



Stress-Strength Weibull Analysis Applied to Estimate Reliability Index in Industry 4.0

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Abstract

With technological advances, companies are allowed to integrate digital data, physical supplies, and human resources, and all this integration capability can be done thanks to Industry 4.0. This concept, also called the fourth industrial revolution, refers to smart companies that work with intelligent cyber-physical systems. Industry 4.0 enables automation, data interchange, and big data processing, among others. Then, the process decision-making, efficiency, and productivity improvement for companies will become faster and more accurate, thanks to real-time data processes and all supply chain integration allowed by Industry 4.0. However, the implementation of Industry 4.0 carries several challenges for companies to have success in the transformation of a normal industry into an Industry 4.0, like the necessity of adding new hardware, software, and other technologic devices. Because of this, the implementation and control of Industry 4.0 come with new issues to handle and new failure modes for both hardware and electronic devices. These problems can be faced using reliability engineering tools. Then the object of this research is the use of reliability engineering methodology stress-strength Weibull analysis, highlighting that the behavior of frequency emitted by electronics devices follows a Weibull distribution most of the time. Also, a stress-strength Weibull with a different shape parameter close solution is presented to increase the efficiency and productivity in Industry 4.0 electronic devices.

Keywords: Reliability engineering, Industry 4.0, Big data, Weibull distribution, Stress-strength analysis, Stress-Strength Weibull, Weibull shape parameters.

1. Introduction

Currently, the increment in technology is very fast, even faster than the level at which companies could understand the advance in this technology [1]. One of the most significant advances in technology is the Internet and the Internet of Things, according to different authors [2]–[5]. Such is the impact in the form of communication, the data interchange, and the data process, among others, that now is possible to make it in real-time. In this sense, because these advances are now possible, all types of devices are connected; this technological advance is called the Internet of Things [6]. Then, the implementation of the Internet of Things in companies to allow the transformation into smart industries is called Industry [7], [8].

Industry 4.0 makes companies create new systems and innovate into smart industries, electronic devices, and instruments [9]. These innovations facilitate

infrastructures for industry development but also generate new and unknown failure mechanisms, technical and structural dependencies among system components, and eventually, new and unknown hazards and risks [10].

Thanks to technological advancement allowed by Industry 4.0, new industries or companies can get more control over products, processes, human resources, supply chain, and transportation, including the final disposition of products [11]. Since the Internet of Things allows a connection between different devices, such as can be computers, cars, refrigerators, smart phones, industrial machines, tools, etc., then now they can share information, data analysis, and decision-making in real-time [12]. However, nowadays, the main issue is the development of infrastructure with physical systems and models to manage Industry 4.0 facilities efficiently [11].

Another issue to be solved is the period of this Industry 4.0, also called the fourth industrial revolution.

Hence it should be solved in a short time-lapse because the emergence of new industrial areas is inescapable [13]. This puts huge pressure on organizations to learn, understand, and implement this technology and to be prepared for the progressive technology advance and process transformation [14]. This research presents the technology key to Industry 4.0, such as the Industrial Internet of Things, big data analysis, horizontal system integration, autonomous robots, and cyber security [15]. This aims to explain how reliability and stress-strength analysis can be used in these fields. Finally, it is important to mention that the connectivity devices depend on the reliability of the hardware and technological devices level [16], [17].

On the other hand, Reliability engineering, as a sub-discipline of system engineering, includes the systematic application of the engineering principles and techniques throughout a product lifecycle, so reliability should be considered from the concept plan to wear out of the device's lifetime [18]. Reliability Engineering defines reliability requirements and analyzes, assesses, and optimizes system performance via reliability techniques [19].

In that sense, the use of engineering reliability methodologies presents a powerful option for companies to implement in Industry 4.0 with the object of measuring accurately both efficiency and productivity [20]. Whereby the stress-strength analysis in reliability engineering is a useful method to measure the performance of hardware and electronic devices that are employed in Industry 4.0 [14]. Stress-strength analysis determines the stress level at which the element fails. Because both the stress and the strength are random variables, the analysis of these variables is made using probability density functions [21]. Industry 4.0 creates a new opportunity for thought leaders and engineers to create new systems and innovate smart devices and instruments. These innovations facilitate infrastructures for industry development but also generate new and unknown failure mechanisms, new and unknown economic, functional, technical, and structural dependencies among system components, and eventually new and unknown hazards and risks. On the other hand, with complexity and dependence increasing, the implementation of new concepts, and the advancements in knowledge, methods, and techniques, such as big data, the Internet of Things, and quick response to changes, make new opportunities for developing reliability engineering techniques and improve reliability prediction capability.

In addition, it should be considered that electronic elements like hardware or any electronic devices almost always present a Weibull distribution behavior [22]–[24]; in such a way, this manuscript also presents a stress-strength Weibull analysis close solution for the case of the different shape parameter $\beta_s \neq \beta_f$.

