We would like to thank the referees for their kind and thoughtful comments and ideas, which have helped us to significantly improve our manuscript.

Below we present the changes to the manuscript as suggested by the referees (Annotated yellow are the referee $2 comments).

List of changes in the submitted PDF file

- Line 22: Sentence modified

What is CAT named after? Please, consider writing its full name the first time you mention it in the manuscript. Acronyms should be extended with their full names the first time they are cited in the body of the text.

- Lines 84-85: Sentence modified

Note that this sentence seems to be either incomplete or to have extra words. Please check and correct it

- Lines 102-104: Paragraph modified

Here a very long sentence is written. The manuscript will benefit from an easier-to-understand version of the sentence, perhaps splitting it into 2-3 sentences in order to help the reader understand it

- Line 107: Word corrected

Missing "n" in word "many".

- Line 130: Sentence modified

I would recommend to mention the full name of JAEA, RIST and KEK before using these acronyms.

- Line 199: Sentence modified

Please write inside the round brackets only the year.

- Lines 240-244: Paragraph rewritten

I find advisable to slightly extend this part of the manuscript.

- Lines 252-253: Sentence rewritten

Please check the grammar tense in this sentence.

Best regards

Overview of Main Radiation Transport Codes

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Abstract. Accurate predictions of expected radiation dose levels in Mars are often provided thanks to specific radiation transport codes, which have been adapted to space conditions. Unsurprisingly, several of the main space agencies and institutions involved in space research and technology tend to work with their self-developed radiation code. We present these codes that are related to the simulation of the radiation on different scenarios on Mars surface. All of them have similar fields of applications but differ in several aspects, including energy range and types of projectiles considered, as well as the models of nuclear reactions considered.

1 Introduction

The manned exploration and habitation of Mars is of great importance to mankind. While Earth's magnetic field and atmosphere protect us from cosmic radiation, Mars has no such a protective magnetosphere. Furthermore, regarding its thin atmosphere, the instrumentation and particularly electronics -and astronauts, eventually- are exposed to considerably harmful levels of radiation. Over the course of about 18 months, the Mars Odyssey probe detected ongoing radiation levels which are 2.5 times higher than what astronauts experience on the International Space Station. Moreover, The Mars rover Curiosity has allowed us to finally calculate an average dose over the 180-day journey. It is the equivalent of 24 CAT scans. A more detailed description of Mars Space radiation environment on Mars will be a critical consideration for everything in the astronauts' daily lives. We present the codes that are most commonly used and we present the main differences between them. Finally, we propose a cloud computing solution with a clear advantage in this area. Cloud computing permits to adapt the infrastructure to the specific needs of each task to improve efficiency which is of great importance in an environment with limitation in power supply.

2 Radiation Codes

2.1 HZETRN2015 (NASA)

HZETRN (High charge(Z) and Energy TRaNsport) is a deterministic code [Wilson et al., 2015a; 2015b; 2016] developed by NASA that has been used for calculating three-dimensional transport in user-defined combinatorial or ray-trace geometry. It is widely considered to provide analysis of the radiation levels, being able to consider a wide range of shielding scenarios. That means, for instance, taking into account relevant issues such as the solar particle events (SPE) or the galactic cosmic rays (GCR), as well as considering low earth orbit (LEO) environments. In more detail, this is actually not only a code, but rather a suite of codes. With them, the Boltzmann transport equation is solved (numerically), just by using the appropriate approximations, which in this case are the continuous slowing down and straight-ahead ones. HZETRN is experiencing a permanent evolution for nearly 30 years, being its initial version based on a NASA Langley Research Center team headed by John W. Wilson. In addition, the extension of HZETRN to include pions, muons, electrons, positrons, and gammas was developed and used [1].

Previous work has validated HZETRN for secondary particle flux in Earth's atmosphere [1]. In addition, Slaba et. al. [2] compared HZETRN on a minute-by-minute basis to International Space Station dosimeter measurements and found good agreement. HZETRN has also been extensively benchmarked against fully three-dimensional Monte Carlo codes for slab geometries [3-4], with results showing that HZETRN generally supports the Monte Carlo codes results, to the extent that they globally agree with each other.

