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RESEARCH ARTICLE

Representation and Assessment of Systems Thinking Competencies Through Soft Logic

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ABSTRACT Systems thinking is a trait that enables seeing the 'big picture'. Therefore, it is critical for engineers in the 21st century, as it empowers them to comprehend the dynamic behaviors exhibited by complex systems and effectively tackle the challenges inherent in such systems. Systems thinking skills are inherently multi-dimensional rather than a singular, scalar measure. When evaluating different candidates for an organizational role, such as engineers, significant challenges can arise due to the dilemmas that the multi-dimensional property may trigger. This study introduces the use of Soft logic, a relatively new mathematical approach, to provide a more comprehensive representation of systems thinking skills. By employing the Soft logic tool, engineers' capacity for systems thinking can be assessed across multiple dimensions, offering a valuable aid in the evaluation process. Soft logic enables accommodating in a single variable both the central values of each dimension, as well as the tensions between these dimensions. The tool allows for ordering individuals according to their systems thinking skills, while considering each dimension's provided weight. In regard to previous research in this field, the current methodology enables focusing on the diversity of the skills dimensions within a specific individual in addition to the diversity between individuals. This tool, for example, can enhance the selection process of engineers, ensure a better fit between engineers and job roles, and ultimately promote more effective problem-solving and decision-making within complex systems.

INDEX TERMS Human resources, recruitment, soft logic, systems thinking.

I. INTRODUCTION

The beginning of the 21st century witnessed significant advancements related to the digital era, with the internet and globalization taking center stage. This process led to unprecedented access to information and intellectual resources, enabling individuals to gain awareness of the increasing complexity of problems and chaotic situations. In such a context, the application of systems thinking principles becomes crucial. Systems thinking is a discipline that enables us to see the big picture; for example, a skilled systems thinker in an organizational context can perceive four levels simultaneously: events, patterns of behavior, systems, and mental models [1]. Thus, systems thinking provides a perspective and a set of tools to tackle the challenges of complexity by recognizing the interconnectedness of elements and perceiving the whole system beyond its individual parts.

Systems thinking offers a framework for understanding the interrelationships and recurring patterns of change, rather than focusing on isolated snapshots or static components. It involves recognizing the underlying constructs that shape complex problems. Richmond [2] likens systems thinking to "forest thinking." It involves taking a step back and viewing the system from a higher vantage point, akin to looking at

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a forest from a height of 10,000 meters rather than getting lost in the details of individual trees. It entails considering how one system influences others across boundaries and how those affected systems, in turn, influence the original system. By adopting a systems perspective, one can see the broader network of relationships rather than being trapped in isolated events.

Systems thinking is regarded as a high-order thinking skill that goes beyond basic factual knowledge. It encompasses elements such as critical thinking, creative thinking, analysis, problem-solving, and importantly, systems thinking itself. It is through systems thinking that the disciplines of personal mastery, mental models, shared vision, and team learning come together. Systems thinking may be applied in many fields, for example, in business by identifying areas for change; in a design process by identifying the complex factors that may be involved; in health care by understanding parts of the systems beyond the interaction between the patient and the physician; and even in green innovation by relating to the large number of green clusters. Kordova and Frank [3] found that systems thinking is essential for engineers because it enables them to approach complex problems with a holistic and integrated mindset, for example, in software development projects [4]. By understanding the interconnectedness and dynamics of systems, the tendency to engage in systems thinking enables engineers to respond in real-time and achieve the desired outcome in the most efficient manner possible.

The essence and strength of a systems thinking tendency represent an important aspect of an individual's personality. The study of tendencies originates in the field of educational and vocational counseling, aiming to clarify and match individuals' interests with different professions. Anastasi's book, *Psychological Testing* (1990), introduced popular tests and the process of test construction and interpretation, suggesting that the assessment of opinions and positions primarily falls under the realm of social psychology [5].

One possible tool for assessing an individual's personality is the questionnaire. Self-report questionnaires evaluate specific personality tendencies of individuals. Most tendency questionnaires are designed to assess an individual's inclinations in various occupational domains [6]. The use of tendency questionnaires has evolved alongside ability tests over time [7]. For example, Hansen and Campbell [8] presented the Strong-Campbell Interest Inventory (SVIB-SCII), an occupational tendencies questionnaire based on the assumption that people working in similar professions share common tendencies that differentiate them from individuals in other occupations. This questionnaire consists of 325 items that assess an individual's interests in occupations, hobbies, leisure activities, and school subjects. Another example of a self-report questionnaire is the scale developed by Camelia, Ferris, and Cropley [9]. This questionnaire assesses students' learning of systems thinking in the affective domain within systems engineering education. The affective domain focuses on emotions, feelings, and the value assigned to cognitive aspects of systems thinking.

In the current study, we utilized a self-report questionnaire to evaluate the propensity for systems thinking. The questionnaire was originally developed by Frank [10], and was subsequently adapted for the purposes of this study (it may be provided upon request from the developer). Its main objective is to assess the various attributes associated with systems thinking within individuals. Through this questionnaire, we aim to gain insights into the extent to which participants exhibit systems thinking characteristics. However, as mentioned above, systems thinking skills are multi-dimensional rather than scalar, and when considering different candidates for a role in the organization, significant dilemmas may arise. In this study, a relatively new mathematical approach called "Soft logic" is adopted for the first time to better represent systems thinking skills. In Soft logic, the zero number is extended from a singular point to a continuous axis, thereby enabling a better mathematical representation of paradoxes, tensions, and dilemmas. To support this article's proposition, Soft logic was further developed to the field of linear algebra.

This paper makes several significant contributions to the field of systems thinking. Firstly, it introduces a novel approach by utilizing Soft logic to assess systems thinking skills in a multi-dimensional manner, effectively capturing the complexities of this critical capability. By extending Soft logic to support linear algebra and developing the Soft number framework, this paper provides a quantitative and comprehensive tool for evaluating individuals' systems thinking abilities across various dimensions. This innovation fills a gap in the existing literature, which often relies on scalar assessments that fail to capture the multifaceted nature of systems thinking. This scalar assessment approach ignores the fact that the skill of systems thinking is not a singular trait; rather, it has several dimensions with potential contrasts between them within each specific individual. These contrasts create tensions between the dimensions, and when we disregard these dimensions, naturally, we also omit the tensions between them. Furthermore, the application of this tool extends beyond academic research and can have substantial real-world implications. It offers a practical framework for organizations and recruiters with which to make informed decisions when selecting candidates for roles that require systems thinking, such as engineering positions. The current approach in the literature omits significant information for decision-makers by collapsing a multi-dimensional model into a singular point. Therefore, this predictive validity can lead to more successful and efficient placements, aligning individuals' systems thinking capabilities with the specific demands of their roles, ultimately benefiting not only the individuals but also the organizations they serve. Beyond recruitment, organizations can use the paper's framework for employee development. It allows organizations to identify employees' strengths and weaknesses in systems thinking across multiple dimensions. This information can guide targeted training programs and thus help employees improve their systems thinking skills where needed. This approach fosters a culture of continuous improvement and adaptability, which is invaluable in an ever-changing business environment.