The structure of the paper is as follows. Section 2 presents the Internet of Things; section 3 shows Industry 4.0; in section 4, reliability engineering in Industry 4.0 is

presented; section 5 presents the generalities of Weibull distribution: in section 6, Weibull Distribution and Industry 4.0 is shown; section 7 presents the proposed method and the numerical application; finally, section 8 presents the conclusion and references.

2. Internet of Things

The concept of the Internet of Things has become relevant in the world because of the advance in technology and mobile devices. The Internet of Things is about billions of products or objects that can sense, communicate, and share data, and all these are interconnected by the Internet protocol network. The objective of this interconnection of objects is the capacity for planning, management, and decision-making; in that sense, the definition of the Internet of Things is a physical object communicated by a network. It is important to remember that the Internet of Things is not only about computer networks, is about all types of devices and all sizes (see fig.1) [25].



Figure 1. Internet of Things

3. Industry 4.0

Industry 4.0 can be defined as a new organization and control level over the value chain if the lifecycle of devices or products is geared to individualizing customer requirements [7]. This control in an organization begins with the raw material and ends with the recycling of the product, including customer service during the lifetime of the product [26]. The relevance of Industry 4.0 is the availability of information in real-time by connecting the instances of the value chain, which results in vital for industries to optimize each link of the product in the value chain [13]. On the other side, the connection of systems, things, and people creates a dynamic value-added organization[27]. i.e., the customers are closer to the industries, and the information is dual between the company and the client (see Table 1) [28].

Table 1. Industry 4.0 Definitions

Author and year	Definition
Kagermann, Wahlster & Johannes. (2013)	Industry 4.0 utilizes the power of communications technology and innovative inventions to boost the development of the manufacturing industry.
Qin, Liu & Grosvenor. (2016)	Industry 4.0 encourages manufacturing efficiency by collecting data smartly, making correct decisions, and executing decisions without any doubts. By using the most advanced technologies, the procedures of collecting and interpreting data will be easier. The operating interoperability ability acts as a 'connecting bridge' to provide a reliable manufacturing environment in Industry 4.0. This overall consciousness gives Industry 4.0 the most important aspect of artificial intelligent functions.
Schumacher, Erol & Sihm. (2016)	Industry 4.0 is surrounded by a huge network of advanced technologies across the value chain. Service, Automation, Artificial Intelligence Robotics, the Internet of Things, and Additive Manufacturing are bringing in a brand-new era of manufacturing processes. The boundaries between the real world and virtual reality are getting blurrier, causing a phenomenon known as Cyber-Physical Production Systems (CPS).
Schwab (2016)	Industry 4.0 is differentiated by a few characteristics of new technologies, for example, physical, digital, and biological worlds. The improvement in technologies is bringing significant effects on industries, economies, and governments' development of global industry and the world economy.
Wang et al., (2016)	Industry 4.0 makes full use of emerging technologies and rapid development of machines and tools to cope with global challenges to improve industry levels. The main concept of Industry 4.0 is to utilize advanced information technology to deploy IoT services. Production can run faster and smoothly with minimum downtime by integrating engineering knowledge. Therefore, the product built will be of better quality, production systems are more efficient, easier to maintain, and achieve cost savings.
Mrugalska & Magdalena (2017)	Modern and more sophisticated machines and tools with advanced software and networked sensors can be used to plan, predict, adjust and control the societal outcome and business models to create another phase of value chain organization. It can be managed throughout the whole cycle of a product. Thus, Industry 4.0 is an advantage for staying competitive in any industry. To create a more dynamic flow of production, optimization of the value chain has to be autonomously controlled.

3.1 Factors that Affect Industry 4.0

The introduction of Industry 4.0 in organizations represents a huge challenge that is for all the facts that are needed in the implantation of Industry 4.0, a relevant factor is the hardware technology[29]. This is because to support all data, processes, and interconnectivity, hardware must provide the requirements to allow Industry 4.0, i.e., the hardware used to process data and connection needs. The correct hardware is not only what the industries need, but it also is very important how long the hardware installed will be efficiently performed through time that is going to support optimal condition communication and data in the industry [30].

Another important aspect in the implementation of Industry 4.0 is the software used in the connection and data process. As is well known, some corporations provide software in the implementation of (ERP) Enterprise Resources Planning SAP and Oracle. But now, Industry 4.0 is not only about communication with all the branches that integrate the whole enterprise, the suppliers, and finally, the customer.

This new software needs to support quantities of data that a decade before was only impossible even to imagine. For now, the data represents quantities like terabytes and even petabytes to support data interchange. Moreover, the industries must not deal only with the correct software but with the time that software will be performed in an efficient way [31].

Another relevant factor that can be part of the success or loss of a company is the connection; this can be the most important factor in dealing with Industry 4.0. the transmission of big data (see fig. 2) between every node in the Internet protocol is a very important problem to deal with, i.e., Industry 4.0 makes those industries must evolve into virtual global companies. We are not just talking of suppliers connection, the necessary connection in Industry 4.0 include multiple countries to interchange data with companies, suppliers, clients, transport, and customer, and at the same time, each one is also connected [32]. On the other hand, it is also important to consider the connection time and the speed of data interchange, it is to say, not only to get the connections but the time of optimal and efficient connection support [33]. Finally, reliability is necessary for optimal performance in Industry 4.0[14].