2.2 OLTARIS

OLTARIS (On-Line Tool for the Assessment of Radiation In Space) is a space radiation analysis tool available on the World Wide Web [https://oltaris.nasa.gov/]. It can be used to study the effects of space radiation for various spacecraft and mission scenarios involving humans and electronics. The transport is based on the HZETRN transport code and the input nuclear physics model is NUCFRG (Wilson et al., 1995) [36].

2.3 SHIELD (ROSCOSMOS)

SHIELD is a Monte Carlo code developed by ROSCOSMOS, the Russian State corporation in charge of space flights and cosmonautics programs. The SHIELD transport code [5] has been used for several space applications [6-13]. SHIELD code is tuned for space shielding and environment applications and can be used for radiation effect simulation at long-term spacecraft missions.

The main applications of this code are:

- Study of the "spallation" process in heavy targets under proton beam irradiation, including generation of neutrons, energy deposition and formation of nuclides in the target.
- Optimization of the targets of pulsed neutron sources on neutron yield.
- Study of direct transmutation of fission products by the proton beam.

- Simulation of heavy ion beam interaction with extended targets. Applications to proton and ion beam therapy.
- Optimization of the pion-producing targets.
- Study of primary radiation damage of structure materials under primary proton beam and secondary radiations.
- Calculations of radiation fluxes behind the shielding from galactic and solar cosmic rays. Modelling of secondary neutron fields inside a space orbital station.
- Study of accumulation of cosmogenic isotopes in iron meteorites.
- Study of background conditions in underground experimental halls, given by hadron cascades in the rock.
- Fluctuations of neutron yield in a hadron calorimeter under a single beam of particles.
- Spreading of neutrons in the neutron moderation spectrometer ("leaden cube").

2.4 GEANT / PLANETOCOSMICS (ESA)

GEANT4 [14,15] is again not only a single radiation code, but rather than that it can be considered a toolkit which can calculate how the different particles are transported through the matter. It is also based on Monte-Carlo methods. On the other hand, we have PLANETOCOSMICS (http://cosray.unibe.ch/laurent/planetocosmics/). It is an application linked to GEANT4, which is able to provide a description of several interesting features of a planetary body, including its geometric figures, the soil, the atmosphere or the magnetosphere. In particular, it works for the planet we are interested in: Mars. PLANETOCOSMICS is particularly useful because of two aspects: 1) it serves to calculate the transport of any arbitrary primary particles which can be found either in or through these planetary environments and 2) it can be employed to obtain an estimation of the number of secondary particles generated at a specific time. Besides, using GEANT4, we can obtain a great number of the so-called physics lists which describe the particles-matter interactions.

PLANETOCOSMICS [16] can be considered as well as a framework for these simulations, being based on Geant4, and capable to compute physical interactions between GCR and planets like Mercury, the Earth or Mars. The group of physical interactions typically included are the electromagnetic and hadronic ones. It is possible to consider for each planetary body its atmosphere, its soil and the presence (or absence) of a magnetic field, Regarding the latter, different magnetic field models are available for each planet, and the same happens for the and atmospheric models. The code has been developed so that including in the future new models recently developed or even other planets shall not be a big issue.

There are many applications of this code, being some of the main ones as follows:

- Computing the particles flux which result from GCR-planet interaction. Notice that this is done at user defined altitudes, atmospheric depths and in the soil.
- Computing the energy which is deposited by GCR’s showers in the planet atmosphere and in the soil.
- Studying the quasi-trapped particle population.
- Simulating using the appropriate computational power to learn about the propagation of charged particles in the planet magnetosphere.
- Computing the cut-off rigidity. It is often done considering the position and the direction of incidence.

- Visualizing the magnetic field lines. Linked to this point, both the primary and secondary particles trajectories in the planet environment can be seen.

2.5 FLUKA (CERN)

FLUKA [17-18] is, once more, a multiparticle Monte-Carlo transport code. Similarly, it is able to deal with electromagnetic and hadronic showers up to very high energies (100 TeV). Therefore, it is well-known when it comes to radioprotection and detector simulation studies.

FLUKA initial version can be found more than half a century ago, in 1964. At that time, CERN used to require Monte-Carlo codes for high energy beams, in order to apply them to many accelerator-related tasks Johannes Ranft began developing such codes for high energy beams. Its name came around 1970, when first attempts to predict calorimeter fluctuations were done on an event-by-event basis. FLUKA is actually named after the cascades which originate in this context (FLUKA = FLUctuating KAskades). The present code [19-21] is basically the heir of the one initiated in 1990 in order to develop an adequate tool which could work for the LHC. This code is nowadays very popular at may laboratories, including naturally CERN. Fact is that it is the tool currently used for nearly all the radiation calculations and the neutrino beam studies developed by CERN.