The theory of Soft logic is explained in section C of chapter II, and the extension of this theory and its adoption to represent systems thinking skills is shown in chapter IV. Chapter V introduces an empirical demonstration of this study.

II. RELATED WORKS

A. SYSTEMS THINKING

Systems thinking involves a process of exploration and understanding, of delving into the underlying mechanisms that shape the challenges we encounter and the opportunities we have. It provides a framework for comprehending the forces and interconnectedness that influence the behavior of systems [11]. Sweeney and Sterman [12] highlighted the significance of representing and assessing dynamic complexity, which refers to the behavior that emerges from the interaction of a system's agents over time. They emphasize the importance of both textual and graphical representations.

Senge et al. [11] and other researchers [13], [14], [15] assert that systems thinkers possess the ability to modify their mental models, control their thought processes, and engage in problem-solving. They propose that within a system, cause and effect may not be directly linked in time and space. Therefore, employing systems thinking in problem-solving involves expanding the boundaries of a system and uncovering its hidden dimensions. In organizational systems, this includes social factors such as values, beliefs, and underlying interests. Furthermore, analyzing a system's behavior over time requires retrospective and prospective thinking skills [16].

Fasser and Brettner [17] differentiate systems thinking from other forms of analytical thinking. They emphasize looking beyond individual components and focusing on the system's functionality rather than its structure and internal workings.

The Engineering Systems Division (ESD) Symposium Committee [18], defined systems thinking holistically. According to this definition, systems thinking encompasses the ability to perceive the system, address crucial systems-level issues, recognize emergent properties within systems, and make informed judgments and trade-offs. Sterman [19] relates systems thinking to perceiving the world as a complex system and to understanding that actions have interconnected consequences and that everything is interrelated. Principles of systems thinking have emerged from observing shared holistic aspects of systems across diverse fields. These principles are grounded in the understanding that there are common relationships among natural and human-made systems that can be valuable to comprehend and leverage [20].

In today's intricate and complex environments, the application of systems thinking has become crucial for practitioners. Nagahiet et al. [21] shed light on the significance of considering demographic factors and personality types in understanding and enhancing practitioners' systems thinking skills. They offer valuable insights for practitioners, organizations, and educators alike, emphasizing the importance of addressing these influential factors in fostering effective systems thinking capabilities.

Jaradat, Keating, and Bradley [22] examined individual capacity and organizational competence in relation to systems thinking. They provided insights into how practitioners and organizations can better navigate complex problem domains that are characterized by increasing levels of complexity, ambiguity, uncertainty, and emergence. To tackle these challenges, systems thinking has been proposed as a cognitive framework rooted in a holistic understanding of systems. Systems engineers, for example, have held a distinctive professional responsibility as "systems thinkers," embodying a big-picture, visionary approach to design and excel in managing technical constraints within stable environments. However, in the context of dynamic multistakeholder infrastructure projects, they face a challenging task. Here, they must strike a delicate balance between technical feasibility, political considerations, and meeting the fundamental objectives of the engineering task [23]. Whitehead, Scherer, and Smith [24] highlighted the need for a common language and a foundational framework in systems thinking to enhance research and practical applications in this field. They mentioned various taxonomies for describing systems and approaches to systems, such as those formulated by the International Council on Systems Engineering (INCOSE), the Department of Defense (DoD), the National Aeronautics and Space Administration (NASA), and the Institute of Electrical and Electronics Engineers (IEEE). While each of the above has defined its own distinct sets of terminology within the boundaries of their respective systems, there is currently no consensus within the systems community regarding a common foundation supported by standardized terminology. Systems thinking is usually related to an individual, however can also be referred to a team when this trait is collaborated [25].

B. EVALUATIONS OF SYSTEMS THINKING

The study's tool for assessing systems thinking skills is based on an original tool developed by Frank [26]. Frank's tool was designed to evaluate the level of interest in positions within the field of systems engineering that require systems thinking skills. According to Anastazi [5], interest may be assessed by an interest inventory, which is very common and frequently used to help people choose a profession, and serves as a selection criterion during the recruitment process.

The tool comprises pairs of statements, and for each pair, the examinee was required to make a preference-based choice. The examinee marked "A" if he/she preferred the first statement or "B" if he/she preferred the second statement. The statements deal with preferences, specifically one's likes and dislikes in relation to a diverse array of activities, occupations, professions, or personality types. Frank's tool was used for the selection, filtering, and screening of candidates for systems engineering job positions, facilitating the placement of the most suitable individuals in their respective roles, thus ensuring the "right person in the right job." In the context of the present study, the questionnaire underwent modifications to accommodate a wider spectrum of engineers and a more diverse participant pool. By implementing these changes, the questionnaire was tailored to encompass systems thinking skills relevant to engineers and individuals from various backgrounds and disciplines. Here are some examples of the nature of the changes that were made to broaden the questionnaire's applicability: a) *Terminology*: the original questionnaire used technical jargon and terminology that are specific to systems engineering and that are not necessarily familiar to individuals from other fields. To make it more accessible, technical terms were replaced with simpler language or explanations; b) *Examples and Scenarios*: The questionnaire originally contained scenarios or examples that were highly specific to systems engineering. These were modified or expanded to include a broader range of contexts or industries; c) *Skills and Traits*: the modified version of the tool included statements related to various skills and traits, such as interpersonal skills, analytical ability, holistic perspective, creativity, abstract thinking, communication skills, drive, technical expertise, curiosity etc. These additions expanded the questionnaire's scope beyond just systems engineering skills; d) *Diversity and Inclusivity*: Actions were taken to ensure that the questionnaire's content is inclusive and relevant to individuals from different backgrounds, genders, ethnicities, and cultures.