4. Reliability Engineering in Industry 4.0

It is important to mention that the efficiency of the interconnection, the hardware performance in optimal conditions, and software support over time depends on the reliability of the user device to perform the interconnection; moreover, wireless transmission of big data depends on a frequency, it is to say, the used signal to connect devices like, smart phones, computers, smart

buildings, etc., is possible through the use of stochastic processes [34], which means, that connections in devices and the wireless technology are representing by a probability density function [35]. More there, the Weibull distribution is widely used in Internet connections; using this distribution provides better goodness-of-fit to real-world data, and as it is known, the Weibull distribution is also widely used in reliability estimation. Then, a methodology to determine the reliability of devices is presented in the framework of the Industry 4.0 approach [36].

Reliability predicts analysis and optimizes products, elements, or systems. This represents an opportunity in Industry 4.0 to be efficient all over the value chain because reliability methods respond to the optimal work of devices like hardware, software, and connectivity. Without any of this, the framework cannot be performed. Consequently, Industry 4.0 can be implemented in any company or organization. Still, all the changes, challenges, and investments in implementation will be irrelevant if the time of performance is unknown i.e. if we don't know the reliability of devices and connectivity, the uncertainty of Industry 4.0 it will be significant [14]. Uncertainty is one of the main challenges in both virtual and physical applications, uncertainty cannot be eliminated because of knowledge lack and uncontrollable processes, but it can be managed using reliability methodology [37].

Reliability methods implementation in Industry 4.0 is very important to deal with uncertainty and possess an efficient physical and virtual fabric in a global network of communication and data interchange based on Internet protocol. In the next section, reliability concepts and generalization are presented.

Moreover, to say that an electronic device or product is safe for use and qualified as reliable is necessary to identify significant factors and conditions that affect de device's performance and find the failure mode. Using this failure mode, the lifetime of the device can be estimated with a high-reliability level [38].

Thus, it is important to understand the mechanisms that cause the failure and important is to identify what factors accelerate or decelerate the failure mechanism to estimate and predict life accurately and mitigate the unexpected failures; in that sense, the methodology of stress-strength possesses an advantage to calculated accurate lifetime probability because this analysis contemplates all the possible stresses which the component will be used [39].

4.1 Reliability Engineering Concepts

Reliability is the best quantitative measure of products, elements, or systems design; that's because reliability refers to quality over time performed a significant function without failure in a specific environment for some time [40]. In other words, the function for which it was created, under the conditions and operational environment established for a given period [41].

It is necessary to remember that reliability only applies once the process is in control, that is, stable and predictable over time, highlighting that it is met only for the given conditions and environment [42].

One of the most used distributions in reliability engineering to model the life of any product whose deterioration is due to physical phenomena is the Weibull Distribution and how was mentioned above Weibull distribution is wide usage to determine electronic devices and Internet protocols, wireless connectivity fit in a Weibull distribution [43]. In other words, reliability in Industry 4.0 is considered the use of the Weibull distribution to get a reliable design over some time (t)[17].

5. Weibull Distribution Generalities

Due to its flexibility in modeling a product's design, production, and wear-out or aging phases, the Weibull distribution is widely used in reliability and lifetime analysis due to its flexibility (see figure 2). And since all products are subjected to a random environment [18].

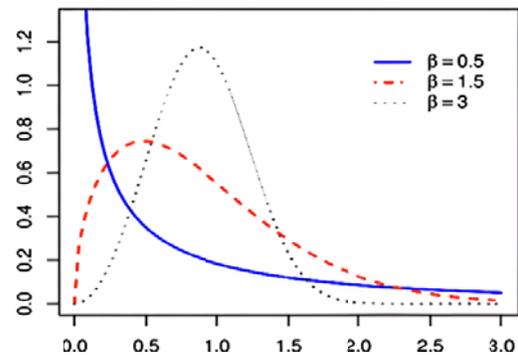


Figure 2. Cumulative Density Function Weibull

The Weibull distribution [44] is given by:

$$f(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^\beta} \tag{1}$$

With cumulative failure function and reliability function given by

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^\beta} \tag{2}$$

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^\beta} \tag{3}$$

Where β is the shape parameter and η is the scale parameter of the Weibull distribution. The estimation of the β and η parameters is performed by using the linear form of Eq. (2) as

$$Y_i = \ln(-\ln(1 - F(t_i))) = -\beta \ln \eta + \beta \ln t_i \tag{4}$$

The linear model is given by

$$Y_i = b_0 + \beta X_i \tag{5}$$

With $Y_i = \ln(-\ln(1 - F(t_i)))$, $b_0 = -\beta \ln(\eta)$, and $x_i = \ln(t_i)$.