A key aspect of FLUKA is its ability to represent the transport and interactions with all the elementary hadrons, with different ions (both heavy and light), and with photons and electrons on a wide energy range, extending up to 104 TeV for all particles, and down to thermal energies for neutrons [22-24]. Due to the built-in capabilities the code has, the particle fluences, yields, and energy deposition can be scored over arbitrary 3-dimensional meshes. It can be done both on an event-by-event basis and averaged over a big number of records. Moreover, benchmarking FLUKA has been widely performed, regarding the available accelerator and GCR experimental data. The beam energies taken into account range from a few MeV (lower limit) to GCR energies (upper limit). Considering an arbitrary solar activity modulation parameter, the spectra can be modulated within FLUKA. If past dates are the target, we can just use the current solar activity obtained through the ground-based neutron counters measurements.

Regarding the types of interactions, the modern version of FLUKA can be used to treat all the components of radiation fields within energy ranges of approximately:

- 0-100 TeV for hadron-hadron and hadron-nucleus interactions
- 1 keV-100 TeV in the case of electromagnetic interactions
- 0-20 MeV for charged particle transport - ionization energy loss Neutron multigroup transport interactions

Besides, analogue or biased calculations are also possible. Finally, the range 0-10000 TeV/n for nucleus-nucleus and hadron-nucleus interactions is still under development.

2.6 PHITS

Particle and Heavy Ion Transport code System (PHITS) is a general purpose Monte-Carlo particle transport simulation code developed and verified under collaboration between JAEA, RIST, KEK and several other institutes [25,26]. It can deal with the transport of all particles over wide energy ranges, using several nuclear reaction models and nuclear data libraries. PHITS is used in the fields of accelerator technology, radiotherapy, space radiation, and in many other fields which are related to particle and heavy ion transport phenomena.

When simulating the transport of charged particles and heavy ions, the knowledge of the magnetic field is sometimes necessary to estimate beam loss, heat deposition in the magnet, and beam spread. PHITS can provide arbitrary magnetic fields in any region of the setup geometry. It is possible to simulate with PHITS the trajectories of charged particles in a field, and at the same time the collisions and ionization process they experience.

2.7 HETC-HEDS

The High Energy Transport Code - Human Exploration and Development of Space (HETC-HEDS) computer code is another Monte-Carlo based method. It is specifically designed to provide solutions to radiation problems [27,28], mainly the ones which involve the secondary particle fields typically produced by the space radiation interaction with the different types of shielding and equipment involved in the different missions. HETC-HEDS is a 3-D generalized radiation transport code, which is able to analyse and handle with the radiation fields that might affect the critical human body organs, in the context of a potential crewed spaceflight. Therefore, we refer to the tissues like the ones which compose the central nervous system, or the bone marrow. It is possible to apply this code to a wide range of particle species and energies, which is very helpful. Among other elements, HETC-HEDS contains a heavy ion collision event generator, which can track nuclear interactions and perform data analysis (statistics). In addition, it is capable to simulate the particle interactions, a crucial issue to solve this type of problems. To do so, it uses a pseudo-random number generator, and together with the appropriate physics characterization, it is possible to record the trajectories followed by both the primary and the secondary particles involved in the nuclear collision of GCR and solar event particles. The typical application is to estimate how would be the interaction with matter, including the shielding material the equipment from crewed spaceflights may have, biological organisms (for instance, for astronauts), and the electronic equipment a mission needs to fly with. This code considers nearly all the particles which are typically required for space radiation calculations. For example, HETC - HEDS takes into account the interactions of protons, neutrons, π+, π-, μ+, μ-, light ions and heavy ions. In the model, an arbitrary position, angle and energy value are assigned throughout a spatial boundary of interest. This Monte-Carlo code tracks each and every particle in a cascade until one of the following issues undergoes: 1) a nuclear collision, 2) absorption, 3) decay/escape from the spatial boundary, or 4) elimination, as a result of crossing a domain variable cutoff. To do this, it is necessary to focus on the nuclear reactions and processes occurring. In this case, they are accounted with physical models, so that the main issues (energy loss, range straggling, Coulomb scattering, etc.) are properly handled. Naturally, the energy and nucleon conservation principles should not be violated when the collisions (elastic and nonelastic) are computed. A more detailed explanation of HETC-HEDS inner workings and benchmarking is given in the following references: Townsend et al. [2005], Miller and Townsend [2004, 2005], Charara et al. [2008], and Heinbockel et al. [2011a, 2011b]. HETC-HEDS, however, (as with HZETRN) this code does not follow the liberated electrons (delta rays) produced by Coulomb interactions. Thus, the code calculates energy lost using the difference between the particle energies entering and exiting a target component (true Linear Energy Transfer) but not the actual energy deposited.

