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Growth Trajectories and Social Returns in Accelerator Technology Evolution

Pranati Atta
School of Liberal Arts and Humanities, Woxsen University, Hyderabad, Telangana, 502345.
pranati.atta_2025@woxsen.edu.in

Cui Feng
Department of Management Science, School of Management, University of Science and Technology of China, Anhui Province, P.R.China.
frng158@ustc.edu.cn

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Corresponding author(s):
Pranati Atta, School of Liberal Arts and Humanities, Woxsen University, Hyderabad, Telangana, 502345.
Email: pranati.atta_2025@woxsen.edu.in

Abstract – This research paper seeks to predict the future developments and trends of accelerator technologies in science, medicine, and industry from the year 1968 to 2050 based on historical growth trends and social cost-benefit analysis. The study starts with gathering and cleaning international dataset on the overall number of accelerators and using the method of cubic spline interpolation to work with the missing values. The Compound Annual Growth Rate (CAGR) for each sector is computed to show different growth trends; a linear growth in science sector while the medicine and industry sectors depict nonlinear growth. Logistic functionality is employed to fit the growth of the industry and simulate future growth based on different levels of saturation. The findings suggest that the accelerator industry may be nearing saturation in the next 15-30 years with the best-fit model estimating that 60% of the market demand was met by 2014. A social Cost-Benefit Analysis (CBA), based upon two case scenarios of the National Centre of Oncological Hadrontherapy (CNAO) and the Large Hadron Collider (LHC), shows that there are important social benefits, especially in terms of technological externalities, human capital formation, and health impacts. Monte Carlo simulations also illustrate the range of possible outcomes, adding to the argument that technological advancement plays a crucial role in identifying an industry's future directions.

Keywords – Social Cost-Benefit Analysis, Accelerator Technologies, Compound Annual Growth Rate, Mean Absolute Prediction Error, Plasma Wakefield Acceleration.

I. INTRODUCTION

The technology responsible for particle accelerators has been advancing for almost a century since its initial tests conducted at the Cavendish Laboratory in Cambridge [1]. There are around 30,000 operational particle accelerators worldwide. The majority of these devices use low-energy beams, typically less than 1 MeV, and are mostly employed in industrial applications [2]. There are somewhat more than a hundred high energy accelerators for research, with a smaller number dedicated to photon science, most of which have been recently built. In particle physics, it becomes mandatory to bring the energy and the intensity of the beams up to the maximum permissible limits.

Although current research is aimed towards creating improved particle colliders including the International Linear Collider, and the Future Circular Collider, there are investigations for new ideas for compact and cheaper devices. An application of PWFA is illustrated through an example and presently under experiment in many of the leading laboratories. The basic concept of the PWFA is that of the propagation of very high-energy charged particles through a quiescent plasma [3]. Plasma may be produced through laser ionization where a laser beam is used to ionize a gas [4] or relativistic field ionization induced by the Coulomb bunch [5]. The second approach allows for generating a dense (1016–1017 cm^{-3}) plasmas which are useful for the PWFA. Furthermore, this technique cuts the experimental configuration process by half. During single-bunch tests using ultrashort electron bunches, it has been seen that the leading part of the bunch initiates the formation

of plasma as well as propels the wake [6]. This wake generates a longitudinal field with a high gradient, which subsequently propels particles located at the rear of the group. The system functions as a transformer, efficiently transferring particle energy in the main body of the group to those in the rear, through the plasma wake. Its physics remains unaltered when there are two different bunches instead of a solitary bunch; the energy from the first bunch is moved to a subsequent witness bunch.
Regardless, this technical breakthrough would likely include a significant and innovative advancement, often resulting in the spread of its impacts to many areas of application [7, 8, 9]. Researchers acknowledge that radical innovation and incremental innovation are distinct within an organization, despite variations in their definitions [10, 11, 12, 13]. They also recognize that radical innovation is crucial for the long-term performance of organizations. However, studies [14, 15, 16] have shown that obtaining backing for innovative initiatives at big corporations may be challenging, as the internal cultures and pressures often steer efforts towards less risky, short-term, and incremental undertakings. Curiously, our knowledge on effectively managing the product development process is much limited in the radical context compared to the incremental context. Extensive research exists on the cross-functional and integrated mechanism to novel product development [17, 18, 19]. Design-For-Manufacturability, Stage Gate Model, and Concurrent engineering [20] all have the objective of integrating the functional areas at an early stage and with regularity in the process of designing a novel product.

The research questions for this study are as follows:

- "What methods can we use to quantify the advantages of an unpredictable innovations in acceleration technologies?"
- "What specific community shareholders are responsible for this type of innovation?"

The need to conduct this research stems from the growing application of accelerator technologies in various fields across the globe in science, health, and commerce among others. Nevertheless, there is very limited information available on the sustainable growth pattern and the socio-economic impact of these technologies. Thus, the objective of this study is to predict the future trends of the accelerator industry by measuring the historical trend and conducting the social cost-benefit analysis which will be helpful for the policymakers, investors and researchers to make right decisions for the further advancement and utilization of these crucial technologies. The structure of the paper is as follows: Section II describes the methodology employed when composing this research paper. The methodology integrates data collection and preprocessing, growth rate estimation and logistic function modelling, forecasting future trajectories, and social CBA and sensitivity analysis. The findings obtained in this research, which includes accelerator industry trajectory, and social CBA have been discussed in Sections III and IV. Lastly, Section V provides detailed concluding remarks this research paper.

II. METHODOLOGY

Data Collection and Preprocessing

The initial stage of analytical processing of the data is to obtain comprehensive information on the total number of accelerators in various fields of application, science, medicine, and industry, for the period from 1968 to 2014. The information used in this paper were mainly collected from [21], which give the total number of accelerators in the world. To complement this data, we incorporated other information from the industry reports, academic papers, and databases to make it as accurate and comprehensive as possible. The dataset was then preprocessed to standardize the values of each of the metrics over the different years and fitted for missing values using the cubic spline technique to ensure that the metrics remained in the form of a time series. The total number of accelerators $N(t)$ at any time t is considered in the dependence on the year, and the number of accelerators in the field of science $(N_s(t))$, medicine $(N_m(t))$, and industry $(N_i(t))$. In **Fig 1**, the application fields are depicted, and one can also see that the growth rates of each sector are not equal.

