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Resilient Sustainability Assessment Framework from a Transdisciplinary System-of-Systems Perspective

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Abstract: The vital role of extensive information exchange among stakeholders across diverse sectors and the interconnection of various scientific fields with nonhomogeneous technology readiness levels has created a new form of a complex engineering problem in the climate change era. Comprehensive sustainability assessment to enable the realization of needs requires transdisciplinary thinking to achieve systematic solutions that bridge the gap between multiple collaborative systems in a portfolio. Although the principal aim of dedicated sustainability regulations is to force companies to move toward sustainability development, general and non-engineered metrics that have not defined clear thresholds for evaluation have encountered severe challenges regarding implementation and economic viability. Therefore, adopting a transdisciplinary systems engineering approach can address multifaceted challenges like sustainability by overcoming collaboration barriers, and traditional disciplinary limits. This paper systematically reviews sustainability-dictated regulations from a transdisciplinary perspective. Different standards are compared, raised opportunities and challenges are discussed, and future remarks are highlighted. The sustainability problem is analyzed from a transdisciplinary systems engineering lens. Finally, a two-level resilient system sustainability assessment framework is proposed to effectively handle and enhance the resilience of companies' sustainability development roadmaps by enabling decision makers to find robust and highly reliable solutions regarding sustainable system design. The impact of this research is to create a new insight into addressing climate change which not only assesses the current situation but also considers uncertainty sources that affect decision making for the future.

Keywords: sustainability assessment; sustainability development; resilience approach; system of systems; systems engineering; transdisciplinarity methodology; systems thinking; uncertainty-based design; multidisciplinary design optimization; many-objective decision making

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1. Introduction

The increasing governmental pressure through approving new policies and regulations on sustainability development rushes companies toward hasty unilateral decisions without considering interactions between different pillars of sustainability [1,2]. The hypothesis is that this coercive pressure pushes companies to assess the environmental impact and commitments to eco-innovation [3]. With authority and clarity of governmental coercion, companies must disclose their sustainability targets, impacts, risks, opportunities, and strategies leading to clarification of their approach to achieving sustainability [2]. The delegation of different standards one after the other, which do overlap in terms of content and the achievement of desired goals, increases the ambiguities and concerns in adopting them [4]. The consequence of a lack of an integrated, transdisciplinary framework was highlighted in an experimental study by Stechemesser et al. that highlighted that the most effective strategies to address the climate change problem result from thoughtful

combinations of policies rather than isolated initiatives [5]. Governmental policies highlight the climate change crisis and the need for long-term human sustainability. However, the generic sustainability metrics proposed in governmental policies and regulations, in many cases, do not have clear thresholds and targets for evaluation [6]. These indicators mitigate the usefulness and clarity in purpose and the achievement of sustainability objectives. Effective measures of performance are not possible when threshold values of achievement are not defined that are consistent with the achievement of the desired system functions for sustainability [7,8].

An important factor to consider in the development of performance threshold measures is the traditional viewpoint of cost held by most businesses. This viewpoint which presents a higher return on investment to improve business competitiveness, may work at odds with the desire to simultaneously reduce environmental impacts when selecting available solution options [9,10]. Recognizing the interconnectedness of the sustainability pillars, some efforts have been undertaken to develop integrated frameworks to pursue sustainability effectively at the product, process, and plant levels [11–17]. Ziout et al. have investigated the advantages of reusing manufacturing systems considering sustainability aspects using a multi-criteria decision-making approach [11]. An integrated method to create sustainable manufacturing mapping relying on value stream mapping, LCA, and discrete event simulation has been proposed by Paju et al. [12]. Yusof et al. have proposed a conceptual framework by connecting the value stream mapping tool and the concept of the 6R method (reduce, reuse, recycle, refuse, rethink, and repair) for assessing sustainability at the process and or plant level [13]. Krajnc and Glavic have developed a model for tracking integrated information regarding different aspects of sustainability through a normalized composite sustainable development index [14]. A framework for collecting data from machined products and machining processes to extract the sustainability metrics is proposed by Lu et al., which highlights the need for data sharing between product and process metrics [15]. Focusing on remanufacturing for sustainable manufacturing, Fatimah et al. have proposed an assessment framework based on existing criteria for sustainable remanufactured products [16]. Chen et al. have presented a quantitative tool for assessing factories' sustainability progress based on key performance indicators at the factory level [17]. Despite the clarity of the challenge and progress in this field, the sustainability assessment community is still inconclusive about its evaluation results and some deficiencies need to be addressed [1]. However, it is essential to acknowledge that a universal best practice for achieving sustainability in organizations does not exist. Each organization is distinct in terms of technology and manufacturing readiness levels, organizational culture, and financial conditions, and requires a tailored approach to choose the best solution in moving toward sustainability. An essential success factor in sustainability realization is the management of the interdependencies within the disciplines involved [6,18].