2.8 COMIMART-MC

The COMIMART-MC (COmplutense and Michigan Mars Radiative Transfer model – Monte Carlo) is a Monte Carlo code to calculate solar irradiance that reaches the surface of Mars in the spectral range from the ultraviolet (UV) to the near infrared (NIR) is developed and validated under different scenarios [29-31]. The model includes up-to-date wavelength-dependent radiative properties of dust, water, ice clouds, and gas molecules. It enables the characterization of the radiative environment in different spectral regions under a wide variety of conditions.

Actually, it is worth exploring the role of dust in Mars atmosphere [31], as it is a quite relevant aspect to consider when trying to reach the goal of improving these radiation transport codes. This element may play a very important role in certain circumstances, particularly because a dust storm may be so intense that it would globally affect the whole planet. In these cases, the effective radius of the dust particles needs to be very well characterized, in order to provide an accurate estimation of several atmospheric properties, including the opacity, scattering and albedo, among others.

In this model, the dust effective radii are employed, so that the radiative properties are properly characterized. Just by using the refractive indexes for different particle sizes and shapes, extinction efficiencies, single-scattering, albedos and scattering phase functions are provided. The main assumption consists on accepting that all the particles have a cylindric shape, being height and diameter of equal magnitude, as done by Wolff et al. (2009) and Wolff et al. (2010) [37, 38].

3 Comparison of transport codes

As earlier mentioned, most of the codes considered by agencies and organizations are based on Monte Carlo codes. A non-exhaustive list of these Monte Carlo codes is:

- ETRAN (Berger, Seltzer; NIST 1978)
- EGS4 (Nelson, Hirayama, Rogers; SLAC 1985) www.slac.stanford.edu/egs
- EGS5 (Hirayama et al; KEK-SLAC 2005) rcwww.kek.jp/research/egs/egs5.html
- EGSnrc (Kawrakow and Rogers; NRCC 2000) www.irs.inms.nrc.ca/inms/irs/irs.html
- Penelope (Salvat et al; U. Barcelona 1999) www.nea.fr/lists/penelope.html

- MARS (James and Mokhov; FNAL) www-ap.fnal.gov/MARS
- MCNPX/MCNP5 (LANL 1990) mcnpx.lanl.gov.

As there have been several studies comparing transport codes one with each other [32-34], it is worth focusing on the wide range of the energy spectrum analysed. The largest differences from one transport code to another occur below the several hundred of MeV region. This may be due to the fact that every code considers a different nuclear model. At the same time, we organized the structure for large and massive simulations in the framework of cloud computing [35], which is partly explained in the following section.

On the other hand, differences are found to be significantly more pronounced for thin shielding conditions, because in that case the transport processes play a not such a relevant role. As discussed by (Matthia et al., 2016), a maximum 20% difference from one to another code is expected. In Figure 1 we depict spectra on the Martian surface by the MSL-RAD measured between (2012-2013) in comparison with calculations from different simulation models for the energy range between 10 MeV/n and 20 GeV/n.