Growth Rate Estimation and Logistic Function Modelling

The Compound Annual Growth Rate (CAGR) was used to calculate the growth rates of accelerators in each field to estimate their mean annual growth rates over the given period. The CAGR can be described using Eq. (1).

$$CAGR = \left(\frac{N(t_{end})}{N(t_{start})}\right)^{\frac{1}{t_{end}-t_{start}}} - 1 \quad (1)$$

where $N(t_{start})$ and $N(t_{end})$ are the total number of accelerators at the beginning and at the end of the period under consideration. This formula was used individually on the data of science, medicine and industry to get the growth rates in the respective sectors. Since the accelerator industry development process has an S-shape, with steep increases in the rates of growth in the medicine and industry fields, we used the logistic function to address the S-shaped time inclination in the overall number of accelerators. Logistic growth model is defined by Eq. (2).

$$N(t) = \frac{K}{1+e^{-r(t-t_0)}} \quad (2)$$

where $N(t)$ is the cumulative amount of the accelerator at t, K refers to the carrying capacity or the ultimate limit of the curve which is the market saturation level, r is the intrinsic growth rate, and t_0 is the time at which the growth rate starts to decline. Accordingly, we have used the least squares nonlinear regression which provided the best fit to the observed data and minimized the difference between the observed and the predicted $N(t)$. Logistic function was adopted because it can describe the slowing down of the growth as the industry gets closer to the level of saturation, and this is observed in the diffusion of technologies.

Forecasting Future Trajectories

To make a prognosis of the further development of the accelerator industry up to 2050, we expanded the logistic model by means of different scenarios depending on the assumed current saturation level S_0. The scenarios take into account deviates in the value of S_0 which reflects the share of potential total demand covered by 2014. The forecasts are obtained by applying the logistic equation (Eq. (2)) to subsequent time points, the following are some of the possibilities. The following trajectories depict the expected growth of accelerators based on each scenario and depict points where growth may decrease or increase due to advances in technology or the market reaching its pinnacle. The Mean Absolute Prediction Error (MAPE) was then computed using Eq. (3) to determine the fitness of the various models.

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{N(t)-\hat{N}(t)}{N(t)}\right| \quad (3)$$

where n is the number of observations, $N(t)$ is the actual number of accelerators and $\hat{N}(t)$ is its predicted values from the logistic model. In order to compare the models, the Mean Absolute Percentage Error (MAPE) was employed with the model that contained the smallest MAPE regarded as the most accurate for both in sample and out of sample forecasts.

Social CBA and Sensitivity Analysis

In order to measure the extent and value of social and economic effects of the accelerator sector, a Social Cost-Benefit Analysis (CBA) was done using the framework by [22]. Net Present Value (NPV) is used to estimate the value of the RI investments where Eq. (4) is employed.

$$NPV_{RI} = NPV_u + PVB_n \quad (4)$$

where NPV_u is the net present value of use-benefits, Benefits are the present value of users (PVB_u) and the present value of economic cost is ($PVEC$). PVB_n is the present value of non-use benefits and it comprises of the future values and the value of scientific discovery. The stochastically expanded model is arrived at using Eq. (5).

$$NPV_{RI} = \sum_{i=1}^{n} E[B_i(t) - E[C_i(t)] \quad (5)$$

where $B_i(t)$ and $C_i(t)$ represent benefits and costs of the accelerator projects at time t, and $E[\cdot]$ stands for the expectation of the probability distribution of the variable enclosed. Monte Carlo simulations were applied to assess the empirical cumulative distribution function of the NPV to identify the possible outcomes. The advantages were decomposed into several parts including scientific value, technological externalities, people capital development, cultural effects, and use value of research. The model was applied to two case studies: the National Centre for Oncological Hadrontherapy (CNAO) and CERN's Large Hadron Collider (LHC) in Italy. The results were displayed as the CDFs of the NPV to demonstrate the distribution of the outcomes as well as the proportion of the benefits of each type.

The sensitivity analysis was done in an attempt to assess the stability of the forecast and CBA results given different assumptions on the key parameters of the logistic model and the CBA framework. To analyze the future trends of the logistic model, we changed the parameters, which are the intrinsic growth rate r, the carrying capacity K, and the initial saturation level S_0. In the CBA, we altered the social discount rate, expected growth of benefits and probability distribution of costs and benefits. Thus, the sensitivity analysis showed the variability of the results and defined the most significant factors that affect the forecast and SROI. The conclusions highlight the need to take into account uncertainty and variability when making long-term forecasts of the industry's development and calculating economic indicators.

III. RESULTS

The Accelerator Industry Trajectory

Fig 1 displays the data from [23] on the total number of accelerators globally, categorized by their area of use. This is a first step towards predicting the future trends in the accelerator industry. The average annual growth rates for research, medicine, and industry are 1%, 9%, and 6% correspondingly, indicating significant heterogeneity across different areas. Accelerators in science have a growth mechanism that may be accurately modeled by a linear function. In contrast, the increased dynamics of accelerators in medicine and industry have a very nonlinear pattern, and shown by Eq. (6).

$$CAGR = \left(\frac{X_T}{X_0}\right)^{\frac{1}{T}} - 1 \quad (6)$$

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Fig 2 utilizes the logistic functionality to model the S-shaped temporal trend based on the information of the overall quantity of accelerators. It also predicts potential paths up to the year 2050. Instead of calculating the ceiling parameters, we have created 4 curves, which vary in their assumption about the unknown steady-state market size, represented by the upper asymptote of the logistic function. If the quantity of accelerators accessible in 2014 accounts for 60% of the total potential demand, then by 2046, the market could be able to meet 95% of the need. Alternatively, if the value in 2014 signifies 90% of the total potential demand, then by 2032, 95% of the need would be met. Based on visual examination, it seems that the sector will achieve maturity during the following fifteen to thirty years.

The Mean Absolute Prediction Error (MAPE) indicated in the caption of **Fig 2** suggests that the most accurate fit to the data is achieved by assuming that 60% of the demand was met in 2014. Remarkably, when it comes to measuring how well the model fits data that it hasn't been trained on, this particular parametrization performs better than models that rely on an exponential or linear trend function. Calculation on out-of-sample MAPE has been done using the latest observations from 2007 to 2014, and re-evaluating models without including these points of data. MAPE for the exponential, linear, and logistic trend models are 12%, 25%, and 16% respectively. Upon examining **Fig 2**, it is evident that there is a noticeable inflection points within the dynamics of the accelerators in the past few decades.