In systems engineering, it is known that applying a new requirement to an existing one increases risk in one of the network nodes. The increased risk is analogous to creating delays in deliverables that affect the entire network [19]. Therefore, a transdisciplinary system-of-systems (TSoS) approach that considers higher-level requirements and models interactions is needed to avoid temporary, impromptu solutions to poorly conceived sustainability measures [20]. Transdisciplinary systems engineering (TSE) relies on transdisciplinary thinking skills which consider visible thinking, systemic thinking, computational thinking, and critical/creative skills in dealing with complex problems [21]. TSE addresses multifaceted challenges like sustainability by overcoming collaboration and cooperation barriers between multiple stakeholders and systems while considering interdisciplinary connections of the organization network, and challenging traditional framework limits [22]. The TSoS nature of the climate change problem is illustrated in Figure 1. As presented in Figure 1, a systematic decomposition of the sustainability problem starting from the SoS level to the product and service level plays a key role in mitigating the root causes of climate change. The TSoS framework creates a practical platform for rethinking, redeciding on required solutions, and finally re-seeding toward a sustainable future.

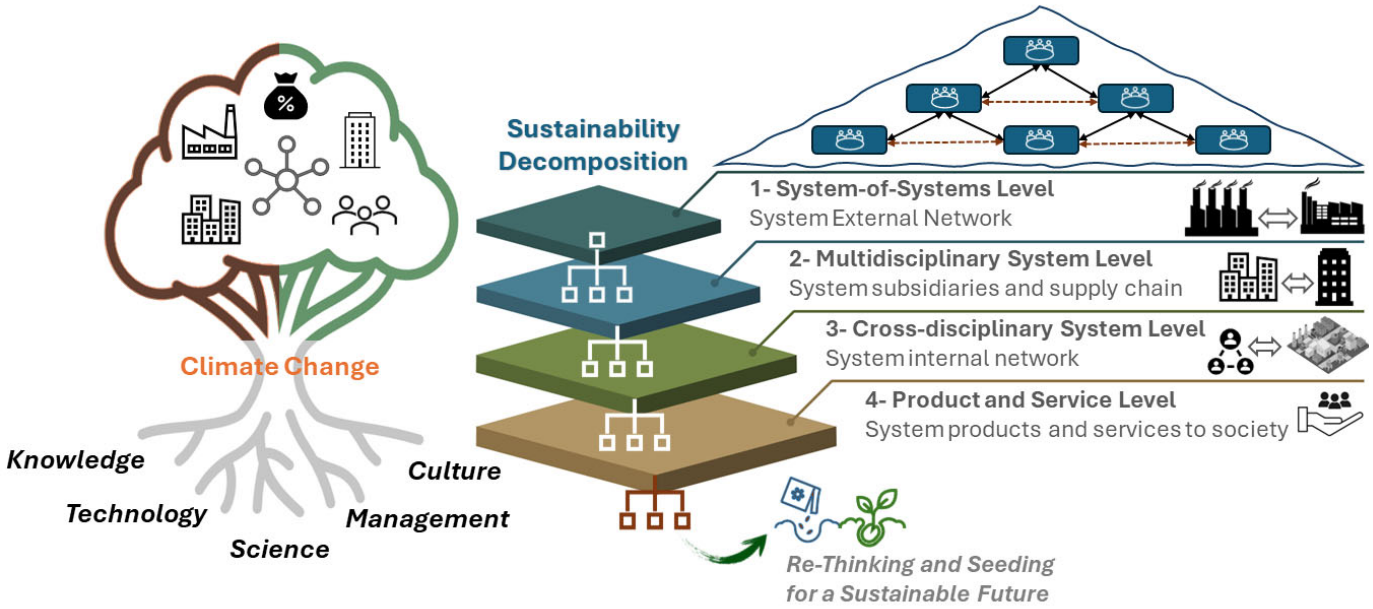

Figure 1. Transdisciplinary system-of-systems nature of sustainability problem.

Nowadays, companies are trying to calculate different metrics related to sustainability based on one of the delegated standards to report their current situation [23–26]. Most requested and disclosed indicators focus on external reporting while lacking usable information for organizations' internal decision makers [27]. To facilitate the sustainability assessment process, consultancy enterprises help prepare companies' sustainability statements using the information received. Therefore, sustainability reports depict a glossy bunch of data without any consideration of the companies' internal and external challenges and business models. This approach not only complicates the evaluation of sustainability reports regarding the accuracy of the reported information but also raises concerns about making critical decisions for the organizations' roadmap relying on the presented results. Some of the consequences of this approach are the lack of consistency in sustainability reporting, damage to the company's credibility and reputation in the market, and misjudgment about the company's management body and roadmaps [28].

Some organizations have been trying to evaluate environmental impact by calculating the carbon footprint, especially greenhouse gas emissions (GHG), throughout the entire supply chain using lifecycle assessment (LCA) tools [29–34]. Most of these tools have focused on one or two of the sustainability pillars (i.e., environmental, economics, social, and governance), the environmental pillar and the economics pillar, and lack a holistic approach to accomplishing a comprehensive analysis [27]. Since it is vital to assess all aspects of sustainability simultaneously in sustainability development, developing a comprehensive sustainability assessment tool to consider the unique nature of the organizations seems obligatory [1]. Besides, capabilities such as continuously monitoring and notifying the changes, finding the root causes of climate change, suggesting solutions, and adjusting processes are essential to create a targeted approach to address sustainability [6].