The modified tool for estimating systems thinking skills was tested and implemented in several studies, and its reliability and validity were examined. Two types of reliability, inter-judge reliability and Alpha reliability coefficient, and four types of validity—content validity, concurrent validity, contrasted group validity, and construct validity—were examined [3], [26], [27]. The results from these three studies confirmed that the tool has the potential to be a valuable instrument for a wide range of stakeholders, including organizations, systems engineering researchers, managers, and educators.

Based on the division by Frank [10], according to which systems thinking includes four different aspects (dimensions)—knowledge, individual traits, cognitive characteristics, and capabilities—a suitable structural model for systems thinking was formulated using AMOS software [27]. TABLE 1 presents the factors of each aspect as found according to the model of systems thinking. These aspects and the derived factors apply both to the original tool (where they were developed), and to the tool used in the current research.

TABLE 1. Factors of systems thinking aspects (dimensions).

Aspect	Factors of the aspect	Factors of the aspect as expressed in the questionnaire items
Knowledge	Interdisciplinary and multidisciplinary knowledge	Knowledge of technological/engineering aspects of the project, multidisciplinary knowledge, knowledge in project management, cost management, management models, organizational systems analysis.
	Extensive experience in dealing with systems tasks, technical experience	
Individual traits	Managerial skills	Preference for engaging in management in the future and incorporating different interdisciplinary engineering areas; desire to get involved in the future in a management discipline as a team head or project manager.
	Group leadership	Willingness to work in a team when a partner is engaged in the project work.
	Good interpersonal skills, building relationships of trust with interested parties, good communication skills, ability to "read" people	Preference to be part of a team that executed the final project as a group (and not individually).
	Desire to deal with systems, strong desire to succeed	Personal preference to focus also on topics that are not core topics.
	Perceiving failures and mistakes as challenges, decisiveness, tolerance of difficulties	
	Self-confidence and personal motivation	Tendency to participate in class discussions affecting the determination of future directions in the business world; willingness to meet the timetable required to complete the final project.
Cognitive characteristics	Understanding the overall system, getting the big picture	Working on a final project that combines multidisciplinary topics.
	Creative thinking	
	Understanding the system without being familiar with all of its details, tolerance of situations of uncertainty	Examining the possible implications of changes in the organizational system—systemically, economically, and otherwise.
	Understanding the synergy between different systems	Dealing with combinations and integrations between systems/products/processes during the final project.
	Curiosity, innovation, originality, invention, promotion	
	Asking good questions	
	Placing limits	

TABLE 1. ***(Continued.)*** **Factors of systems thinking aspects (dimensions).**

	Considering non-engineering factors, such as economic, commercial, political factors	Relating to economic and managerial aspects of the project beyond the operational/engineering areas presented in it; awareness of non-engineering considerations, such as commercial and economic considerations, welfare considerations, business advantages, feasibility analyses, etc.; taking political and organizational considerations into account while providing a solution to the problem being examined in the final project.
Capabilities	Ability to perform an analysis of requirements	The ability to understand the needs and requirements of the client; the ability to analyze the needs, requirements, and preferences of the client.
	Abstract thinking and the ability to develop the solution	The ability to find a solution to a problem by "bypassing" the problem.
	Functional analysis	
	"Seeing the future," vision of the future	
	Use of simulation and engineering tools	
	Optimization	The ability to apply cost-effective considerations.
	Resolving system failures and problems	

As mentioned above, the revised questionnaire was modified to suit a broader range of engineers, and this was achieved for example by replacing specific technical terms that may be unfamiliar to the broad population. However, the revised questionnaire also addresses the same four dimensions of systems thinking.

C. THE THEORY OF SOFT LOGIC

Soft logic is a mathematical theory that facilitates richer and more diverse situations than the regular logical distinction between right and wrong, true and false, etc. [28]. It is a mathematical theory that includes the invention of a new type of number called a "Soft number" [29]. By using Soft logic, new approaches have been developed, including a novel approach to defining random variables in a way that can enhance splitting criteria in decision trees [30]; a mathematical presentation of the privacy paradox [31]; and a way to present physical vacuums (whose existence was proved by the French mathematician and physicist Blaise Pascal) as an extension of zero. Soft logic is closely related to soft computing which enables handling, vague truth and uncertainty, and is applicable, for example, in predicting permeability - a pivotal to petroleum engineers [32].

Our times fundamentally require a new mathematical representation that is Soft and dialogical. Accordingly, Soft logic emerged from the desire to find a holistic mathematical approach that is capable of containing vague situations, or as some call it, "non-mathematical elements". This is why Soft logic has the potential to handle issues such as systems thinking skills. The ability of Soft logic to contain contradictory and opposing situations may assist in cases of human conflicts and disputes, and this is why Soft logic is suitable for presenting systems thinking skills, which are multi-dimensional and can introduce tensions and dilemmas.

Life is richer and more varied and colorful than two binary extremes. To use the color analogy, one can say that the Soft logic approach is more colorful; it has more colors and shades than just black and white. Regular mathematics avoids paradoxical situations that contain internal contradictions. On the other hand, Soft logic by definition combines logical and linear thinking with a type of thinking based on the mathematical exercise of dividing zero by itself, an expression with infinite correct results.

Soft logic is based on a new perspective on the number zero, which was invented in India in the seventh century. This invention is relatively modern, compared to the invention of all the natural numbers tens of thousands of years ago. The invention of the zero was revolutionary since it gave a special sign to an amount that is nothing at all. This invention enabled the development of the decimal system of writing numbers. Soft logic expands the effect of the location of the number zero, as it assumes a continuum of zeros rather than a discrete location of zeroes.

The mathematician Leibnitz developed the binary system based on two numbers only, one and zero; later it became the mathematical infrastructure for the development of the computer. Leibnitz himself strove to develop a new mathematical language that would be at the same time rational and softer than the dichotomy of right and wrong [33]. The term "Soft logic" was inspired by him.

Soft logic assumes the existence of a continuum of distinct multiples $a\bar{0}$, where a is any real number and $\bar{0}$ symbolizes an object that may be called a 'Soft zero', while its multiples are also called "Soft zeros". In other words, zero is no longer a singular point. The real part of a number is denoted by $\bar{1}$ and is actually the real (old) number 1, where all other real numbers are conceived as its multiples. The term absolute zero (bolded) is define as: $\mathbf{0} = 0\bar{0}$.