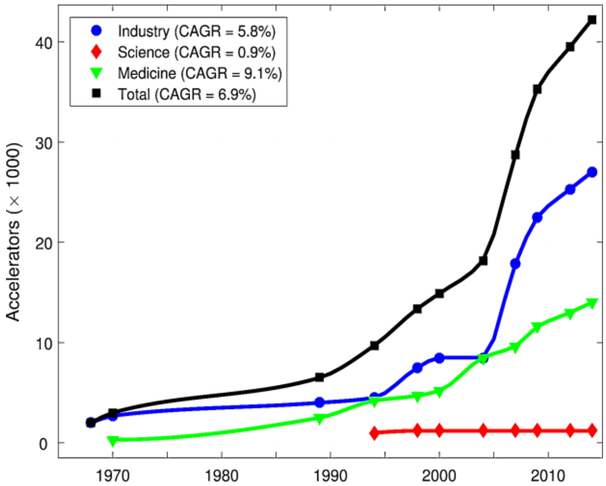

Fig 1. Total Number of Accelerators Worldwide From 1968 To 2014, Categorized by Their Area of Use

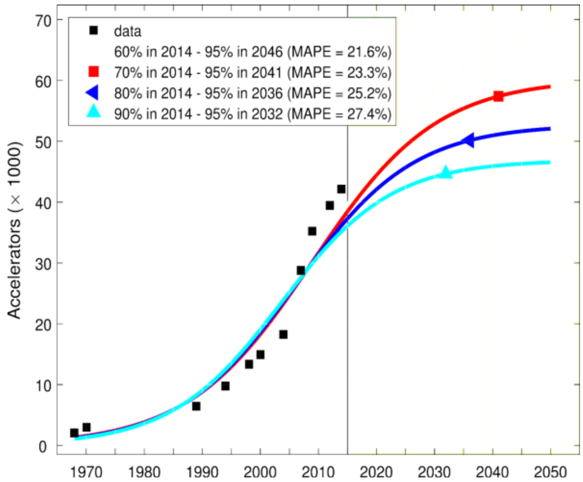

Fig 2. Quantity of Accelerators Worldwide, with Different Projections for The Time Between 2015 And 2050

Notes: The lines depict cubic spline interruption of given data, specifically for certain years indicated by symbols. Each graphical legend displays CAGR (Compound Annual Growth Rate) which is computed using Eq. (6). The lines in **Fig 1 reflect the estimated values obtained from non-linear regression analysis using logistic function, which considers the overall number of accelerators, as well as a constant term and a temporal trend. Legends show the percentage of total demand that is projected to be met in 2014 for each of the four lines, as well as the year in which this percentage is expected to reach 95%. The caption further displays MAPE computed over the time frame of 1968 to 2014. In-sample fitness is inversely proportionate to model MAPE and is represented using Eq. (7).

$$MAPE - 100 \times n^{-1} \sum_t^n \left| \left(\frac{x_t - \hat{x}_t}{x_t} \right) \right| \quad (7)$$

The variables n, $\hat{x}_t$, and x_t represent the number of observations in the sample, fitted values, and actual values correspondingly. The gray region represents the time period from 2015 to 2050, which is beyond the range of the sample.

Previous work [24] indicates that a technical advancement is probable at this point, since it is the only means to alter the convergence towards a stable condition. Technological convergence refers to the phenomenon where advancements or innovations that are introduced and adopted in one area have a substantial effect on the condition of product development, competitiveness, and value creation in other industries. Convergence can result in competitive conditions where products or services from one industry become increasingly connected, absorbed, or combined with a wider range of offerings from another industry. This can be achieved by promoting the development of substitute or complementary products that add more value and redefine the structure of the industry. Convergence results in the gradual disappearance of formerly distinct borders within sectors, as they start to exhibit increasingly comparable competitive, market-oriented, and technical features.

As industries converge, companies must acquire and invest in novel core competencies that enable them to use valuable abilities and fundamental product frameworks. These frameworks should be readily adaptable and adjustable to cater to a broader consumer base across various marketplaces. **Fig 2** is associated with the Livingston plot, which illustrates the nonlinear growth in lab energy of particles beam generated by accelerators over time [25]. The Livingstone plot is a valuable and well-regarded tool that demonstrates how the primary factor behind the rise in energy of accelerators is the introduction of new technology, rather than just improving or advancing old machines and their spread [26].

Social CBA and Two Case Scenarios

Our conceptual framework uses Cost–Benefit Analysis (CBA) to evaluate research infrastructure (RI). The CBA is one of the most popular tools employed by economists and governments to determine the social and economic efficiency of investments. It is useful in predicting the outputs, inputs and their corresponding MSVs to determine the anticipated NPV of a project. The CBA hypothesis has been discussed in relation to Mishan and Quah [27] and Nye [28]. In this concept, a project is considered good if the benefits obtained in the long run are worth more than the costs. This approach receives a lot of support from different organizations such as the European Commission, OECD, EIB, WB and many other national/international organizations [29].

Currently, the use of Cost-Benefit Analysis (CBA) in research infrastructure (RI) has been impeded due to arguments that the uncertainty surrounding the future economic advantages of scientific endeavors poses a challenge for making accurate quantitative predictions. Woithe et al. [30] conducted research on the social effect of CERN and suggested that a qualitative methodology is favored over quantitative ones due to potential criticism. Cellini and Kee [31] conducted a survey on past experience and found that although there have been significant advancements in analyzing how research expenditures benefit society, it is not possible to directly compare the various ways in which these benefits are spread or to quantify the total benefits level from normal research in relation to the amount of public investment in this form of research. Makridakis [32] propose that using quantitative forecasts could result in underestimating the advantages. Lappe and Spang [33] found that based on survey data, companies that invest in university research do not try to analyze the costs and benefits of this investment because they consider it to be excessively intricate and expensive. The suggested model may be expressed using Eq. (8).

$$\mathbb{E}(NPV_{RI}) = \mathbb{E}\left[(S + T + H + C + A) - (TC + E) + PV_{B_n}\right] \tag{8}$$

NPV_{RI} refers to the NPV of the RI, which is calculated by adding the NPV for infrastructure users (NPV_u) and the current value for non-users (PV_{B_n}). The latter concept incorporates both potential future advantages arising from the RI and the inherent worth of novel scientific information for the public good. Eq. (8) utilizes the concept that overall use-benefits are determined by subtracting the current economic cost of benefits for individuals of the $RI(PVB_u)$ from the current value of its economic cost (PVEC). Variables in a Cost-Benefit Analysis (CBA) are considered "present values" because they have been converted to a common measurement unit, which is the monetary element in a certain base year. This conversion takes into account the future and past values of the variables, and it is done using a predetermined societal discount rate. Additionally, these values are aggregated throughout the whole time period covered by the CBA.