$F(t_i)$ in Eq. (2) is estimated by the median rank approach [45] given by

$$F(t_i) = \frac{1-0.3}{n+0.4} \quad (6)$$

From [18], the sample size n is determined as

$$n = \frac{-1}{\ln(R(t))} \quad (7)$$

And the mean μ and the standard deviation σ are given as

$$\bar{T}_1 = \eta * \Gamma_1 \left(\frac{1}{\beta} + 1 \right) \quad (8)$$

$$\sigma_T = \eta \left(\Gamma \left(\frac{2}{\beta} + 1 \right) - \Gamma \left(\frac{1}{\beta} + 1 \right)^2 \right)^{\frac{1}{2}} \quad (9)$$

6. Weibull Distribution and Industry 4.0

The information on the mean values of signals in telecommunications like cell phones, Internet protocol, computers, radios, printers, and all devices that use a frequency to communicate, i.e., wireless connectivity, is not sufficient to characterize the performance of communication systems; the variation in time, space and frequency, must also be taken into account [46], [47].

The dynamic behavior of the desired and interfering signals plays a decisive role in the analysis of system reliability and the choice of system parameters; in such a way, the signals must be considered as a random variable, and to model this variable, a probability density function needs it [48].

On the other hand, electronic devices are used physically and virtually everywhere, then; an aspect of Industry 4.0 success is the accuracy of these electronic devices and the communication between all of them; in other words, electronic communication needs to be able to reach the entire world [7]. The wireless that connects the world with information and streaming data into and out of an organization term the Industry 4.0 era [49].

To describe the life of a product or element known as the bathtub curve (see fig. 3). The bathtub curve consists of three periods: an infant mortality period with a decreasing failure rate followed by a normal life period with a low, relatively constant failure rate, concluding with a wear-out period.

The bathtub describes the relative failure rate of an entire population of products over time [50]. The success factor is the choice of the reliability model that captures lifetime variables for parameter estimation and defines the distribution adequately. In that way, an adequate distribution to fit the failure mode in electronic devices and connectivity protocol is the Weibull distribution because the Weibull distribution is based on the weakest link, and this allows electronic and virtual devices to identify the failure mode and calculate with accuracy and precision the reliability of components being physical or virtual [51].

On the other hand, the Weibull distribution is very useful in modeling Internet traffic data sessions, flows, and packets at different Internet network connections; also, the scale parameter η of the Weibull distribution can be used to characterize the Internet traffic and flow [52].

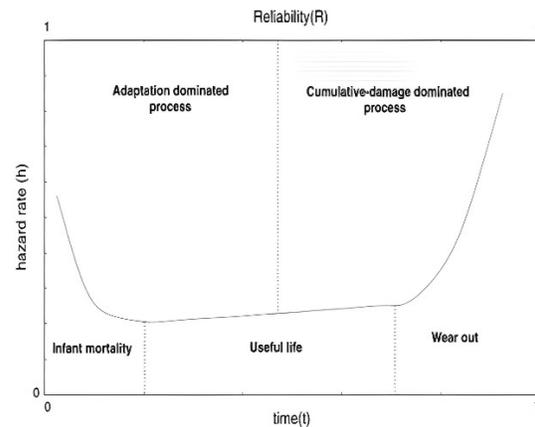


Figure 3. Bathtub Curve

6.1 Reliability Design Estimation in Industry 4.0

It is well known that quality in components is very important to ensure the correct function in different aspects of Industry 4.0 and Internet protocol, such as the performance of the routers, the bandwidth, the people knowledge, the data process, etc. [53]. On the other hand, this quality for how long is going to work at optimum conditions, i.e., what is the probability of a component to perform the function in a period without failures [54]. Here is where reliability engineering is very helpful in preventing these failures and knowing the reliability index of any component [55]. In such a way, Industry 4.0 works with very significant factors that can be a key success but also a problem that affects all the chains in the Industry 4.0 performance [56]. Then, using reliability methodologies in Industry 4.0 will help industries to get better quality over time and to have the best knowledge about their supply, helping to prevent possible failures [57]. In the next section, a methodology to estimate the real reliability of different kinds of components is presented and applied to a set of data of routers experiment just like an example of the efficiency of the methodology.

7. Proposed Method to Estimate the Design Reliability

The proposed method is based on the stress-strength Weibull analysis emphasizing that the Weibull distribution has no additive property, and the stress-strength analysis is an algebraic sum of two probability density functions (see figure 4). Then a method to estimate reliability level in the case of different shape parameters $\beta_s \neq \beta_S$ is performed.

- Determine the logarithm of each one of the collected data and determine their log-average values as

$$\mu_{ln-strength} = 8.933$$

$$\mu_{ln-stress} = 9.81$$

- Next, determine the exponential of the average of the estimated logarithms as

$$\mu_{exp-strength} = 7579.02$$

$$\mu_{exp-stress} = 18338.53$$

- With the average of step 2 and step 4 calculate the corresponding Ratio as

$$Ratio = (10501.631^2 - 7579.02^2)^{0.5} = 7269.299$$

$$Ratio = (19458.21^2 - 18338.53^2)^{0.5} = 6505.38$$

- Determine the maximum and minimum strength and stress as Strength maximum and minimum.