The core advantage of Soft logic is the ability to represent and handle mathematically vague situations, but its advantages also extend to many other fields, such as probability theory. Kolmogorov developed the axioms of probability theory in the 20th century [34]. He formulated the axioms according to the principles of the laws of probability developed by Pascal and Fermat in the 17th century CE. Kolmogorov ignored the heated debate surrounding the probabilistic interpretation of quantum mechanics. Soft logic aims to express not only the uncertainty regarding what will happen in the future, but also the different interpretations of current reality made by the observer of a phenomenon. For example, in the probability theory of continuous variables, it is impossible to distinguish between the probability that a random variable will take on a value less than a certain number, and the probability that it will take on a value less than or equal to that number. The probability that a specific (singular) event will occur is zero. We resolve this lack of distinction by using Soft numbers, by multiplying the density function by a Soft zero. This is one of the advantages of Soft logic.

Another advantage of Soft logic is creating a new, concrete mathematical model of the infinitesimal world. These are mathematical quantities that decrease infinitely and are smaller than any real number. Throughout the history of mathematics, several models have been developed for this world. For comparison, we will mention two such models: The first one is the dual numbers developed by Clifford, which are of the form $a + b\varepsilon$, where $\varepsilon^2 = 0$ [35]. Another model is the theory called nonstandard analysis, developed by Robinson [36]. The difference between Soft logic and these models is the specific use of the number zero and its extension to a continuum of zeros distinguished from each other. In this way, we create a tangible model of the infinitesimal world, as opposed to just proving existence as is done in nonstandard analysis.

To construct Soft logic, several axioms were defined [37]. To this end, let a, b be any real numbers and $a\bar{0}, b\bar{0}$ be two corresponding Soft zeros as defined above. The first four axioms of Soft logic are related to the axioms of dual numbers. The difference is in using the number zero and its extension, instead of the abstract notion of ε. The fifth axiom of non-commutativity does not exist for dual numbers.

Axiom 1 (Distinction): If $a \neq b$ then $a\bar{0} \neq b\bar{0}$. This relation expresses the extension of zero from a singular point to a straight line (axis). It creates a distinction between different multiples of $(\bar{0})$. From this axiom we derive the **Definition 1 (of Order)**: If $a < b$ then $a\bar{0} < b\bar{0}$.

This axiom is related to the inequalities ($a \leq b$ if and only if there exists c such that $a + c = b$) derived from the second-order induction axiom of the Peano axiom system [38].

Now, consider the addition operator:

Axiom 2 (Addition): $a\bar{0} + b\bar{0} = (a + b)\bar{0}$.

The $\bar{1}$ axis behaves regularly: $a\bar{1} + b\bar{1} = (a + b)\bar{1}$.

This axiom is related to the distributive property $(a\cdot (x + y) = a\cdot x + a\cdot y)$ of classic algebra [39].

Now, consider the multiplication operator:

Axiom 3 (Nullity): $a\bar{0} * b\bar{0} = 0$.

Numbers on the zero axis "collapse" under multiplication operations. Addition has significance and meaning, but multiplication does not make any distinction. On the other hand, $a\bar{1} * b\bar{1} = ab\bar{1}$, $a\bar{0} * b\bar{1} = ab\bar{0}$, and $b\bar{1} * a\bar{0} = ba\bar{0}$.

This axiom is related to the property of dual numbers ($\varepsilon^2 = 0$) developed by Clifford [35].

Axiom 4 (Bridging): A bridge exists between the zero axis and the real axis and vice versa (denoted by $\perp$).

Thus, Soft logic defines a value that combines a value from the zero line ($\bar{0}$-axis) with a value from the real line ($\bar{1}-$ axis), which is denoted as $a\bar{0} \perp b\bar{1}$.

This axiom is similar to the property that defines complex numbers ($a + bi$) as a combination of a real part and an imaginary part [40]. It is also related to the dual numbers property mentioned above.

Axiom 5 (Non-commutativity): $a\bar{0} \perp b\bar{1} \neq b\bar{1} \perp a\bar{0}$.

Note that the multiplication of a zero-axis number with a regular real number, as defined in Axiom 3, is commutative, but for the subsequent parts of the theory, the order of these numbers is important.

This property holds for certain algebraic structures that are non-commutative, e.g., the $(a\cdot b \neq b\cdot a)$ property of the non-abelian group [41].

Soft number theory is based on these five axioms (and no more), and from this point of origin, the rest (some are shown in this chapter) can be developed.

Definition 2 (Soft number):

A Soft number is a construction of the following form:

$$a\bar{0}\dot{+}b\bar{1} = \{(a\bar{0}) \perp (b\bar{1})\,;\,(b\bar{1}) \perp (a\bar{0})\} \tag{1}$$

where a, b are any real numbers.

Any soft number denominated as $a\bar{0}\dot{+}b\bar{1}$ has a component from the real line or $\bar{1}$ line, and a component from the $\bar{0}$ line (later on, we will omit the bar above the numeral 1, or even the 1 itself, but the bar above the numeral 0 is essential). The dot above the sign '+' implies that unlike a regular sum, a Soft number does not have one single value but rather two distinct values, presented by its definition. Now, the set of all Soft numbers defines all possible Soft numbers and is denoted by SN:

$$\mathrm{SN} = \{a\bar{0}\dot{+}b : a, b \in \mathbb{R}\} \tag{2}$$

The addition operator of two Soft numbers is defined as follows:

$$(a\bar{0}\dot{+}b) + (c\bar{0}\dot{+}d) = (a + c)\,\bar{0}\dot{+}\,(b + d) \tag{3}$$

The set SN is a group under addition (SN, +), where the + sign represents the addition operation for this group.

The multiplication of two Soft numbers is defined as follows:

$$(a\bar{0}\dot{+}b) \times (c\bar{0}\dot{+}d) = (ad + bc)\,\bar{0}\dot{+}\,(bd) \tag{4}$$

This operation is commutative and satisfies the laws of associativity and distribution. With these two operations, + and ×, Soft numbers create the ring (SN, +, ×), in which the + and × signs represent the addition and multiplication operators of the ring.

The inverse of a Soft number exists when $b \neq 0$, and it is defined as:

$$(a\bar{0}\dot{+}b)^{-1} = \left(-\frac{a}{b^2}\bar{0}\dot{+}\frac{1}{b}\right) \tag{5}$$

(SN, +, ×) is almost a field, an algebraic structure with two operations, addition and multiplication, that satisfy certain rules ("almost" because the inverse is undefined only when $b = 0$).