In addition, TSoS should consider the inevitable uncertainties that play a key role in realizing sustainability objectives. Uncertainties can be of internal and external origin, which can affect the realization of goals by increasing the risk in different sectors. The multidisciplinary nature of the sustainability problem significantly increases the sensitivity of addressing uncertainty sources [35–38]. The impact of the various uncertainty sources on the interdisciplinary interactions and the whole system performance can be analyzed by incorporating them into the multidisciplinary modeling through an uncertainty-based multidisciplinary design optimization (UMDO). To trace the impact of uncertainties on needs and requirements throughout the portfolio network, the UMDO approach can be implemented through model-based systems engineering (MBSE) tools to create an inte-

grated analysis environment. Therefore, developing a new framework across enterprises by integrating UMDO and MBSE relying on the concept of TSoS is required to have a targeted sustainability assessment [39,40]. In this respect, this paper proposes an integrated framework that creates an uncertainty-based transdisciplinary systems optimization (UTSO) approach to enhance synergy among different systems involved in the sustainability problem. The UTSO makes this synergy through providing online traceability and communication which is crucial in making better holistic decisions in the presence of uncertainties. The UTSO approach, covering both deterministic and non-deterministic insights, can enable organizations to achieve a set of resilient and sustainable solutions.

This study will address four main questions that shape the research methodology to achieve a targeted framework for sustainability assessment (see Figure 2). These questions encompass, "Why have different standards been enacted for sustainability development?", "What is sustainability statement and what awaits companies?", "Why do we need a systems engineering lens for sustainability realization?", "How to create a resilient roadmap toward sustainability?". In this regard, the continuation of the paper is structured as follows. First, the sustainability development background is presented, outlining some of the regulations, standards, impacts, and challenges of reporting. Second, the research that sees sustainability from a transdisciplinary systems engineering lens is provided. Third, a comprehensive sustainability assessment framework is proposed focusing on both deterministic and non-deterministic aspects. Finally, the paper is closed by concluding remarks and envisioning future sustainability assessment tools from a transdisciplinary viewpoint.

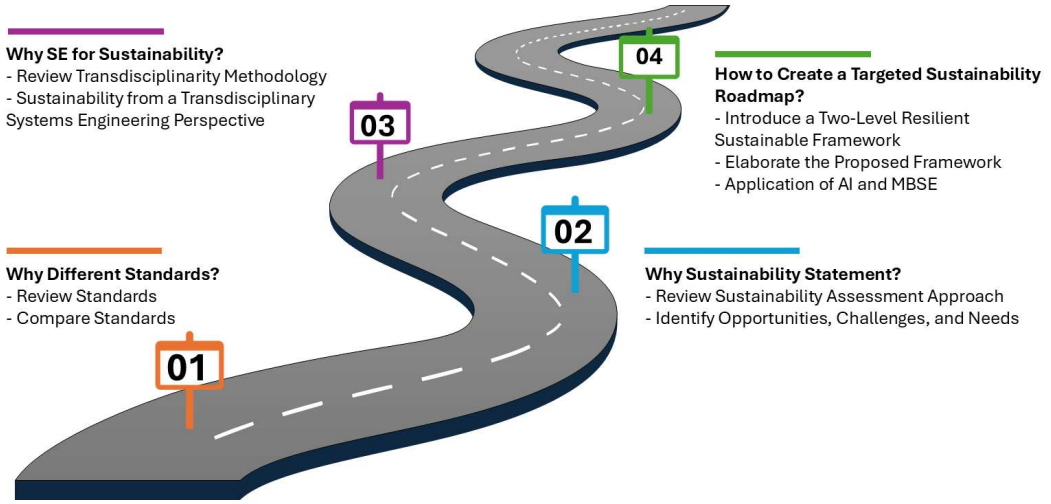

Figure 2. Research methodology of this study.

2. Sustainability Development

Despite more than two decades of experience with different regulations and standards regarding climate change agreed upon around the world, there is neither consensus in science nor policy on establishing one comprehensive and integrated regulation on sustainability development [4]. Within this period, which started with the development of the Global Reporting Initiative (GRI) in 1997, other frameworks encompass the United Nations Sustainable Development Goals (UN SDGs), the European Union Corporate Sustainability Reporting Directive (EU CSRD), European Sustainability Reporting Standards (ESRS), and the Corporate Sustainability Due Diligence Directive, (CS3D or CSDDD) have been developed (see Figure 3). Companies often use some of these frameworks in tandem and align their reports with several standards to show their contribution to broader global sustainability objectives [2]. However, according to the Global Risks Report 2024, misinformation and disinformation can be the main drivers of misleading sustainability goals, potentially resulting in societal polarization and an economic downturn [41]. Although companies

have been forced to report their sustainability statement in certain timeframes starting from January 2024, scheduled based on the company's size, balance sheet, and net turnover, the unclear consequences of missing milestones, non-measurable thresholds, and uncertain targets have turned reporting into a non-transparent and ambiguous issue [2].

Figure 3. Sustainability framework's development highway.

2.1. Frameworks and Standards

Understanding the differences and overlaps between various sustainability regulations is crucial to achieving principal sustainability goals. By presenting guidelines and frameworks, regulations and standards provide companies with instruction and structure for a holistic sustainability assessment. Nowadays, the European Parliament's CSRD, ESRS, and CS3D frameworks emphasize and follow the GRI and SDGs for addressing sustainability and corporate responsibility [2]. Aiming to form a comprehensive corporate reporting regime for sustainability reporting, released standards have been making collaboration agreements and can be viewed as interconnected reporting pillars that address distinct perspectives. According to the EFRAG-GRI MoU, a GRI-ESRS Interoperability Index has been developed to align the ESRS and GRI as much as possible. Therefore, companies that report under ESRS will be considered as reporting "with reference" to the GRI standards, and current GRI reporters will be able to utilize their existing reporting processes to compile their ESRS sustainability statement [42]. However, some key differences require attention. When preparing for sustainability reporting, companies need to understand the intersection, scope, and relationship between existing frameworks. Table 1 summarizes the comparison between these frameworks from six different points of view encompassing geographical focus, regulatory framework, legal compliance, scope and applicability, development process, and content and structure.