$$\sigma_1 = 10501.632 + 7269.2997 = 17770.931$$

$$\sigma_2 = 10501.632 - 7269.2997 = 3232.331$$

Stress maximum and minimum

$$\sigma_1 = 19458.211 + 6505.3813 = 25963.591$$

$$\sigma_2 = 19458.211 - 6505.3813 = 12952.829$$

- Estimate the Y_i elements and the average

$$\mu_{yi} = -0.5444$$

- Calculate the corresponding shape parameter β using equation (17) as follow

$$\beta_{Strength} = \frac{-4 * -0.5444}{0.99 * \ln(17770.931/3232.331)} = 1.2786$$

$$\beta_{Stress} = \frac{-4 * -0.5444}{0.99 * \ln(25963.5919/12952.8292)} = 3.1339$$

- By using the estimated β value of step 8, determine the corresponding Weibull scale η parameters as

$$\eta_{strength} Exp\left(\ln \mu_{exp} - \frac{\mu_{yi}}{\beta}\right) = 11590.615$$

$$\eta_{stress} Exp\left(\ln \mu_{exp} - \frac{\mu_{yi}}{\beta}\right) = 21809.1249$$

- With the Weibull family of both the stress using, the strength of steps 8 and 9, and the desired reliability, estimate the common β_c that represents the corresponding strength and stress using eq. (19).

$$\beta_{common} = \frac{[\ln R(t_w)/F(t_w)]}{\ln\left[\frac{\eta_{Strength}}{\eta_{Stress}}\right]} = 4.657$$

- Using the common β and the η of the strength and stress calculated the corresponding reliability as

$$R(t/x, y) = \frac{21809.1249^{4.657}}{11590.615^{4.657} + 21809.1249^{4.657}} = 0.949971642$$

This means that the real reliability of the system speed received with the router is 94.99%, and even more, the probability safety factor can be estimated using equation (21), as shown above.

$$S_{fW} = \frac{\eta_{Strength}}{\eta_{Stress}} \tag{21}$$

$$S_{fW} = \frac{21809.1249}{11590.615} = 1.886$$

Table 3. Numerical application results

Nomenclature	Formula	Results
Number of observations	$n = \frac{-1}{\ln(R(t))}$	19
Average	$\mu = \sum_{i=1}^n \frac{X_i}{n}$	-
Stress Average	$\mu_s = \sum_{i=1}^n \frac{X_i}{n}$	10501.631
Strength Average	$\mu_S = \sum_{i=1}^n \frac{X_i}{n}$	19458.21
Logarithm strength	$\mu_{ln-strength}$	8.933
Logarithm stress	$\mu_{ln-stress}$	9.81
Exponential strength	$\mu_{exp-strength}$	7579.02
Exponential stress	$\mu_{exp-stress}$	18338.53
Ratio	$Ratio = (\mu^2 \mu_y^2)^{0.5}$	6505.38
Maximum strength	$\sigma_{max} = \sigma_1 = \mu + Ratio$	17770.931
Minimum strength	$\sigma_{min} = \sigma_2 = \mu - Ratio$	3232.331
Maximum stress	$\sigma_{max} = \sigma_1 = \mu + Ratio$	25963.591
Minimum stress	$\sigma_{min} = \sigma_2 = \mu - Ratio$	12952.829
Elements Y average	$\mu_{yi} = \frac{\sum_{i=1}^n \ln(-\ln(1 - (i - 0.3) / n))}{n}$	-0.5444
Stress shape parameter	$\beta_s = \frac{-4 * \mu_{yi}}{0.99 * \ln(\sigma_1/\sigma_2)}$	1.2786
Strength shape parameter	$\beta_S = \frac{-4 * \mu_{yi}}{0.99 * \ln(\sigma_1/\sigma_2)}$	3.1339
Stress scale η parameter	$\eta_s = Exp(\ln \mu_{exp} - \frac{\mu_{yi}}{\beta})$	21809.1249
Strength scale η parameter	$\eta_S = Exp(\ln \mu_{exp} - \frac{\mu_{yi}}{\beta})$	11590.615
Common shape parameter	$\beta_{common} = \frac{[\ln R(t_w)/F(t_w)]}{\ln\left[\frac{\eta_{Strength}}{\eta_{Stress}}\right]}$	4.657
Reliability	$R(t/x, y) = \frac{\eta_{Strength}^{\beta_c}}{\eta_{Strength}^{\beta_c} + \eta_{Stress}^{\beta_c}}$	0.949971642

8. Conclusion

The technological advances have allowed the growth of the organization to a new level in all the supply chain by

using infrastructures or tools like Industry 4.0, which help companies to receive and process data in quantities never seen before and even more this big data process, and transmission is made in real-time. However, Industry 4.0 need the use of both hardware and software that can be very useful, but also the probability of failure is always present because, as it is well known, all products, i.e., software and hardware, are random variables that need to be controlled and analyzed to prevent failures not only in some hardware but in the transmission, received and data processed. In this manner, reliability engineering possesses tools to help with this failure issue. Hereby, in this paper, the reliability stress-strength Weibull distribution with different shape parameters $\beta_S \neq \beta_T$ analysis is presented to estimate the real reliability level of the frequency and durability in internet routers, showing that it is possible to measure the efficiency and productivity of processes in Industry 4.0. On the other hand, since all products or elements are subjected to random stress and in the same way, products possess an inherent random strength to support this stress and both are random variables, a probability density functions need to calculate the reliability level by using the stress-strength Weibull analysis above mentioned. Even more, it is well known that electronic products and devices with additives, i.e., physical phenomena behavior, follow a Weibull distribution; then, the use of a stress-strength Weibull distribution tool to verify the real device reliability is a good option in the decision-making process.