A social discount rate is the comparative assessment of a society on the value of present well-being compared to future well-being. The selection of a suitable social discount rate is vital for conducting cost-benefit analysis and has significant consequences for the distribution of resources. Setting the social discount rate too high may prevent the implementation of many socially beneficial public initiatives, while setting it excessively low poses the danger of making numerous economically wasteful investments. In addition, a higher social discount rate, which assigns less importance to benefits and costs that occur in the far future, supports projects with advantages that occur sooner. Conversely, a lower social discount rate supports projects with benefits that occur later.

The selection of the social discount rate has an impact on both the initial determination of whether a particular public sector project is worthy of financing and the subsequent assessment of its success. The benefits of a Research Institution (RI) can be categorized into various shareholders; the publication value for scholars (S), technological development for collaborative companies and other agents (T), accumulation of human capital for early career searches (H), cultural impacts for the general public (C), as well as additional benefits for users in applied researches (A). In the same way, economic costs may be categorized as investment and operation costs (TC) as well as negative externalities (E, such as pollution). Therefore, it is evident that a social CBA is different from financial evaluation of a project. Thus, Eq. (8) is transformed into Eq. (9).

$$\mathbb{E}(NPV_{RI}) = \mathbb{E}\left[(S + T + H + C + A) - (TC + E) + PV_{B_n}\right] \tag{9}$$

The model has been employed in two prior research studies that evaluate the societal advantages of accelerators in the fields of research and health. The investigations focused on the LHC at CERN [34] and the CNAO in Pavia, Italy [35].

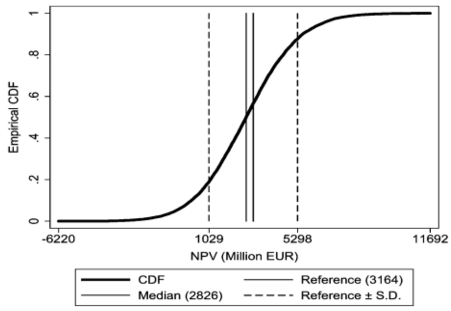

Fig 3. NPV_{LHC}—Empirical CDF

Fig 3 provides a concise overview of these studies. Both projects have a positive Expected Net Present Value ($\mathbb{E}(NPV_{RI})$) and hence pass the Cost-Benefit Analysis (CBA) test satisfactorily, but with differing probabilities. The structure of overall benefits also varies. CERN attributes 33% of its overall benefit to enhanced career chances for former researchers and students (H), and another 33% to technological spillovers (T). In contrast, the majority of CNAO's benefits, specifically 97% of the total, are derived from the health benefits it provides to patients (A).

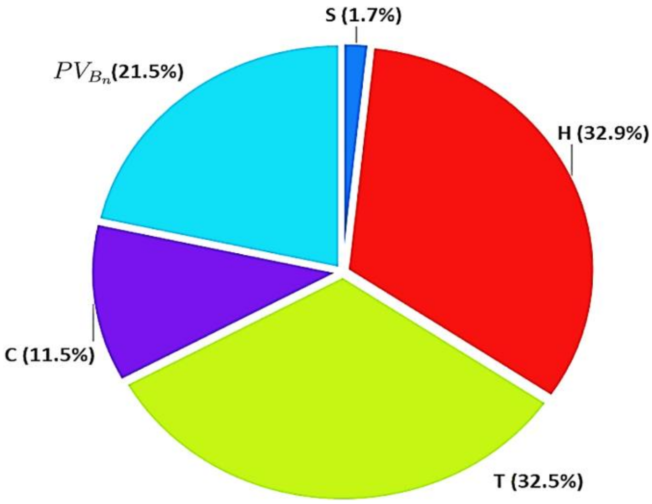

Fig 4. LHC—Benefits

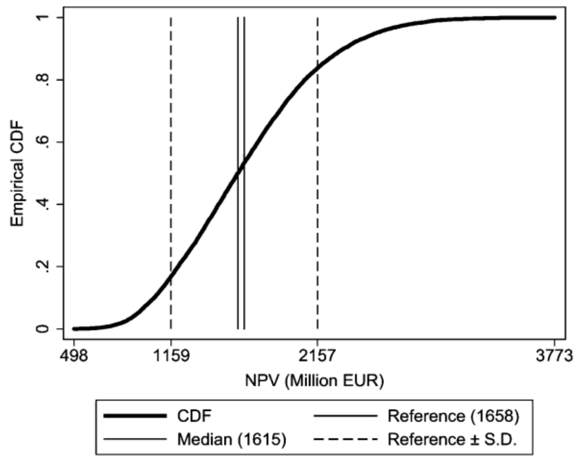

Fig 5. NPV_{CNAO}—Empirical CDF

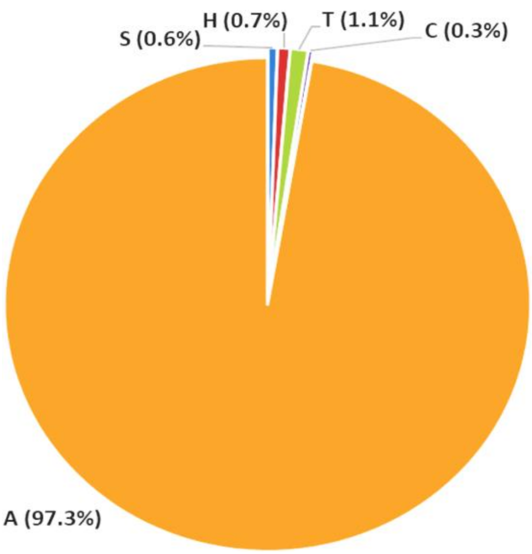

Fig 6. CNAO—Benefits

Cost-Benefit Analysis (CBA) of the LHC and the CNAO. **Fig 3** and **Fig 4** were derived from [36], while **Fig 5** and **Fig 6** were derived from [37]. **Fig 3** and **Fig 5** indicate the cumulative density function of NPV of CNAO and LHC, respectively. These functions are derived from Monte Carlo simulations. **Fig 4** and **Fig 6** demonstrate the distribution of advantages among different stakeholders. These stakeholders include cultural impacts (C), human capital (H), technical spillovers (T), scholarly publications (S), benefits for other applied research users (A), and non-use benefits (PVB_n). In **Fig 4**, PVB_n indicates the LHC value on the basis of its existence. In **Fig 6**, A integrates both the patients' health benefits (95%) and the benefits for experimental beam users (2.2%).