The $n-$th power of a Soft number is given by:

$$\left(a\bar{0}\dot{+}b\right)^n = nab^{n-1}\bar{0}\dot{+}b^n \tag{6}$$

where n is any natural number ($n \in \mathbb{N}^+$, $\mathbb{N}^+ = \{0, 1, 2, 3, \ldots\}$).

The square root of a Soft number exists when $b > 0$, and it has two values:

$$\sqrt{a\bar{0}\dot{+}b} = \left(+\frac{a}{2\sqrt{b}}\bar{0}\right)\dot{+}\left(+\sqrt{b}\right), \left(-\frac{a}{2\sqrt{b}}\bar{0}\right)\dot{+}\left(-\sqrt{b}\right) \tag{7}$$

The $n-$th root of a Soft number satisfies that for $b\neq 0$ and for an odd n:

$$\sqrt[n]{a\bar{0}\dot{+}b} = \left(+\frac{a}{n \cdot b^{\left(\frac{n-1}{n}\right)}}\bar{0}\right)\dot{+}(+\sqrt[n]{b}) \tag{8a}$$

and for $b > 0$ and an even n: $\sqrt[n]{a\bar{0}\dot{+}b} =$

$$\left(+\frac{a}{n \cdot b\left(\frac{n-1}{n}\right)}\bar{0}\right)\dot{+}(+\sqrt[n]{b}), \left(-\frac{a}{n \cdot b\left(\frac{n-1}{n}\right)}\bar{0}\right)\dot{+}(-\sqrt[n]{b}) \tag{8b}$$

The projection of Soft numbers to calculus is expressed in the following equation:

$$\left(a\bar{0}\dot{+}x\right)^n = (n \cdot a \cdot x^{n-1})\bar{0}\dot{+}x^n = \left(ax^n\right)'\bar{0}\dot{+}x^n \tag{9}$$

To generalize the basic calculus equation, if $P(x)$ is a real polynomial function, then any Soft number $a\bar{0}\dot{+}x$ satisfies:

$$P\left(a\bar{0}\dot{+}x\right) = aP'(x)\,\bar{0}\dot{+}P(x) \tag{10}$$

The definition of a function of a Soft variable arises from the real differentiable function f(x), so that for any Soft number $a\bar{0}\dot{+}x$:

$$\bar{f}\left(a\bar{0}\dot{+}x\right) = af'(x)\,\bar{0}\dot{+}f(x) \tag{11}$$

III. SOFT LINEAR ALGEBRA

The issue of evaluating systems thinking is multi-dimensional as will be detailed in the next section. Therefore, for the purpose of representing systems thinking skills with Soft logic, this theory has to be extended to the field of linear algebra. This section describes the extension we made to Soft logic to support the matrix.

As defined above, $\mathrm{SN} = \left\{a\bar{0}\dot{+}b,\ a, b\in R\right\}$. Now, let a Soft vector be defined as follows:

$$v = (v_1, v_2, \ldots, v_n)\,|v_i \in SN \text{ when } v_i = u_i\bar{0}\dot{+}w_i \tag{12}$$

The presentation of a Soft vector can be split:

$$v = (u_1, \ldots u_n)\,\bar{0}\dot{+}\,(w_1, w_2, \ldots w_n)\,|u_i \in R, w_j \in R\} \tag{13}$$

The addition operator on the two Soft vectors $v = (v_1, v_2, \ldots, v_n)\,|v_i\in SN$ and $u = (u_1, u_2, \ldots, u_n)\,|u_i\in SN$ will be defined as:

$$v + w = (v_1 + u_1, v_1 + u_2 \ldots, v_n + u_n) \tag{14}$$

The multiplication operator of a Soft vector v(as defined above) with a scalar $k(k\in R \text{ or } k\in SN)$(real or Soft) will be:

$$kv = (kv_1, kv_2, \ldots, kv_n)\,|v_i\in SN \tag{15}$$

Now, a Soft matrix can be defined as:

$$C = \left\{c_{i,j} \mid c_{i,j} \in SN\right\} \text{ when } 1 \leq i \leq n, 1 \leq j \leq m,$$

where each element of the matrix C can be split:

$$\begin{aligned} &c_{i,j} = a_{i,j}\bar{0}\dot{+}b_{i,j} \\ &\mathrm{A} = \left\{a_{i,j}\right\} \qquad a_{i,j} \in R \quad 1 \leq i \leq n \quad ; 1 \leq j \leq m \\ &\mathrm{B} = \left\{b_{i,j}\right\} \qquad b_{i,j} \in R \quad 1 \leq i \leq n \quad ; 1 \leq j \leq m \end{aligned} \tag{16a}$$

Therefore, C can have a canonical presentation:
$C = A\bar{0}\dot{+}B$ (where A and B are real matrices)

$$C = \left\{\begin{matrix} c_{1,1} & c_{1,2} & \ldots & c_{1,n} \\ c_{2,1} & c_{2,2} & \ldots & c_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n,1} & c_{n,1} & \ldots & c_{n,n} \end{matrix}\right\} \tag{16b}$$

The addition operator of two Soft matrices $C_1 = A_1\bar{0}\dot{+}B_1$ and $C_2 = A_2\bar{0}\dot{+}B_2$ is:

$$C_1 + C_2 = (A_1 + A_2)\,\bar{0}\dot{+}\,(B_1 + B_2) \tag{17}$$

The multiplication operator of two Soft matrices will be

$$C_1 \cdot C_2 = (A_1 \cdot B_1 + A_2 \cdot B_1)\,\bar{0}\dot{+}B_1 \cdot B_2 \tag{18}$$

The powers of the Soft matrix $C = A\bar{0}\dot{+}B$:

$$\begin{aligned} \mathrm{C}^2 &= 2\mathrm{AB}\dot{+}B^2 \\ \mathrm{C}^n &= n\mathrm{AB}^{n-1}\bar{0}\dot{+}B^n \end{aligned} \tag{19}$$

And the inverse of a Soft matrix:

$$(A\bar{0}\dot{+}B)^{-1} = -A\left(B^2\right)^{-1}\bar{0}\dot{+}(B)^{-1} \tag{20}$$

The Soft matrices C can be presented as:

$$\mathrm{C} = \left\{\begin{matrix} \vec{c_1} \\ \vdots \\ \vec{c_n} \end{matrix}\right\} \tag{21}$$