Table 1. Comparison between GRI, SDGs, ESRS, and CS3D.

Criteria	GRI [23] and SDGs [24]	ESRS [25]	CS3D [26]
Geographical Focus	Worldwide	EU	EU
Regulatory Framework	Independent	EU directives	EU directives
Legal Compliance [1]	Voluntary	Large EU companies, listed SMEs, non-EU companies	EU companies Non-EU companies
Scope and Applicability	A general set of standards that cover a broad range of sustainability topics	Sustainability reporting within the European context, covering the entire "value chain"	Mitigation of negative risks to the environment and human rights in a narrower "chain of activities" of a company
Development	GRI: Global Sustainability Standards Board (GSSB) SDGs: United Nations	European authorities and EU stakeholders	European Commission and its Corporate Sustainability Due Diligence Directive (CSDDD)
Content and Structure	Materiality of impact	Dual materiality	Materiality of impact

[1] Companies that fall under the scope of both ESRS and CS3D are distinguished based on their number of employees, balance sheet, and net turnover and must report in different timeframes.

2.2. Sustainability Statement

Given the diversity in sustainability reporting frameworks coupled with the varied perspectives of stakeholders, there is no unique and globally accepted process for sustainability statements [43]. Figure 4 provides a schematic representation of the necessary steps for creating a sustainability statement. Since sustainability reporting structure is the core of sustainability assessment, an inconclusive understanding of frameworks misleads the organizations to capture all required metrics for sustainability assessment [44]. Therefore, localizing the sustainability reporting frameworks as a first step would be a game changer and alleviate most of the concerns raised in the sustainability development journey. Therefore, localizing the sustainability reporting frameworks as a first step would be a game changer and alleviate most of the concerns raised in the sustainability development journey. Companies must clarify their situation concerning global and regional sustainability regulations. It includes identifying company scope and category (based on industry, location, size and impact, and net turnover), extracting relevant deadliness (based on regulatory or voluntary standards), and identifying relevant metrics and customizing them (core metrics and sector-specific indicators). This information will be transferred to the company's strategy and operations plan to make decisions and adjust timelines on the roadmap.

The localization of standards should be based on the company's technology and manufacturing readiness levels to set practical and achievable short- and long-term plans. Moreover, it is crucial to thoroughly comprehend the requirements and application of each company at this step. Setting up managerial and technical teams is essential to identify subsidiaries that fall under the reporting scope. Since targeted sustainability assessment encompasses disclosures throughout the entire value chain, the localization step also requires mapping the value chain. After gaining a thorough understanding of the utilized framework and scoping the requirements, the next crucial step is double materiality assessment (DMA) through the identification of impacts, risks, and opportunities that are material to the company [45]. DMA involves a dual perspective, the effects of the company on the environment and society, and individuals' influence on the company's economic position. The outcome of this step indicates which materials should be considered in sustainability reporting. The third step involves the gap analysis to evaluate the availability of the data related to materials and to identify the sources of required data. This step streamlines the data collection process. Conduction of the gap analysis in parallel with DMA can significantly save reporting time by eliminating the waiting time for materiality assessment results. In addition, a detailed and comprehensive review in this loop can

effectively realize sustainability development goals while keeping continued progress in financial turnover by highlighting the company's main cores and making resilient decisions. After completion of the gap analysis and materiality assessment, companies are then equipped with the necessary structured information to initiate the reporting process. Therefore, the company is able to organize the data collection and establish actions to address the identified gaps. Due to the extensive data points required to be reported, automation of data collection and development of digital dashboard tools should be considered to streamline the sustainability reporting process and accelerate evaluation and action procedures. After understanding the current situation of the company, it is essential to look for robust and reliable solutions by monitoring and reviewing the results to create a resilient roadmap in the presence of core uncertainties like political shifts.