According to the methods considered, radiation transport codes can be classified into deterministic methods (HZETRN) and Monte-Carlo methods (SHIELD, GEANT4, FLUKA, PHITS, HETC-HEDS). Let us analyse them with a little more detail. Deterministic methods are computationally less demanding. The main disadvantage they have is that they can only be used in cases where transport equations can be solved analytically. Thus, the method is accurate for simple shielding geometries. Furthermore, deterministic codes suffer from systematic errors due to the need for phase space discretization. Monte Carlo methods, on the other hand, are typically more difficult to implement, usually require more processing power and unfortunately cannot produce accurate results in deep radiation penetration problems. Nevertheless, they can simulate complex shielding geometries [39], which can be an advantage in certain situations. Globally, we can consider that deterministic and Monte-Carlo methods complement each other and provide accurate results in space related applications. On the one hand, deterministic methods can be used when working under limited computational resources (i.e. Mars rover, orbiters, etc.) or on the early phase of a space shielding design, where the geometric requirements are still unknown. On the other hand, Monte-Carlo methods perform better in the latest shielding design stage, in order to obtain fine-tuning. In Table 3.1 we present the main advantages and disadvantages of both Deterministic and Monte-Carlo methods.

	Deterministic methods	**Monte-Carlo methods**
Advantages	Relatively fast to implement.	Can simulate complex environments.
Disadvantages	1.Systematic errors 2.Cannot handle complex geometries	1.Difficult to implement. 2.Computationally expensive. 3. Not suitable for deep radiation penetration problems

Table 3.1: Deterministic and Monte-Carlo methods comparison

4 A Serverless Computing Approach

The execution of the tasks necessary to process the radiation data and to perform the calculations of the models requires a high computational processing capacity. A highly scalable system is necessary for the execution of distributed processes to reduce calculation time and in order to obtain results with high accuracy.

Cloud computing is based on the use of different computing resources (CPU, memory, disk, network, etc.) that can be scaled on demand and used together to execute different tasks [40]. This methodology provides a clear advantage in this area thanks to its dynamism when it comes to managing computing resources. Its elasticity permits to adapt the infrastructure to the specific needs of each task to improve efficiency [41].

Currently, Cloud computing is very advanced and widespread, and there are many Cloud infrastructure providers. Among others Amazon Web Services, Google Cloud, IBM Softlayer and Microsoft Azure.

In addition, new Cloud computing paradigms have been developed in recent years to adapt to the high demand for new technologies. One of them is Serverless computing [42], a Function-as-a-Service computing model in which infrastructure management is completely performed by Cloud providers, so that the only element that is required to execute processing is the source code of the tasks to be executed [43].

Serverless computing is very interesting for the execution of distributed tasks that are necessary for the processing of radiation data. There have been many studies of the advantages of Serverless computing for other research areas in the literature [44-46]. The use of Serverless technology can be proven useful in many aspects.

Simplification of the configuration by not having to manage complex infrastructure [47]. Dynamic and elastic scaling is assured and adapts according to the capabilities required by each of the tasks at all times [48].

Reduced execution costs. It is no longer necessary to hire infrastructure, and the cost is limited only to the execution time of each process [49].

As an example, the Amazon AWS Cloud infrastructure can be used to execute a generic code that needs some input data and produces data results to be stored. The architecture is based on two Amazon AWS services: AWS Lambda, the Serverless computing platform responsible for processing the code and Amazon S3, the Object Storage service where the input data are uploaded, and the result data is saved.

5 Conclusions and prospects

We have shown that there are several radiative transfer codes currently employed by the different space agencies and institutions, mainly developed by themselves, respectively. These codes are useful for specific applications in each case, as they can simulate the radiation at Mars surface considering a variety of scenarios. This code taxonomy proves that all of them have can be considered in similar fields, and therefore their application in most of the conditions is possible. However, as they differ in key aspects, like the energy range, the types of projectiles considered, or the models of nuclear reactions considered, all of them have a specific situation in which they are the most appropriate ones.

A deep comparison on the computation time required by each of the codes, as well as considering cloud computing or traditional computing, is suggested as a research line to follow. With such studies the performance of the codes and techniques can be evaluated and therefore optimization on the available resources can be reached.