9. References

- [1] O.-G. Ciobanu and D. M. Neamtu, "The impact and importance of new technologies in business development in context of economic diversity," *Proc. Int. Conf. Bus. Excell.*, vol. 11, no. 1, pp. 698–710, 2017, doi: 10.1515/picbe-2017-0074.
- [2] W. F. Cascio and R. Montealegre, "How Technology Is Changing Work and Organizations," *Annu. Rev. Organ. Psychol. Organ. Behav.*, vol. 3, no. 1, pp. 349–375, 2016, doi: 10.1146/annurev-orgpsych-041015-062352.
- [3] V. D. Gowda, S. B. Sridhara, K. B. Naveen, M. Ramesha, and G. N. Pai, "Internet of things: Internet revolution, impact, technology road map and features," *Adv. Math. Sci. J.*, vol. 9, no. 7, pp. 4405–4414, 2020, doi: 10.37418/amsj.9.7.11.
- [4] J. Wielki, "THE IMPACT OF THE INTERNET OF THINGS CONCEPT DEVELOPMENT ON CHANGES IN THE OPERATIONS OF MODERN ENTERPRISES," *Polish J. Manag. Stud.*, vol. 15, no. 1, pp. 262–275, 2017, doi: 10.17512/pjms.2017.15.1.25.
- [5] S. Kumar, P. Tiwari, and M. Zymbler, "Internet of Things is a revolutionary approach for future technology enhancement: a review," *J. Big Data*, vol. 6, no. 1, 2019, doi: 10.1186/s40537-019-0268-2.
- [6] I. Yaqoob *et al.*, "Internet of Things Architecture: Recent Advances, Taxonomy, Requirements, and Open Challenges," *IEEE Wirel. Commun.*, vol. 24, no. 3, pp. 10–16, 2017, doi: 10.1109/MWC.2017.1600421.
- [7] G. Lampropoulos, K. Siakas, and T. Anastasiadis, "Internet of Things in the Context of Industry 4.0: An Overview," *Int. J. Entrep. Knowl.*, vol. 7, no. 1, pp. 4–19, 2019, doi: 10.2478/ijek-2019-0001.
- [8] J. M. Müller, D. Kiel, and K. I. Voigt, "What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability," *Sustain.*, vol. 10, no. 1, 2018, doi: 10.3390/su10010247.
- [9] T. C. Ng, S. Y. Lau, M. Ghobakhloo, M. Fathi, and M. S. Liang, "The Application of Industry 4.0 Technological Constituents for Sustainable Manufacturing: A Content-Centric Review," *Sustain.*, vol. 14, no. 7, 2022, doi: 10.3390/su14074327.
- [10] J. M. Katz, *Structural reforms, productivity and technological change in Latin America*. 2001.
- [11] G. Zhang, Y. Yang, and G. Yang, "Smart supply chain management in Industry 4.0: the review, research agenda and strategies in North America," *Ann. Oper. Res.*, 2022, doi: 10.1007/s10479-022-04689-1.
- [12] V. Alcácer and V. Cruz-Machado, "Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems," *Eng. Sci. Technol. an Int. J.*, vol. 22, no. 3, pp. 899–919, 2019, doi: 10.1016/j.jestch.2019.01.006.
- [13] J. Nagy, J. Oláh, E. Erdei, D. Máté, and J. Popp, "The role and impact of industry 4.0 and the internet of things on the business strategy of the value chain-the case of hungary," *Sustain.*, vol. 10, no. 10, 2018, doi: 10.3390/su10103491.
- [14] M. A. Farsi and E. Zio, "Industry 4.0: Some Challenges and Opportunities for Reliability Engineering," *Int. J. Reliab. Risk Saf. Theory Appl.*, vol. 2, no. 1, pp. 23–34, 2019, doi: 10.30699/ijrrs.2.1.4.
- [15] OECD, "The Next Production Revolution: A Report for the G20," 2017. [Online]. Available: <https://www.oecd.org/g20/summits/hamburg/the-next-production-revolution-G20-report.pdf>
- [16] M. Bennis, M. Debbah, and H. V. Poor, "Journal of Industrial Information Integration," *Proc. IEEE*, vol. 106, no. 10, pp. 1834–1853, 2018, doi: 10.1109/JPROC.2018.2867029.
- [17] S. Pokorni, "Reliability and availability of the Internet of things," *Vojnoteh. Glas.*, vol. 67, no. 3, pp. 588–600, 2019, doi: 10.5937/vojtehg67-21363.
- [18] M. R. Piña-Monarrez, M. L. Ramos-Lopez, A. Alvarado-Iniesta, and R. D. Molina-Arredondo, "Robust sample size for Weibull demonstration test plan," *DYNA Colomb.*, vol. 83, no. 197, p. In press, 2016.
- [19] M. R. Piña-Monarrez, "Weibull stress distribution for static mechanical stress and its stress/strength analysis," *Qual. Reliab. Eng. Int.*, vol. 34, no. 2, pp. 229–244, 2018, doi: 10.1002/qre.2251.
- [20] M. Baro and M. P. Monarrez, "Reliability Engineering in Industry 4.0," in *Critical Factor in Industry 4.0*, vol. 1, no. 4, Ciudad Juárez: El Colegio de Chihuahua, 2021, pp. 37–72.
- [21] R. de la Cruz, H. S. Salinas, and C. Meza, "Reliability Estimation for Stress-Strength Model Based on Unit-Half-