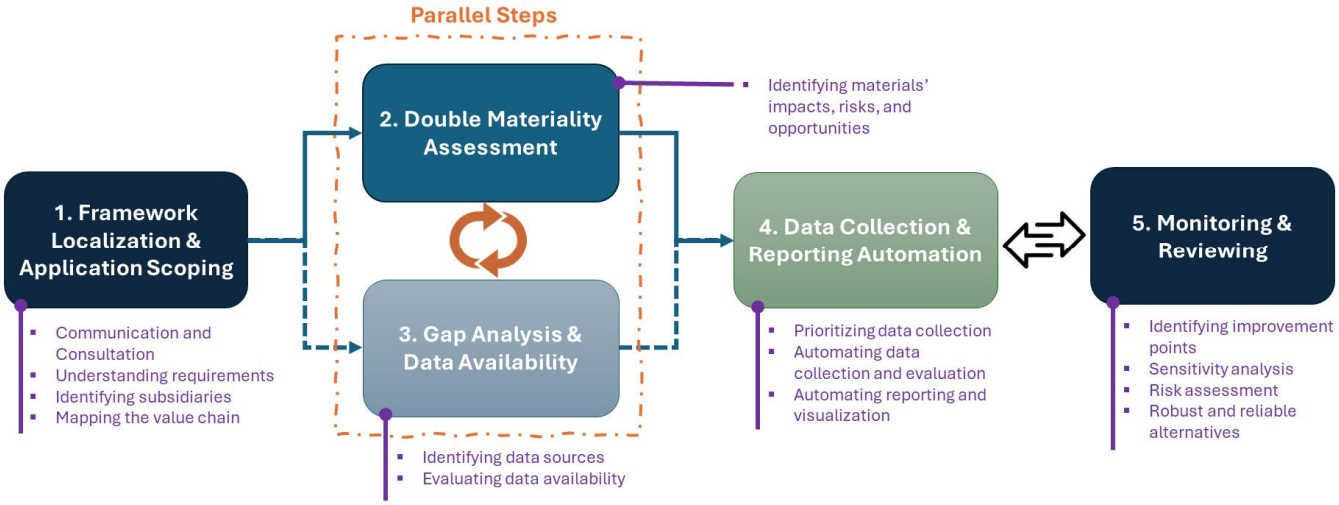

Figure 4. Sustainability statement process.

2.3. Opportunities, Challenges, and Needs

Disclosing sustainability indicators alone falls short of reducing the acceleration of climate change [46]. The main roots need to be identified, the main arteries must be introduced, and incorrect and correct actions must be explained by setting boundaries. Identifying correct actions from falsehoods in the presence of unevaluatable amounts of sustainability information has become increasingly difficult and delays sustainability action [47]. Despite significant efforts in dedicating regulations and developing standards, the current political paradigm has failed to achieve sustainability goals [48]. Partly, it is due to the failure to create a culture and business model of sustainability, which takes a long time. In addition, inadequate maturity in sustainability science has also not been ineffective in delaying the realization of sustainability [49]. Lack of understanding of the fundamentals, and limited skills with which to implement these fundamentals are common causes of stress and even crisis in sustainability development. How to select between different sustainability strategies, the scope of and relationships between different science, technology, and engineering activities, why and how to perform key action plans, and even the ability to adapt knowledge to different contexts and scenarios—these are all serious issues. This multi-sector problem with a complex network and the centrality of humans is beyond all the engineering problems that humanity has faced so far. This problem is created because of the actions of humanity and the way to deal with it is completely different from other problems that humanity has defined and then solved. From the engineering point of view, humans and the economy in this problem play both design variable and objective function roles at the same time, which has created a new form of a highly chaotic and heterogeneous problem. This new problem requires transdisciplinary thinking to meet holistic feasible solutions.

The pursuit of company-specific solutions for attaining net-zero emissions, zero waste, and sustainable production has created a competitive landscape unique to each business, fostering a new era of innovation [2]. The new Eco-friendly solutions will push the technology edges which affect current infrastructure. Comprehensive evaluations are needed so that the pressure on the infrastructure does not create new springs to sustainability issues. Since in complex multidisciplinary problems deciding on one disciplinary objective directly or indirectly influences other disciplines, a holistic model considering all interactions is mandatory. Therefore, investment in developing multidisciplinary analysis software in each company could be a game changer. Furthermore, sustainability assessment requires dealing with massive repositories of unstructured data. Collecting, classifying, analyzing, and visualizing data has created both a challenge and an opportunity. In this way, moving toward digitalization, big data-driven, and artificial intelligence-driven methodologies seem to be mandatory and should be one of the goals of each company. Accelerating the implementation of concepts such as Industry 4.0 and Industry 5.0 along with the continuous development of advanced sensors will also lead to technological innovation [2]. In the meantime, many business spaces are being created and many startups are emerging to facilitate sustainability reporting by developing various integrated software. It is evident that the development of sustainability-driven self-optimization tools, which address all aspects of sustainability at once, is a hierarchical process. This path will inevitably face challenges, and new issues will arise with the implementation of innovative technologies.

3. Sustainability from Transdisciplinary Systems Engineering Lens

For the first time in 1985, Basarab Nicolescu proposed the inclusion of the "beyond disciplines" concept which led to the emergence of transdisciplinarity methodology [50]. In 1995, Ervin Laszlo laid the foundation of the "transdisciplinary unified theory" relying on the interconnected universe concept and human desire to develop complex systems [51]. While the multidisciplinary perspective is concerned with studying the interdisciplinary interactions between several disciplines simultaneously, the transdisciplinarity approach not only considers interdisciplinary interactions but also goes beyond all disciplinary boundaries concerning their external interactions [50]. The need to look at the climate change problem from beyond systems, multi-networking, and interdisciplinary perspectives has steered us to employ a meta-systemic mode of thought relying on systems theory [52]. Capra et al. have highlighted that the economy must operate with, rather than dominate the environment, society, and culture, and achieving this requires connecting the terms "ecological" and "economics" by creating systemic principles of life [53]. Although the systems theory is concerned with the study of complex systems, considering all sustainability aspects simultaneously has created a new level of complexity or a mess (hint at the mess management concept of Russell L. Ackoff [52]). Sustainability has become a multifaceted ever-increasing complex problem exacerbated by the hyper-connectivity and interdependence of technologies, sectors, systems, and disciplines which could not be addressed with single-disciplinary and anthropocentric thinking. Today's systems have been transforming into a composition of cyber, physical, and human parts with intelligent and smart features, making their understanding extremely complicated [54]. All these systems are also embedded in larger systems which creates a complex network of system-of-systems (SoS) problems. To understand the situations and the interlinkages that generate and propagate sustainability issues transdisciplinary systems thinking is vital to move away from reductionist approaches and define preventive actions [55]. Indeed, these kinds of problems are resistant to a global solution. Each company can choose one of the locally feasible optimal solutions from the design space that fulfills the constraints without paying attention to its robustness and reliability. Occasionally, with new regulations and policies, new disciplines and requirements will emerge. Although systems try to converge and adapt to these conditions, the interdisciplinary knowledge gap complicates sustainability realization. Therefore, transdisciplinary thinking strives to harmonize multidisciplinary interactions by reaching beyond system boundaries to identify and fill gaps and overcome