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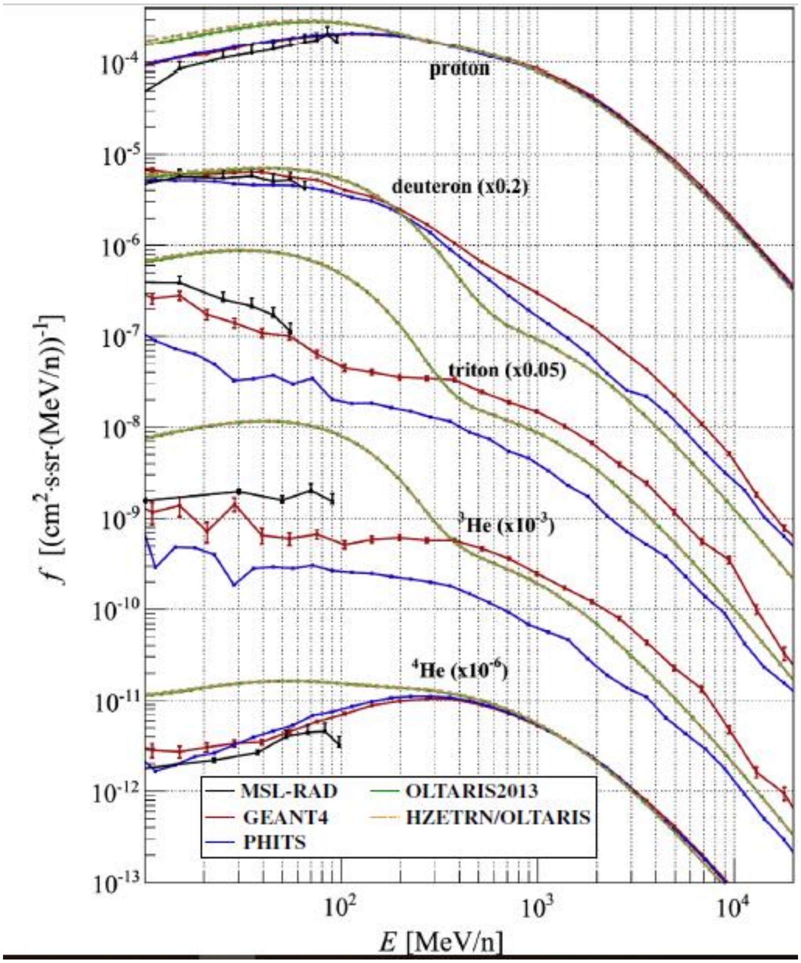

Figure 1: Spectra on the Martian surface measured between (2012-2013) by MSL-RAD (Ehresmann et al. 2014) and calculated for the same period by different simulation tools for energy range from 10 MeV/n to 20 GeV/n.

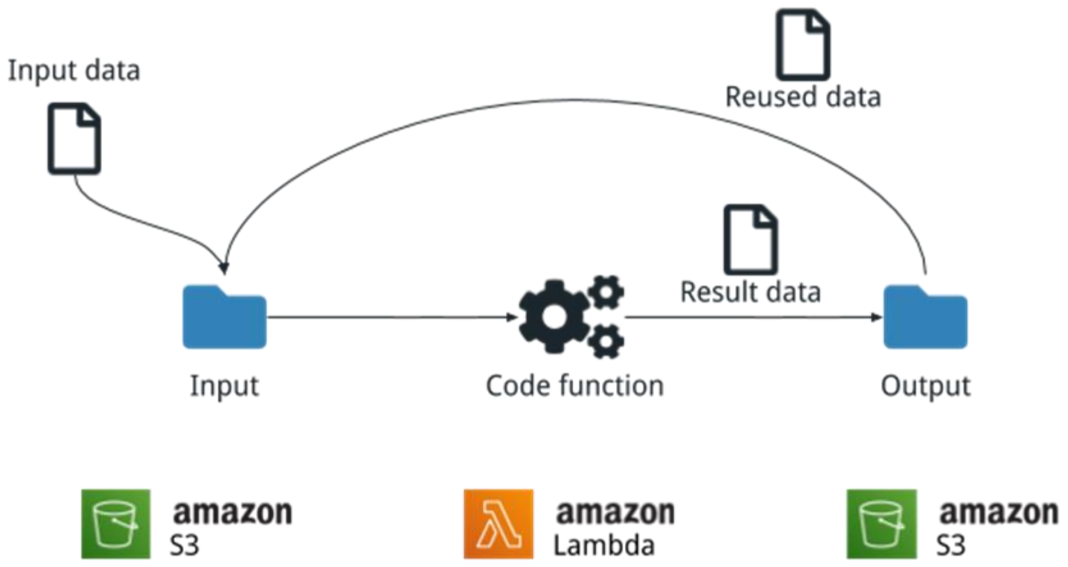

Figure 2: Generic serverless processing architecture using Amazon Lambda.