IV. DISCUSSION

Several electrostatic high-voltage generators were developed throughout the 19th century [38]. Their performance was erratic and electric breakdown became a significant issue above some few kilovolts. Earlier accelerators consisted of a pair of electrodes contained in a vacuum tubing, with exterior links to higher sources of voltage. An electron or proton source is positioned near an electrode at an electron-Volt (eV) potential. The particles are then propelled towards the second electrode, which has its potential at the earth [39]. They appeared or were seen via a tiny aperture in the grounded electrode. The energy gained by every particle with an eCoulombs charge is equal to eV Joules, or in units generally employed for the accelerated beam. An eV is equivalent to 1.6×10^{-19} Joules. The energy of a completely exposed ion with a charge of Z and an atomic number A equals ZV/A eV/nucleon.

Cockcroft and Walton constructed the first high-voltage generator in the 1930s, which achieved an approximate energy of 1 MeV [40]. This generator was designed to accelerate various particles for fission tests [41, 42, 43]. Their utilization of capacitors and diodes, referred to as a rectifier circuit, continues to be used now to administer higher voltage to protons and ions at the initiation of several synchrotrons and linacs, although they are progressively getting substituted by quadrupoles with radio frequency. In the 1930s, Van der Graaf founded an electrostatic generator, which employed a moving belt to transport charge to higher voltage terminals, eventually reaching a potential of many megavolts [44]. Van der Graaf accelerators continue to serve as a valuable source of low voltage particles, although they are necessarily constrained by issues related to voltage breakdown [45]. The device has achieved voltages of up to 27 MV while operating in a gas environment that suppresses discharges, such as SF6. In theory, it is possible to connect multiple electrostatic accelerators in a series, with each cathode linked to the next anode. However, every phase of this setup raises the potential difference between the devices' end and ground. Ultimately, this leads to electrical breakdown and the discharge of higher voltage terminal.

Epidemiological research [46, 47] may be used to infer long-term patterns of accelerators sold to hospitals. Socio-demographic variables have a crucial role in determining the availability of radiation in medium- and low-income nations. Currently, accessibility to radiotherapy is restricted in these countries. However, as these countries experience economic growth, there will be an increased need for medical accelerators [48]. The depletion of the present inventory of accelerators is an extra factor that stimulates demand, due to the variation in the lifespans of the machines now being used. For example, in the European Union, the majority of machines used for radiation are advanced linear accelerators (linacs), but in Asia and Eastern Europe, around 2/3 of machines are outdated Cobalt-60 units, which are likely to be substituted in the near future [49]. Furthermore, the emergence of novel industrial uses, such as implantation of ions in semi-conductors might result in the need for accurate demand predictions.

In addition, we propose that the fluctuations in the overall quantity of accelerators globally may be accurately represented by a "S-shaped" temporal pattern. Curves exhibiting this particular form have a rich historical background in the field of statistics and are extensively employed in the domains of economics, demography, and biology [50]. In the field of innovation researches, S-shaped curves are used to depict the progression of technology adoption over time. These curves show that the rate of diffusion initially increases, reaches a peak, and then gradually decreases. This pattern results in rapid diffusion that is led by a slow beginning and followed by a gradual decline and convergence to saturation in later stages [51]. The logistic function is a prominent sample of an S-shaped temporal trend that is employed to describe this pattern.

Prior work provides a rationale for why the overall spread of technology often follows an S-shaped pattern [52]. The S-shaped dissemination pattern and the rates of diffusion are a collective representation of the many underlying factors of adoption. Diffusion is a process that is not unary. Instead, diffusion events are most effectively understood as progressing through several phases of a "diffusion life cycle." Each step of the process is distinguished by distinct market niches, varying factors that drive diffusion, and unique interactions with other diffusion processes, including both competitive and interdependent dynamics [53]. Therefore, it is important to analyze diffusion processes by considering multiple variables and attributes. This means studying innovation diffusion cases in relation to other cases and using various measures to describe the trajectories of diffusion. Additionally, it involves developing comprehensive vectors of driving variables. This multi-tiered perspective on diffusion also prompts the inquiry as to whether the word "diffusion" really encapsulates the fundamental nature of the majority of technical or social/institutional change processes. Very little invention spreads without any influence or interaction with its surroundings [53].

During its development, an invention engages with established methods, relies on the creation of a framework to be effectively integrated into the sociotechnical system, and undergoes changes in its technological, economic, and social aspects. From a comprehensive viewpoint, diffusion may be most accurately characterized as a "evolutionary process that occurs through a series of replacements" [55], including a progression of substitutes across different specialized (growing) market segments. To fully understand diffusion, it is necessary to thoroughly evaluate the series of replacements involved, rather than considering each step in isolation [56]. The debate surrounding the mathematical models of diffusion, specifically the question of symmetrical versus asymmetrical models, seems to arise from different perspectives on innovation. One perspective considers an innovation growing in isolation, while the other analyzes an innovation's market share in relation to competing technologies. Diffusion phenomena often need a multivariate approach, although this method has not been widely used in the several fields of diffusion study [57].

The notion of "competition-legitimation" suggests that some technologies gain acceptance as their user base expands ("legitimation"), but the struggle for limited resources eventually limits the extent of their spread [58]. The presence of diversity across populations and nations is another potential reason. Legitimacy refers to the widespread view or assumption that the activities of a certain entity align with the accepted norms, values, beliefs, and definitions within a given social system [59]. The term may be adjusted to integrate the environmental and social aspects, such as the idea that a company's environmental performance is desirable, suitable, or acceptable. Díez-Martín, Prado-Roman, and Blanco-González [60] argue that the strategic managerial approach of legitimacy refers to organizations' ability to strategically modify their legitimacy position and acquire resources via corporate activities. This is achieved by inclining their activities and altering perceptions.