Now, let $\vec{w}$ be a weights vector that provides different weights to the different dimensions:

$$\vec{w} = (w_1, w_2, \ldots, w_n), \quad w_k \in R \tag{22}$$

Weighting C by $\vec{w}$, which is actually the multiplication of Soft matrices with a real weight vector, is represented by:

$$\mathrm{C}\vec{w} = \left\{\begin{matrix} \vec{c}_1\vec{w} \\ \vdots \\ \vec{c}_n\vec{w} \end{matrix}\right\}$$

where

$$\begin{aligned}\vec{c}_1\vec{w} &= \left(a_{1,1}\bar{0} + b_{1,1}\right) w_1 + \left(a_{1,2}\bar{0} + b_{1,2}\right) w_2 \\ &\quad + \cdots \left(\left(a_{1,n}\bar{0} + b_{1,n}\right) w_n\right. \\ \vec{c}_k\vec{w} &= \left(a_{k,1}\bar{0} + b_{k,1}\right) w_1 + \left(a_{k,2}\bar{0} + b_{k,2}\right) w_2 \\ &\quad + \cdots \left(\left(a_{k,n}\bar{0} + b_{k,n}\right) w_n\right. \\ \vec{c}_n\vec{w} &= \left(a_{n,1}\bar{0} + b_{n,1}\right) w_1 + \left(a_{n,2}\bar{0} + b_{n,2}\right) w_2 \\ &\quad + \cdots \left(\left(a_{n,n}\bar{0} + b_{n,n}\right) w_n\right. \end{aligned} \tag{23}$$

The order of the two Soft numbers $c_1 = a_1\bar{0}\dot{+}b_1$ and $c_2 = a_2\bar{0}\dot{+}b_2$ is defined by a lexicographic approach. First, we compare the real part and then, if necessary, we compare the Soft part but in the opposite direction. The formal definition is:

$$c_1 < c_2 \Leftrightarrow (b_1 < b_2)\; or\; ((b_1 = b_2)\; and\; (a_2 < a_1)) \tag{24}$$

IV. ADOPTING SOFT LOGIC TO SYSTEMS THINKING

A. PRELIMINARIES

Systems thinking in this study is expressed and measured through four dimensions: knowledge, individual traits, cognitive characteristics, capabilities, marked as $S = \{s_1, s_2, s_3, s_4\}$ respectively. For a specific individual, each dimension s_i may receive a continuous value on a predetermined scale, representing the level of this dimension (the higher, the better) regarding this individual. While the literature on systems thinking suggests these four dimensions [27], the model is flexible enough to accommodate any discrete number of dimensions of other proficiencies or skills.

The core issue is the fact that different people do not line up and correlate with regard to the elements of S. For example, imagine two people, one with $S_1 = \{9, 5, 3, 7\}$, and the other with $S_2 = \{9, 3, 5, 7\}$; it can be noticed that the first one is stronger in s_2, while the second one is stronger in s_3.

B. REPRESENTATION OF SYSTEMS THINKING

Considering the combination of each two dimensions, the central values of these dimensions, which are their averages, are expressed in the matrix $S^{\bar{1}}$ as defined in (25). Each row and column index of the matrix $S^{\bar{1}}$ is formed by S. The diagonal represents the combination of each dimension with itself; therefore, the sole dimension. The values above the diagonal represent the average of two dimensions, while the values below the diagonal are discarded, as they are a mirror image of the ones above. In the Soft logic representation, this matrix stands for the $\bar{1}$ component of the Soft number. Semantically, the matrix $S^{\bar{1}}$ represents the **central values** of the dimensions, ignoring the differences between them.

$$S^{\bar{1}} = \left(\frac{s_i + s_j}{2}\right) = \begin{pmatrix} s_1 & \frac{s_1+s_2}{2} & \cdots & \cdots \\ \cdot & \ddots & \vdots & \vdots \\ \cdot & \cdot & \ddots & \ddots \\ \cdot & \cdot & \cdot & \ddots \end{pmatrix} \tag{25}$$

The differences between the dimensions span a combinatorial space of the combinations of each two dimensions (naturally, order is neglected), and are expressed in the matrix S' as defined in (27). Each row and column are indexed in the same way as in (25), and each value above the diagonal is the distance (therefore, the expression is based on the absolute value) between the average value expressed in (25)and each of the values (which is the same for both of them). The diagonal represents the combination of each dimension with itself and, therefore, must be 0, and as in (25), the values are mirrored, and consequently, both are not mentioned.

$$S' = \left(\left|s_i - s_j\right|\right) = \begin{pmatrix} 0 & |s_1 - s_2| & |s_1 - s_3| & |s_1 - s_4| \\ \cdot & 0 & |s_2 - s_3| & |s_2 - s_4| \\ \cdot & \cdot & 0 & |s_3 - s_4| \\ \cdot & \cdot & \cdot & 0 \end{pmatrix} \tag{26}$$

However, to handle small and insignificant differences, we introduce a threshold, in which below this value the difference is set to 0; thus, the complete differences matrix $S^{\bar{0}}$ is defined as shown in (27). In the Soft logic representation, this matrix stands for the $\bar{0}$ component of the Soft number. Semantically, the matrix $S^{\bar{0}}$ represents the **tension** between the dimensions.

$$S^{\bar{0}} = \left(\begin{cases} \frac{|s_i - s_j|}{2} & |s_i - s_j| > T \\ 0 & otherwise \end{cases}\right) = \begin{pmatrix} \cdot & \begin{cases} \frac{|s_1 - s_2|}{2} & |s_1 - s_2| > T \\ 0 & otherwise \end{cases} & \cdots & \cdots \\ \cdot & \cdot & \vdots & \vdots \\ \cdot & \cdot & \cdot & \ddots \\ \cdot & \cdot & \cdot & \cdot \end{pmatrix} \tag{27}$$

Finally, the comprehensive ranking of an individual's systems thinking skills is expressed by STS, as shown in (28). STS is a Soft number that encapsulates both the central values of the dimensions and the tensions between them.

