitstestplanung mit Berücksichtigung von Vorwissen aus stochastischen Lebensdauerberechnungen
191	J. Totz	Funktionsuntersuchungen an Dichtsystemen mit weichgeschliffenen Dichtungsgegenlaufflächen und Radial-Wellendichtringen aus NBR
192	M. Stoll	Entwicklung und Funktionsanalyse rückenstrukturierter Manschettendichtringe aus PTFE-Compound
193	N. Dakov	Elastohydrodynamische Simulation von Wellendichtungen am Beispiel der PTFE-Manschettendichtung mit Rückförderstrukturen
194	Z. Beslic	Modellierung der Schadensdegradation Zahnradgrübchen bei Fahrzeuggetrieben
195	St. Jetter	Zuverlässigkeitsprognose mechanischer Komponenten auf Basis simulierter Betriebsfestigkeit