- Normal Distribution,” *Symmetry (Basel)*, vol. 14, no. 4, pp. 1–17, 2022, doi: 10.3390/sym14040837.
- [22] M. R. Piña-Monarez, J. F. Ortiz-Yañez, and M. I. Rodríguez-Borbón, “Non-normal Capability Indices for the Weibull and Lognormal Distributions,” *Qual. Reliab. Eng. Int.*, p. n/a-n/a, 2015, doi: 10.1002/qre.1832.
- [23] L. C. Méndez-González, L. A. Rodríguez-Picón, D. J. Valles-Rosales, A. Alvarado Iniesta, and A. E. Q. Carreón, “Reliability analysis using exponentiated Weibull distribution and inverse power law,” *Qual. Reliab. Eng. Int.*, vol. 35, no. 4, pp. 1219–1230, 2019, doi: 10.1002/qre.2455.
- [24] S. Z. Hosseinfard and B. Abbasi, “Process Capability Analysis in Non Normal Linear Regression Profiles,” *Commun. Stat. - Simul. Comput.*, vol. 41, no. 10, pp. 1761–1784, 2012, doi: 10.1080/03610918.2011.611313.
- [25] Y. Lu, “Industry 4.0: A survey on technologies, applications and open research issues,” *J. Ind. Inf. Integr.*, vol. 6, pp. 1–10, 2017, doi: <https://doi.org/10.1016/j.jii.2017.04.005>.
- [26] A. Kormut’ák *et al.*, “Introgressive hybridization between Scots pine and mountain dwarf pine at two localities of northern Slovakia,” *Folia Oecologica*, vol. 40, no. 2, pp. 201–205, 2013.
- [27] B. LAWSON and D. SAMSON, “Developing Innovation Capability in Organisations: a Dynamic Capabilities Approach,” *Int. J. Innov. Manag.*, vol. 05, no. 03, pp. 377–400, 2001, doi: 10.1142/s1363919601000427.
- [28] B. Tjahjono, C. Esplugues, E. Ares, and G. Pelaez, “What does Industry 4.0 mean to Supply Chain?,” *Procedia Manuf.*, vol. 13, pp. 1175–1182, 2017, doi: 10.1016/j.promfg.2017.09.191.
- [29] A. M. R. Tortora, A. Maria, D. P. Valentina, R. Iannone, and C. Pianese, “A survey study on Industry 4.0 readiness level of Italian small and medium enterprises,” *Procedia Comput. Sci.*, vol. 180, pp. 744–753, 2021, doi: 10.1016/j.procs.2021.01.321.
- [30] J.-S. Chen and H.-T. Tsou, “Performance effects of IT capability, service process innovation, and the mediating role of customer service,” *J. Eng. Technol. Manag.*, vol. 29, no. 1, pp. 71–94, Jan. 2012, doi: 10.1016/j.jengtecman.2011.09.007.
- [31] P. Breeding and W. Smith, “Welcome to Software Industry 4.0,” *Digit. Evol.*, vol. 248, no. 5, pp. 70–75, 2013.
- [32] V. Koch and S. Kuge, *Industry 4.0 in Practice*. 2015.
- [33] P. Biggs, *The State of Broadband 2015*, no. September. 2019. doi: 10.1017/CBO9781107415324.004.
- [34] K. Govindan, K. Zeng, and P. Mohapatra, “Probability density of the received power in mobile networks,” *IEEE Trans. Wirel. Commun.*, vol. 10, no. 11, pp. 3613–3619, 2011, doi: 10.1109/TWC.2011.080611.102250.
- [35] T. P. Raptis, A. Passarella, and M. Conti, “Data management in industry 4.0: State of the art and open challenges,” *IEEE Access*, vol. 7, pp. 97052–97093, 2019, doi: 10.1109/ACCESS.2019.2929296.
- [36] C. Liu, R. W. White, and S. Dumais, “Understanding web browsing behaviors through weibull analysis of dwell time,” *SIGIR 2010 Proc. - 33rd Annu. Int. ACM SIGIR Conf. Res. Dev. Inf. Retr.*, pp. 379–386, 2010, doi: 10.1145/1835449.1835513.
- [37] M. Andrzej, “Uncertainty in the Sphere of the Industry 4.0 – Potential Areas To Research,” *Business, Manag. Educ.*, vol. 14, no. 2, pp. 275–291, 2016, doi: 10.3846/bme.2016.332.
- [38] P. Phister, “Reliability , Availability , and Maintainability,” in *Reliability, Availability, and Maintainability*, SEBok, Ed. 2019.
- [39] P. V Varde, “Physics-of-Failure Based Approach for Predicting Life and Reliability of Electronics Components,” *Barc Newsl.*, no. 313, pp. 38–46, 2010.
- [40] H. Rinne, *Distribution The Weibull Distribution A Handbook*. Giessen, Germany, 2009. doi: 10.1201/9781420087444.
- [41] R. Sorenson, “Accelerated Life Testing,” *Syst. Reliab. Theory Model. Stat.*, pp. 1–26, 2011, doi: 10.1002/9780470316900.ch12.
- [42] H. K. Mohajan, “Two Criteria for Good Measurements in Research: Validity and Reliability,” *Ann. Spiru Haret Univ. Econ. Ser.*, vol. 17, no. 4, pp. 59–82, 2017, doi: 10.26458/1746.
- [43] M. Kihl, P. Ödling, C. Lagerstedt, and A. Aurelius, “Traffic analysis and characterization of internet user behavior,” *2010 Int. Congr. Ultra Mod. Telecommun. Control Syst. Work. ICUMT 2010*, pp. 224–231, 2010, doi: 10.1109/ICUMT.2010.5676633.
- [44] W. Weibull, “A Statistical Theory of the Strength of Materials,” *Ingenjors Vetenskaps Akad. Handl.*, vol. 151, pp. 1–45, 1939.
- [45] C. R. Mischke, “A Distribution-Independent Plotting Rule for Ordered Failures,” *J. Mech. Des.*, vol. 104, no. 3, p. 593, 1979, doi: 10.1115/1.3256391.
- [46] D. A. Guimaraes, *Digital Transmission: A Simulation-Aided Introduction with VisSim/Comm*. 2009. doi: 10.1007/978-3-642-01359-1.
- [47] O. C. Ugweje, *Radio Frequency and Wireless Communications*, no. April 2004. 2004. doi: 10.1002/047148296x.tie151.
- [48] K. K. Aggarwal, *TOPICS IN SAFETY, RELIABILITY AND QUALITY*, vol. 53, no. 9. 2013. doi: 10.1017/CBO9781107415324.004.
- [49] V. Roblek, M. Meško, and A. Krapež, “A Complex View of Industry 4.0,” *SAGE Open*, vol. 6, no. 2, pp. 0–11, 2016, doi: 10.1177/2158244016653987.
- [50] K. S. Wang, F. S. Hsu, and P. P. Liu, “Modeling the bathtub shape hazard rate function in terms of reliability,” *Reliab. Eng. Syst. Saf.*, vol. 75, no. 3, pp. 397–406, 2002, doi: 10.1016/S0951-8320(01)00124-7.
- [51] O. Hasan, W. Ahmed, S. Tahar, and M. S. Hamdi, “Reliability block diagrams based analysis: A survey,” *AIP Conf. Proc.*, vol. 1648, no. March, 2015, doi: 10.1063/1.4913184.
- [52] M. A. Arfeen, K. Pawlikowski, D. McNickle, and A. Willig, “The role of the Weibull distribution in Internet traffic modeling,” *Proc. 2013 25th Int. Teletraffic Congr. ITC 2013*, 2013, doi: 10.1109/ITC.2013.6662948.