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The notion of "competition-legitimation" suggests that some technologies gain acceptance as their user base expands ("legitimation"), but the struggle for limited resources eventually limits the extent of their spread. The presence of diversity across populations and nations is another potential reason. Legitimacy refers to the widespread views and assumptions that activities of a certain firm are desirable, suitable, or fitting within a socially formed framework of definitions, beliefs, values, and norms [64]. The term may be adjusted to integrate the environmental and social aspects, such as the idea that a company's environmental efficiency is suitable, desirable, or acceptable. Filatotchev and Nakajima [65] argue that the strategic managerial approach of legitimacy refers to the ability of organizations to strategically modify their legitimacy status and acquire resources through corporate actions. This is achieved by adjusting their activities and influencing how they are perceived.

V. CONCLUSION

Based on the growth rate forecast, it has been established that the accelerator industry will be ready to grow to maturity in the next 15-30 years depending on the current market penetration. The most accurate model, which presupposes that 60% of the potential demand was satisfied in 2014, suggests a gradual slowing down of growth as the industry reaches its capacity limit. This decrease is in line with the logistic growth model as it tends to predict the natural boundaries of a given market, especially when technological advancement is becoming more of a prerequisite for growth. Beyond anticipating for future growth, this study also establishes the social Cost-Benefit Analysis (CBA) for accelerator technologies and the socio-economic values of the LHC and the CNAO. The results of this research posit that these technologies provide high returns in the streams of revenues and also in terms of technological externality, human resource development, and health outcomes. The Monte Carlo simulations carried out in the present study underscore the fact that long-term projection is highly uncertain and sensitive to the choice of model parameters and technological developments that might occur in the future.

CRediT Author Statement

The author reviewed the results and approved the final version of the manuscript.

Data Availability

The datasets generated during the current study are available from the corresponding author upon request.

Conflicts of Interests

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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References