$$STS = S^{\bar{0}} \otimes \bar{0}\dot{+}S^{\bar{1}} \otimes \bar{1} \tag{28}$$

C. ORDERING

Assume we have two individuals with systems thinking levels of STS_1 and STS_2 respectively. In addition, the recruiter weighted the dimensions of S with the vector $\vec{w} = (w_1, w_2, \ldots, w_n)$, where $w_k \in R$ and $\sum_{\forall i} w_i = 1$. Each element of w_i refers to the parallel element of S and indicates its weight. The overall rank of the central values of STS, denoted by $STS^{r\bar{1}}$, is the sum of the multiplications of each member of the diagonal of matrix $S^{\bar{1}}$ with the corresponding member of $\vec{w}$:

$$STS^{r\bar{1}} = \sum_{\forall i} S^{\bar{0}}{}_{i,i} \cdot w_i \tag{29a}$$

And the overall rank of the tensions of STS, denoted by $STS^{r\bar{0}}$, is the sum of the multiplication of each member of the matrix $S^{\bar{0}}$ by the average of the corresponding members of $\vec{w}$:

$$STS^{r\bar{0}} = \sum_{\forall i \text{ and } j} S^{\bar{0}}{}_{i,j} \cdot \frac{w_i + w_j}{2} \tag{29b}$$

Now, the STS_1 and STS_2 can be ordered according to the rule derived from Eq. (24):

$$STS_1 < STS_2 \Leftrightarrow \left(STS^{r\bar{1}}{}_1 < STS^{r\bar{1}}{}_2\right) \text{ or } \left(\left(STS^{r\bar{1}}{}_1 = STS^{r\bar{1}}{}_2\right) \text{ and } \left(STS_2^{r\bar{0}} < STS^{r\bar{0}}{}_1\right)\right) \tag{30}$$

V. EMPIRICAL DEMONSTRATION

A. DESIGN

To empirically demonstrate the methodology, we collected data from a population of $n = 153$ valid participants. These participants were asked to complete a questionnaire consisting of 31 pairs of statements designed to assess their systems thinking tendency.

The sample included 42 undergraduate students majoring in industrial engineering and management, and 111 high school students studying in the industrial engineering and management track. Both the students and the high school students were required to present a capstone project in industrial engineering and management that has the potential to enhance their systems thinking skills.

The self-report questionnaire used to assess the systems thinking tendency was originally developed by Frank [26]. As explained above, the questionnaire was modified for the current study to suit a broader range of engineers and a more diverse population. The adaptation was necessary, as the original questionnaire was specifically designed for systems engineers. Through the modifications, the questionnaire was tailored to capture the systems thinking characteristics applicable to engineers, managers, and individuals from different backgrounds and disciplines. The revised questionnaire was formulated to address the four dimensions of systems thinking: knowledge, individual traits, cognitive characteristics, and capabilities. Each question included two propositions, whereby one of them indicates a systems thinking tendency while the other does not. The participants had to select one of them, and the fact that "there is no right or wrong answer" was emphasized. Here are two example items from the modified questionnaire:

Example 1:

A. When I take care of a product, it is important for me to concentrate on this product, assuming that other engineers will take care of the other parts of the system.
B. When I take care of a product, it is important for me to see how it functions as a part of the system.

In Example 1, answer B indicates a systems thinking tendency because it shows a holistic approach rather than a reductionistic one. Example 1 refers to the Individual traits aspect (dimension), dealing with combinations and integrations between systems/products/processes.

Example 2:

A. I think that every employee should gain interdisciplinary knowledge and general knowledge in several fields.
B. I think that every employee should become an expert in his/her field. Learning more fields may lead to sciolism (to know a little about many subjects).

In Example 2, answer A indicates a systems thinking tendency because it shows various perspectives. Example 2 refers to the Knowledge aspect (dimension), dealing with interdisciplinary and multidisciplinary knowledge.

The questions were divided into four groups, each indicating the systems thinking level of each of the four dimensions. For each question, a score of 1 was given if the answer indicated systems thinking and otherwise 0. The final grade of the individual for each of the dimensions is given by the sum of the scores of the questions in each dimension group, divided by the number of questions in the group. Therefore, the rank can range from 0 (the lowest level of systems thinking skills) to 1 (the highest level of systems thinking skills).

The participants of this experiment provided full consent and were allowed to drop off at any stage. The experiment was authorized by the institutional ethics committee.

B. RAW RESULTS

The results indicated that for knowledge, the rank was ($\mu = 0.72$, $\sigma = 0.26$), for individual traits ($\mu = 0.69$, $\sigma = 0.17$), for cognitive characteristics ($\mu = 0.68$, $\sigma = 0.19$), and for capabilities ($\mu = 0.58$, $\sigma = 0.17$). The distributions of the ranks are depicted in FIGURE **1**. The X-axis describes the ranks (from 0 to 1), while the Y-axis describes the frequencies for each rank and dimension. Each line represents one dimension. Two insights can be deduced from the graphical presentation: a) There is a clear distribution in the empirical study population across the rank of each dimension, i.e., people do differ in their systems thinking skills; and b) It is suggested that the ranks also distribute between dimensions, i.e., within each subject. The latter insight, which is significant for the contribution of this paper, was proved statistically in section C of this chapter.

C. SOFT LOGIC PRESENTATION

Given the final rank $r_{i,j}$ for each individual i and for each group (dimension) j, the individuals' Soft matrices can be calculated. We selected a threshold $T = 0.2$, but this selection is subjective and should be determined by an expert in the specific field of employment under consideration. The representative matrix $STS = S^{\bar{0}} \otimes \bar{0} \dot{+} S^{\bar{1}} \otimes \bar{1}$ for an individual can be calculated based on equations (25) and (27).

For a general impression, the averages of the central values for the entire study population, which are the $\bar{1}$ components are depicted in FIGURE ***2***. The X-axis and the Y-axis describe the dimensions, while the Z-axis describes the average of the

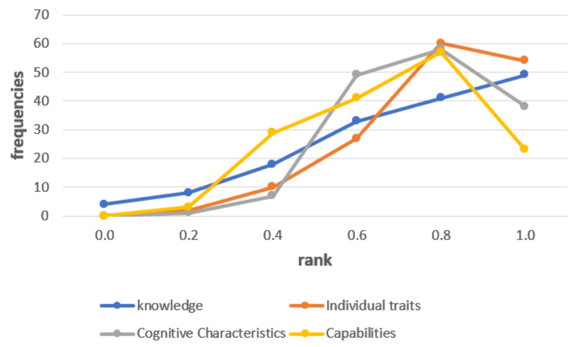

FIGURE 1. The distribution of the ranks for each dimension among the study population.