incompatibilities with the SoS network [56]. In this respect, the focus of today's research and science is on tackling sustainability challenges through developing and implementing systems thinking approaches to create more integrated decision-making tools and trade-offs on all sustainability pillars simultaneously [22,35,57–59].

3.1. Transdisciplinary Systems Engineering

According to the 2019 INCOSE definitions [60], "transdisciplinarity" is introduced as an approach that "crosses many disciplinary boundaries to create a holistic approach." This holistic view feature distinguishes it from the multidisciplinary approach, which mainly emphasizes the interdisciplinary interaction of a system. Transdisciplinary systems engineering (TSE) as a meta-discipline has both transdisciplinary and multidisciplinary, not only considering systems interdisciplinary interactions but also extending beyond to contemplate the system's interactions and impacts on the system's environment [56,61]. Since the sustainability problem deals with a network of systems, this concept should be extended to the TSoS to cover interactions among a wide range of nodes in the climate change network. Since the sustainability problem deals with a network of systems, this concept should be extended to the TSoS to cover interactions among a wide range of nodes in the climate change network. Figure 5 presents sustainability in the frame of transdisciplinary engineering.

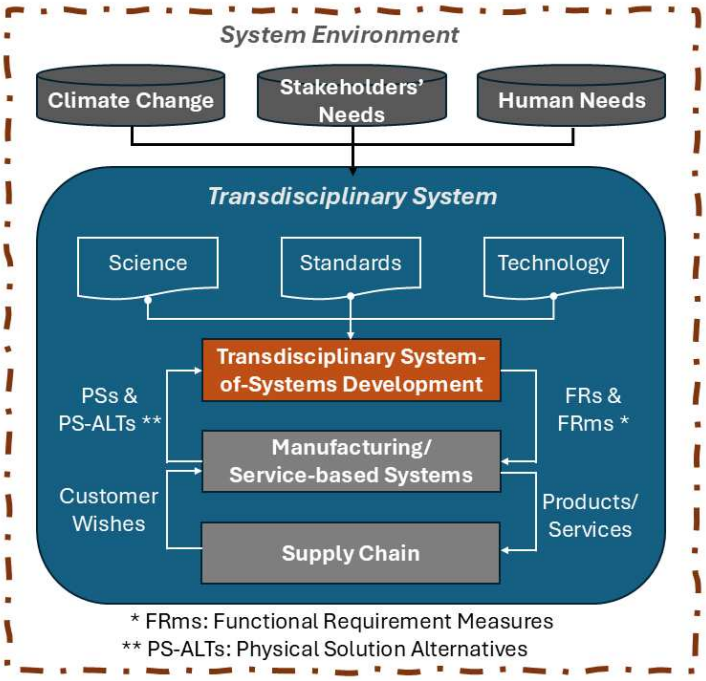

Figure 5. Sustainability in the frame of transdisciplinary engineering.

As depicted in Figure 5, this framework considers the TSoS development as the core element of the system which connects needs with manufacturing systems. A comprehensive system decomposition will be conducted in the TSoS process which covers many different needs coming from outside of the boundary, such as stakeholders, society, market, and the climate crisis. These sources of needs may often not be directly involved and contain a set of quantitative and qualitative concerns. By translating needs into a set of functional requirements (FRs), TSoS is looking for robust and reliable solutions to realize the sustainability that companies with innovative and technological plans offer [62] The TSoS development is performed in collaboration and cooperation with experts from different disciplines involving information exchange with people from the solution system. Furthermore, the physical solutions (PSs) suggested by manufacturing- or service-based systems to fulfill the functional requirements extracted from decomposition in the TSoS

development system can be a transdisciplinary system, but there is no need for a unique solution. On the contrary, in higher layers, more alternative solutions need to be available so that the hands of decision makers are not tied to making the right decision. The TSoS process may also identify the need for new technologies that must be developed elsewhere outside the system boundary. In addition to meeting upstream needs, companies always try to meet customers' wishes through continuous communication with the supply chain. The technologies and processes adapted in each step are often different than each other because of the different knowledge required. What is necessary is the online connection of this whole collection with each other.

3.2. Transdisciplinary Systems Engineering for Sustainability

After the definition of TSE and explaining how sustainability can be considered in the frame of transdisciplinary engineering, this section will present TSE implementation steps for addressing the sustainability problem. The six main steps of TSE [55] which can lead companies systematically from sustainability drivers to a targeted sustainability plan are (see Figure 6): (1) disciplinary convergence; (2) transdisciplinary collaboration; (3) collective intelligence; (4) transdisciplinary research integration; (5) transdisciplinary engineering; and (6) transdisciplinary analysis and assessment. These steps are described in detail in the continuation of this section.