- [53] J. W. Veile, D. Kiel, J. M. Müller, and K. I. Voigt, “Lessons learned from Industry 4.0 implementation in the German manufacturing industry,” *J. Manuf. Technol. Manag.*, vol. 31, no. 5, pp. 977–997, 2019, doi: 10.1108/JMTM-08-2018-0270.
- [54] D. H. Collins and R. L. Warr, “Failure time distributions for complex equipment,” *Qual. Reliab. Eng. Int.*, vol. 35, no. 1, pp. 146–154, 2019, doi: 10.1002/qre.2387.
- [55] P. Hilber, *Component reliability importance indices for maintenance optimization of electrical networks (RCM)*. 2005.
- [56] D. Horváth and R. Z. Szabó, “Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities?,” *Technol. Forecast. Soc. Change*, vol. 146, no. October 2018, pp. 119–132, 2019, doi: 10.1016/j.techfore.2019.05.021.
- [57] N. H. M. Zaidin, M. N. M. Diah, and S. Sorooshian, “Quality management in industry 4.0 era,” *J. Manag. Sci.*, vol. 1, no. 2, pp. 182–191, 2018, doi: 10.26524/jms.2018.17.
- [58] M. Baro-Tijerina, M. R. Piña-Monárrez, and B. Villa-Covarrubias, “Stress-strength weibull analysis with different shape parameter β and probabilistic safety factor,” *DYNA*, vol. 87, no. 215, pp. 28–33, 2020, doi: 10.15446/dyna.v87n215.84909.