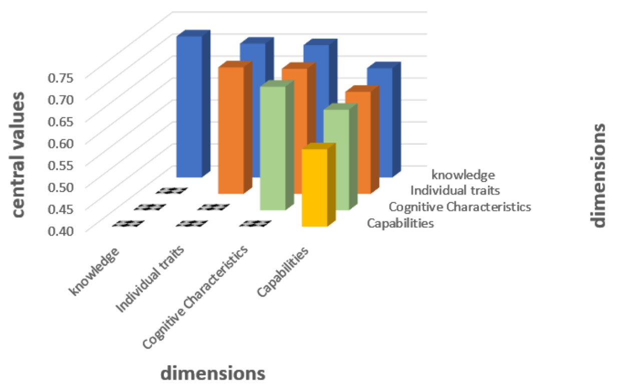

FIGURE 2. The averages of the central values of the study population.

central values. The flat spotted black and white bars represent combinations that are mirrored.

The averages of the tensions between the dimensions for the entire study population, which are the $\bar{0}$ components are depicted in FIGURE**.** 3. The X-axis and the Y-axis describe the dimensions, while the Z-axis describes the average of the tensions. The flat spotted bar represents combinations that are mirrored, or a dimension combined with itself.

The major contribution of this research is the representation of the diverse dimensions and the tension between them, which enables a more thorough analysis. However, diversity must exist in the empirical population in order to effectively demonstrate the methodology. To this end, a repeated measure ANOVA was conducted on the empirical study results ($n = 153$) to focus on within-subjects analysis rather than on between-subjects. The results of the multivariate tests analysis indicate that $Wilks' Lambda = 0.92$, $F(3, 153) = 20.641$, $p < 0.01$, i.e., the null hypothesis can be rejected, and there is a significant difference between the dimensions. The Pairwise-comparison analysis indicated a significant difference between all pairs of dimensions except for knowledge – individual traits, knowledge – cognitive characteristics, and individual traits – cognitive characteristics. These results indicate that diversity does exist and justifies the necessity of the proposed methodology.

Now, for each individual in the study, *STS* can be calculated. For the purpose of this demonstration, we kept the threshold T=0.2 and assigned the same weight to each dimension, i.e., $w_i = 0.25\ \forall i$. FIGURE. 4 presents all the participants in the study, ordered by their final rank. The X-axis describes the participant's index, while the Y-axis is the systems thinking level.

The presentation and flexibility of the results of the current research are significantly enhanced in comparison to previous research. For example, one study aimed to develop a scale to assess students' learning about systems thinking [9]. In this research, conducted among 180 undergraduate engineering students, the assessment base was also a questionnaire (30 questions); however, all questions were treated homogenously and thus did not provide information about the various dimensions nor, naturally, about the tension

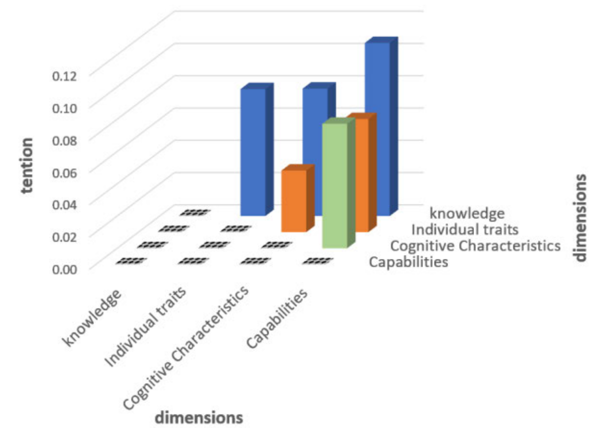

FIGURE 3. The averages of the tensions of the study population.

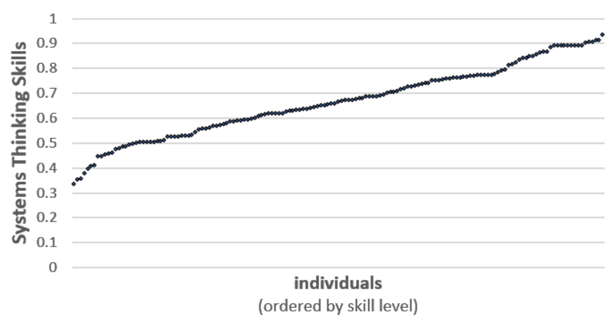

FIGURE 4. Ranks of individual systems thinking skills ordered from low to high.

between them. The PCA analysis that was conducted yielded several factors of mathematically vague meaning from the decision-making point of view. A similar situation can be noticed in other research that explored the effect of an online cross-disciplinary learning process on the development of systems thinking skills [42]or examined the development of systems thinking among engineers and engineering students [43]. Again, internal factors of systems thinking were not addressed, and while these research handled the analysis of differences in-between groups of participants, the internal diversity of each individual's systems thinking skills remained unaddressed.

VI. CONCLUSION

This paper introduces a method for presenting systems thinking competencies through Soft logic for the first time. Soft logic has some core characteristics that make it suitable for this task; however, since systems thinking is a multi-dimensional issue, Soft logic had to be extended to support linear algebra.

Systems thinking skills are multi-dimensional, so that each dimension represents a distinct aspect of systems thinking, and candidates may excel in different dimensions based on their individual strengths and expertise. As explained in section IV, a Soft number (*STS*) was developed to encapsulate both the central values of systems thinking dimensions and the tensions between these dimensions. The tool enables ordering individuals according to their *STS* scale while considering the provided weight of each dimension and a selected threshold to distinguish if tension exists. Having a tool that can effectively define an individual's tendency for systems thinking across multiple dimensions is crucial for making informed decisions when selecting the right engineer for a particular job.

This Soft logic tool enhances the selection process by enabling a comprehensive evaluation and allowing decision-makers to compare engineers' or other candidates' abilities on each dimension of systems thinking. In other words, this tool can provide a quantitative framework for assessing candidates' skills. An adequate mathematical representation of systems thinking skills opens the door to a wide range of operations that can be applied to these measures.

Further research may apply this tool in a real-life scenario. This type of research can compare decisions about candidates that are accepted using this structured methodology to the decisions made by managers and by human resources personnel in the conservative way. Another aspect that may be researched is the literacy level of managers, enabling them to apply this methodology, which also may be a limitation that has to be addressed.

The predictive validity of this tool can be instrumental in predicting the success of recruiting the right engineer for the right job. Systems thinking skills are crucial for engineering roles that require an understanding of interconnected systems and the ability to address multifaceted challenges. By utilizing the predictive validity of this tool, recruiters can make informed decisions based on an applicant's systems thinking scores, increasing the likelihood of selecting candidates who are well-suited for the specific job requirements. This approach enhances the recruitment process by aligning individuals' systems thinking capabilities with the role's demands, ultimately leading to more successful and efficient engineering placements.

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