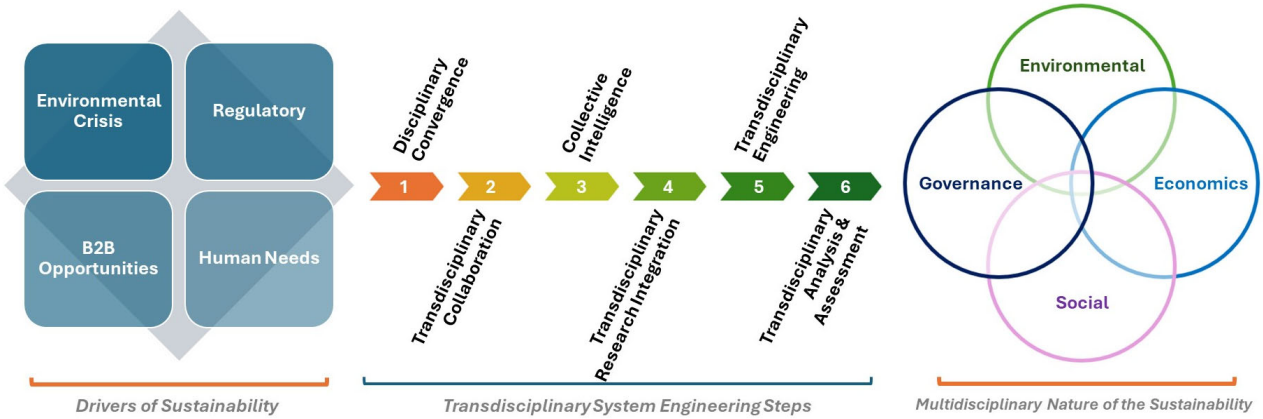

Figure 6. From sustainability needs to sustainability assessment using transdisciplinary systems engineering steps.

3.2.1. Disciplinary Convergence

Disciplinary convergence serves as the first step in transdisciplinary systems engineering [56]. TSE creates a meaningful grounding for a wide collaboration between subject matter experts by simultaneously engaging all actors in the unstructured sustainability issue. These actors can be from industry, academia, regulatory, and funding bodies. A comprehensive disciplinary convergence provides a structured and well-planned sustainability journey so that stakeholders and managers can make informed decisions.

This step starts with the identification of the needs, which is essential for thoroughly understanding the problem domain and building a research team. Then, stakeholders and customers must be identified to consider their viewpoints while addressing the main problem. Disciplinary convergence creates a communication substrate on how internal and external actors may assist in harmonizing disciplines to improve sustainability development. For instance, if the management group recommends switching from fossil fuels to wind energy, the engineering group would outline infrastructure restrictions, while the finance group would address the issue of investment, and the other groups would provide feedback similarly. By considering interactions between conflicting objectives from different disciplines, a convergence in decision-making bodies may occur.

3.2.2. Transdisciplinary Collaboration

The transdisciplinary team collaboration is the heart of TSE to identify various angles of a complex problem [61]. To address the sustainability problem, a transdisciplinary collaboration is imperative to finding social–technical solutions [63]. Relying on a collaborative thinking approach, the information and knowledge from different disciplinary groups will be exchanged and possible solutions will be discussed. The structured discussions will continue to discover and classify the main functional requirements of the problem while strategically thinking about their independence to decrease the problem's complexity level. Since the interdependency of adopted solutions to satisfy FRs determines the independence of FRs, collaborative thinking based on the axiomatic design theory could revolutionize not only the system-level sustainability solutions but also the system-of-systems level approaches toward sustainability by decreasing the level of the system complexity. This kind of collaborative thinking systematizes the swap between different solutions and accelerates achieving holistic solutions.

3.2.3. Collective Intelligence

Collective intelligence, rooted in interactive management, is a structured approach to managing complex problems by gaining knowledge from diverse viewpoints [64]. Diversity of thoughts creates a brainstorming environment that leads to innovative solutions. To this end, the critical issues will be identified and a group of skillful experts in the field will be invited to participate in interactive workshops. A new set of functional requirements will be derived accordingly, providing the fundamentals for the next level of system decomposition. New functional requirements resulting from this step will be satisfied with creative solutions and their alternatives through a recursive process to ensure the autonomy of functions and solutions.

3.2.4. Transdisciplinary Research Integration

The result of the collective intelligence step will be assessed in the transdisciplinary research integration step [64]. To ensure compatibility and alignment with the main problem, the collective intelligence results will be compared with the upper levels of the system decomposition. This step will create a database of approaches and involved disciplines and highlight and introduce nonordered key attributes. For each attribute, the feedback of the knowledgeable disciplinary leaders will be recorded in a structured form [55].