[1]. M. S. Livingston, "Early history of particle accelerators," in Advances in electronics and electron physics, 1980, pp. 1–88. doi: 10.1016/s0065-2539(08)61061-6.
[2]. P. V. Logachev, D. A. Malyutin, and A. A. Starostenko, "Application of a low-energy electron beam as a tool of nondestructive diagnostics of intense charged-particle beams," Instruments and Experimental Techniques, vol. 51, no. 1, pp. 1–27, Jan. 2008, doi: 10.1134/s0020441208010016.
[3]. B. Hidding et al., "Progress in hybrid plasma wakefield acceleration," Photonics, vol. 10, no. 2, p. 99, Jan. 2023, doi: 10.3390/photonics10020099.
[4]. R. Fabbro, J. Fournier, P. Ballard, D. Devaux, and J. Virmont, "Physical study of laser-produced plasma in confined geometry," Journal of Applied Physics, vol. 68, no. 2, pp. 775–784, Jul. 1990, doi: 10.1063/1.346783.
[5]. J. H. Cobb, W. W. M. Allison, and J. N. Bunch, "The ionisation loss of relativistic charged particles in thin gas samples and its use for particle identification I. Theoretical predictions," Nuclear Instruments and Methods, vol. 133, no. 2, pp. 315–323, Mar. 1976, doi: 10.1016/0029-554x(76)90625-x.
[6]. M. Uesaka et al., "Experimental verification of laser photocathode RF gun as an injector for a laser plasma accelerator," IEEE Transactions on Plasma Science, vol. 28, no. 4, pp. 1133–1142, Jan. 2000, doi: 10.1109/27.893293.
[7]. Gambardella and A. M. McGahan, "Business-Model Innovation: General Purpose Technologies and their Implications for Industry Structure," Long Range Planning, vol. 43, no. 2–3, pp. 262–271, Apr. 2010, doi: 10.1016/j.lrp.2009.07.009.
[8]. H.-J. Steenhuis and L. Pretorius, "The additive manufacturing innovation: a range of implications," Journal of Manufacturing Technology Management, vol. 28, no. 1, pp. 122–143, Feb. 2017, doi: 10.1108/jmtm-06-2016-0081.
[9]. R. Garcia and R. Calantone, "A critical look at technological innovation typology and innovativeness terminology: a literature review," Journal of Product Innovation Management, vol. 19, no. 2, pp. 110–132, Mar. 2002, doi: 10.1111/1540-5885.1920110.
[10]. D. Jugend, T. R. De Araujo, M. L. Pimenta, J. A. Gobbo, and P. Hilletofth, "The role of cross-functional integration in new product development: differences between incremental and radical innovation projects," Innovation, vol. 20, no. 1, pp. 42–60, Sep. 2017, doi: 10.1080/14479338.2017.1364971.
[11]. C. S. Koberg, D. R. Detienne, and K. A. Heppard, "An empirical test of environmental, organizational, and process factors affecting incremental and radical innovation," The Journal of High Technology Management Research, vol. 14, no. 1, pp. 21–45, Mar. 2003, doi: 10.1016/s1047-8310(03)00003-8.
[12]. J. E. Souto, "Business model innovation and business concept innovation as the context of incremental innovation and radical innovation," Tourism Management, vol. 51, pp. 142–155, Dec. 2015, doi: 10.1016/j.tourman.2015.05.017.
[13]. P. J. Holahan, Z. Z. Sullivan, and S. K. Markham, "Product development as core competence: How formal product development practices differ for radical, more innovative, and incremental product innovations," Journal of Product Innovation Management, vol. 31, no. 2, pp. 329–345, Oct. 2013, doi: 10.1111/jpim.12098.
[14]. R. Kanter, "Supporting innovation and venture development in established companies," Journal of Business Venturing, vol. 1, no. 1, pp. 47–60, Dec. 1985, doi: 10.1016/0883-9026(85)90006-0.
[15]. Gupta, A. Dey, and G. Singh, "Connecting corporations and communities: Towards a theory of social inclusive open innovation," Journal of Open Innovation Technology Market and Complexity, vol. 3, no. 3, pp. 1–34, Sep. 2017, doi: 10.1186/s40852-017-0062-3.
[16]. J. Birkinshaw, "Entrepreneurship In Multinational Corporations: The Characteristics Of Subsidiary Initiatives," Strategic Management Journal, vol. 18, no. 3, pp. 207–229, Mar. 1997, doi: 10.1002/(sici)1097-0266(199703)18:3.
[17]. G. Gemser and M. A. A. M. Leenders, "Managing Cross-Functional cooperation for new product development success," Long Range Planning, vol. 44, no. 1, pp. 26–41, Feb. 2011, doi: 10.1016/j.lrp.2010.11.001.
[18]. S. Holland, K. Gaston, and J. Gomes, "Critical success factors for cross-functional teamwork in new product development," International Journal of Management Reviews, vol. 2, no. 3, pp. 231–259, Sep. 2000, doi: 10.1111/1468-2370.00040.
[19]. E. Fredericks, "Cross-functional involvement in new product development," Qualitative Market Research an International Journal, vol. 8, no. 3, pp. 327–341, Sep. 2005, doi: 10.1108/13522750510603370.
[20]. R. G. Cooper and A. F. Sommer, "The Agile–Stage-Gate hybrid model: a promising new approach and a new research opportunity," Journal of Product Innovation Management, vol. 33, no. 5, pp. 513–526, Feb. 2016, doi: 10.1111/jpim.12314.
[21]. L. Morgan, "Impact of accelerators on technology," IEEE Transactions on Nuclear Science, vol. 20, no. 3, pp. 36–39, Jan. 1973, doi: 10.1109/tns.1973.4327038.
[22]. M. De Nooij, "Social cost-benefit analysis of electricity interconnector investment: A critical appraisal," Energy Policy, vol. 39, no. 6, pp. 3096–3105, Jun. 2011, doi: 10.1016/j.enpol.2011.02.049.
[23]. P. W. Roberts and S. A. Lall, Observing Acceleration: Uncovering the Effects of accelerators on Impact-Oriented entrepreneurs. 2018. [Online]. Available: https://openlibrary.org/books/OL27772289M/Observing_Acceleration
[24]. G. Dosi, "Technological Paradigms and Technological Trajectories: A suggested interpretation of the determinants and directions of technical change," SSRN Electronic Journal, Jan. 1982, [Online]. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1505191
[25]. D. H. H. Hoffmann et al., "Particle accelerator physics and technology for high energy density physics research," The European Physical Journal D, vol. 44, no. 2, pp. 293–300, Jun. 2006, doi: 10.1140/epjd/e2006-00125-0.
[26]. D. A. Edwards and M. J. Syphers, An introduction to the physics of high energy accelerators. 1993. doi: 10.1002/9783527617272.
[27]. E. J. Mishan and E. Quah, Cost-Benefit analysis. 1976. [Online]. Available: http://ci.nii.ac.jp/ncid/BA14049486
[28]. J. S. Nye, "Corruption and Political Development: A Cost-Benefit Analysis," American Political Science Review, vol. 61, no. 2, pp. 417–427, Jun. 1967, doi: 10.2307/1953254.
[29]. F. De Francesco, "Transfer Agents, knowledge Authority, and Indices of Regulatory Quality: A comparative analysis of the World Bank and the Organisation for Economic Co-operation and Development," Journal of Comparative Policy Analysis Research and Practice, vol. 18, no. 4, pp. 350–365, Apr. 2014, doi: 10.1080/13876988.2014.882648.
[30]. J. Woithe, A. Müller, S. Schmeling, and J. Kuhn, "Motivational outcomes of the science outreach lab S'Cool LAB at CERN: A multilevel analysis," Journal of Research in Science Teaching, vol. 59, no. 6, pp. 930–968, Jan. 2022, doi: 10.1002/tea.21748.
[31]. S. R. Cellini and J. E. Kee, "Cost-Effectiveness and Cost-Benefit Analysis," Wiley Online Library, pp. 636–672, Aug. 2015, doi: 10.1002/9781119171386.ch24.
[32]. S. Makridakis, "Metaforecasting," International Journal of Forecasting, vol. 4, no. 3, pp. 467–491, Jan. 1988, doi: 10.1016/0169-2070(88)90112-4.
[33]. M. Lappe and K. Spang, "Investments in project management are profitable: A case study-based analysis of the relationship between the costs and benefits of project management," International Journal of Project Management, vol. 32, no. 4, pp. 603–612, May 2014, doi: 10.1016/j.ijproman.2013.10.005.
[34]. R. Vogt, "Cold nuclear matter effects onJ/ψandϒproduction at energies available at the CERN Large Hadron Collider (LHC)," Physical Review C, vol. 81, no. 4, Apr. 2010, doi: 10.1103/physrevc.81.044903.
[35]. S. Rossi, "The National Centre for Oncological Hadrontherapy (CNAO): Status and perspectives," Physica Medica, vol. 31, no. 4, pp. 333–351, Jun. 2015, doi: 10.1016/j.ejmp.2015.03.001.
[36]. Magazinik, J. S. Bedolla, N. C. Lasheras, and S. Makinen, "Societal impact as Cost-Benefit Analysis: Comparative analysis of two research infrastructures," IEEE, Jun. 2019, doi: 10.1109/ice.2019.8792600.

[37]. M. Florio and E. Sirtori, "Social benefits and costs of large scale research infrastructures," Technological Forecasting and Social Change, vol. 112, pp. 65–78, Nov. 2016, doi: 10.1016/j.techfore.2015.11.024.

[38]. Y. Peng et al., "A High-Voltage generator and multiplexer for electrostatic actuation in programmable matter," IEEE Journal of Solid-State Circuits, vol. 58, no. 4, pp. 915–928, Apr. 2023, doi: 10.1109/jssc.2022.3230927.

[39]. S. Masuda, M. Washizu, and M. Iwadare, "Separation of small particles suspended in liquid by nonuniform traveling field," IEEE Transactions on Industry Applications, vol. IA-23, no. 3, pp. 474–480, May 1987, doi: 10.1109/tia.1987.4504934.

[40]. K. Wille, The Physics of Particle Accelerators: An Introduction. 2001. [Online]. Available: https://ci.nii.ac.jp/ncid/BA52520641

[41]. W. B. Lewis, "The intense neutron generator and future factory type ion accelerators," IEEE Transactions on Nuclear Science, vol. 16, no. 1, pp. 28–35, Jan. 1969, doi: 10.1109/tns.1969.4325078.

[42]. B. K. Das, A. Shyam, R. Das, and A. D. P. Rao, "Development of compact D-D neutron generator," Instruments and Experimental Techniques, vol. 56, no. 2, pp. 130–133, Mar. 2013, doi: 10.1134/s0020441213010260.

[43]. M. Letournel, "Brief review of the development of electrostatic accelerators and continuing work at Strasbourg," IEEE, Jan. 2003, doi: 10.1109/pac.1989.73366.

[44]. D. O. Boerma and Ph. B. Smith, "The Groningen 5 MV van de Graaff accelerator," Nuclear Instruments and Methods, vol. 86, no. 2, pp. 221–240, Sep. 1970, doi: 10.1016/0029-554x(70)90705-6.

[45]. S. Tazzari and M. Ferrario, "Trends in high energy particle accelerators," Reports on Progress in Physics, vol. 66, no. 6, pp. 1045–1094, May 2003, doi: 10.1088/0034-4885/66/6/204.

[46]. M. R. Pranzo, E. D. Prà, and A. Besana, "Epidemiological geography at work: An exploratory review about the overall findings of spatial analysis applied to the study of CoViD-19 propagation along the first pandemic year," GeoJournal, vol. 88, no. 1, pp. 1103–1125, Mar. 2022, doi: 10.1007/s10708-022-10601-y.

[47]. J. F. Schwensen, D. Bregnbak, and J. D. Johansen, "Recent trends in epidemiology, sensitization and legal requirements of selected relevant contact allergens," Expert Review of Clinical Immunology, vol. 12, no. 3, pp. 289–300, Nov. 2015, doi: 10.1586/1744666x.2016.1120159.

[48]. Šoltés and B. Gavurová, "Innovation policy as the main accelerator of increasing the competitiveness of small and medium-sized enterprises in Slovakia," Procedia Economics and Finance, vol. 15, pp. 1478–1485, Jan. 2014, doi: 10.1016/s2212-5671(14)00614-5.

[49]. B. J. Healy, D. Van Der Merwe, K. E. Christaki, and A. Meghzifene, "Cobalt-60 Machines and Medical Linear Accelerators: competing technologies for external beam radiotherapy," Clinical Oncology, vol. 29, no. 2, pp. 110–115, Feb. 2017, doi: 10.1016/j.clon.2016.11.002.

[50]. L. Fendler and I. Muzaffar, "The History Of The Bell Curve: Sorting And The Idea Of Normal," Educational Theory, vol. 58, no. 1, pp. 63–82, Feb. 2008, doi: 10.1111/j.1741-5446.2007.0276.x.

[51]. Grübler, "Diffusion: long-term patterns and discontinuities," in Springer eBooks, 1991, pp. 451–482. doi: 10.1007/978-3-662-02700-4_18.

[52]. J. R. Ortt and J. P. L. Schoormans, "The pattern of development and diffusion of breakthrough communication technologies," European Journal of Innovation Management, vol. 7, no. 4, pp. 292–302, Dec. 2004, doi: 10.1108/14601060410565047.

[53]. M. M. Danziger, I. Bonamassa, S. Boccaletti, and S. Havlin, "Dynamic interdependence and competition in multilayer networks," Nature Physics, vol. 15, no. 2, pp. 178–185, Nov. 2018, doi: 10.1038/s41567-018-0343-1.

[54]. W. W. Powell and E. Giannella, "Collective invention and inventor networks," in Handbook of the economics of innovation, 2010, pp. 575–605. doi: 10.1016/s0169-7218(10)01013-0.

[55]. M. L. Rosenzweig and R. D. McCord, "Incumbent replacement: evidence for long-term evolutionary progress," Paleobiology, vol. 17, no. 3, pp. 202–213, Jan. 1991, doi: 10.1017/s0094837300010563.

[56]. P. C. Fife, Mathematical aspects of reacting and diffusing systems. 1979. doi: 10.1007/978-3-642-93111-6.

[57]. D. W. Stroock and S. R. S. Varadhan, Multidimensional diffusion processes. 1997. doi: 10.1007/3-540-28999-2.

[58]. Özsomer and S. T. Cavusgil, "The effects of technology standards on the structure of the global PC industry," European Journal of Marketing, vol. 34, no. 9/10, pp. 1199–1220, Oct. 2000, doi: 10.1108/03090560010342601.

[59]. P. C. Stern, L. Kalof, T. Dietz, and G. A. Guagnano, "Values, beliefs, and proenvironmental action: attitude formation toward emergent attitude objects1," Journal of Applied Social Psychology, vol. 25, no. 18, pp. 1611–1636, Sep. 1995, doi: 10.1111/j.1559-1816.1995.tb02636.x.

[60]. F. Díez-Martín, C. Prado-Roman, and A. Blanco-González, "Beyond legitimacy: legitimacy types and organizational success," Management Decision, vol. 51, no. 10, pp. 1954–1969, Nov. 2013, doi: 10.1108/md-08-2012-0561.

[61]. J. Fagerberg and B. Verspagen, "Technology-gaps, innovation-diffusion and transformation: an evolutionary interpretation," Research Policy, vol. 31, no. 8–9, pp. 1291–1304, Dec. 2002, doi: 10.1016/s0048-7333(02)00064-1.

[62]. K. Harley, P. Van Heijster, and G. J. Pettet, "A geometric construction of travelling wave solutions to the Keller--Segel model," ANZIAM Journal, vol. 55, p. 399, Aug. 2014, doi: 10.21914/anziamj.v55i0.7801.

[63]. B. Ganapathysubramanian and N. Zabaras, "Modeling diffusion in random heterogeneous media: Data-driven models, stochastic collocation and the variational multiscale method," Journal of Computational Physics, vol. 226, no. 1, pp. 326–353, Sep. 2007, doi: 10.1016/j.jcp.2007.04.009.

[64]. B. Alrazi, C. De Villiers, and C. J. Van Staden, "A comprehensive literature review on, and the construction of a framework for, environmental legitimacy, accountability and proactivity," Journal of Cleaner Production, vol. 102, pp. 44–57, Sep. 2015, doi: 10.1016/j.jclepro.2015.05.022.

[65]. Filatotchev and C. Nakajima, "Corporate governance, responsible managerial behavior, and corporate social responsibility: organizational efficiency versus organizational legitimacy?," Academy of Management Perspectives, vol. 28, no. 3, pp. 289–306, Aug. 2014, doi: 10.5465/amp.2014.0014.

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