3.2.5. Transdisciplinary Engineering

After identifying and defining the key attributes through interactive collective intelligence management, a contextual relationships matrix using the interpretative structural modeling (ISM) technique will develop in this step [55]. The interrelationships of the key attributes will be extracted utilizing a structural self-interaction matrix (SSIM), which is the first step of ISM [64]. The results will pass to ISM analysis for level partitioning and to propose a digraph or flow of factors. Then, the driving power and dependencies of the highlighted key attributes will be identified using matrix impact cross-reference multiplication methodology [65]. The result will assist managers and stakeholders in creating the highest value proposition in sustainability realization by identifying the most impressive attributes. The schematic illustration of this process, including developing different matrixes, is presented in Figure 7. Following the steps outlined in Figure 7, the key attributes will be systematically prioritized [61]. First, the contextual relationship between attributes and the relation direction will be determined. Then, an adjacency matrix will be developed by translating the SSIM matrix to binary numbers. Third, the reachability matrix is created by applying the transitive rule which states "If A has a relationship to B and B has a relationship to C, then A has a relationship to C". Using the reachability matrix data, the attributes' driving power and dependence will be calculated. Finally, the information collected in all steps will be put together to partition the level of attributes and form the

prioritization digraph. A deeper explanation of the indicated steps in Figure 7 can be found in [61].

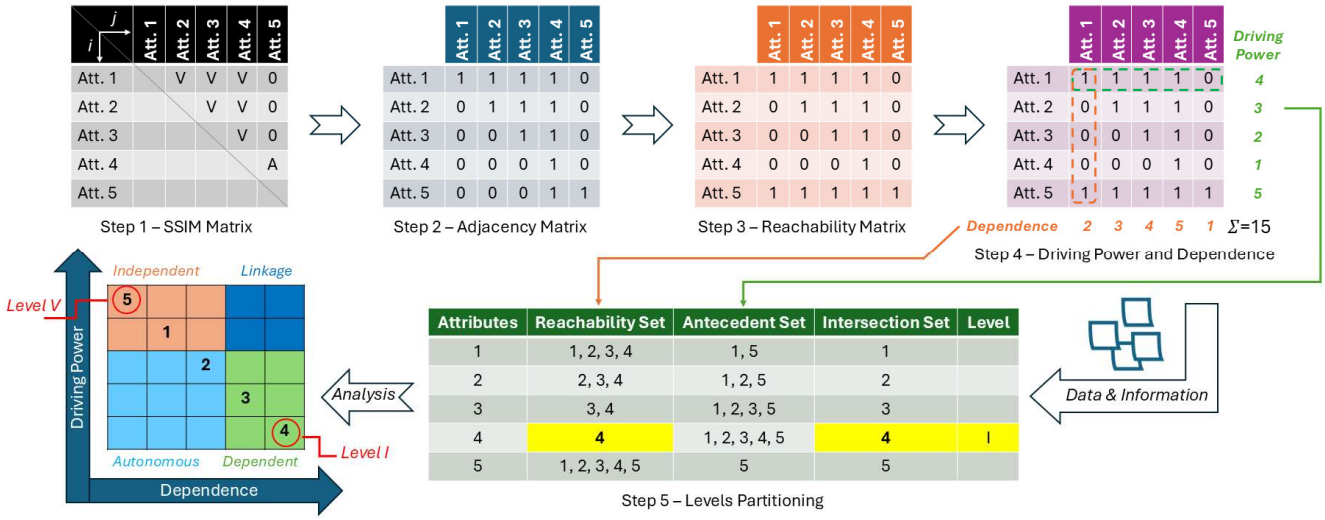

Figure 7. Transdisciplinary systems engineering for sustainability.

3.2.6. Transdisciplinary Analysis and Assessment

The last step in TSE is analysis and transdisciplinary assessment to highlight the critical disciplines and extract the gaps in addressing the key attributes [55]. Therefore, first, the current situation of disciplines concerning the key attributes should be assessed. Then, the responsibility of different disciplines for each attribute will be checked to identify gaps. For the identified gap, the system will look for a responsible discipline and will check whether the existing modules are capable of filling it. Otherwise, new modules will be proposed to address the gap. Afterward, a quantitative analysis of the maturity level of current disciplines per each attribute is required by scoring their level in addressing different issues. Finally, a qualitative analysis of the feedback received from each discipline will be performed, which will determine the interactions of the disciplines in closing the gaps.

Prioritizing the key attributes, identifying the responsible disciplines, and required interactions to fill the gaps enable organizations to recognize responsible parts in an organization for providing essential information for key sustainability metrics. In addition, the maturity level, strengths, and weaknesses of the various organization's parts in responding to the sustainability criteria requested to be disclosed in the standards will be determined, which streamlines the sustainability assessment procedure.

4. Resilient Sustainability Assessment Framework

Uncertainty is an inevitable part of any system, whether with direct or indirect impacts [66]. Uncertainty is one of the most important factors that challenges the performance of solutions to complex problems and diverts organizations from accomplishing the strategic roadmap [67]. Therefore, understanding uncertainty sources is crucial for creating a resilient strategic roadmap, since making decisions within the sustainability development roadmap without considering uncertainty will only provide a temporary solution [36]. This section proposes a two-level framework to streamline the way to achieve resilient sustainable solutions.

4.1. Uncertainty Sources in Sustainability Problem

The hotbed of uncertainty lies in the lack of knowledge/information and the imprecise and incompleteness of data [68]. These fountains can grow inside a system and during the product development process or can have an external origin that penetrates the system from outside the system boundary and puts it under the influence. Looking at the big picture of the sustainability problem, the SoS-level uncertainties can arise from, "Mother Companies

Needs and Requirements, Regulatory Bodies, Standards, Customers Demand, Market Intentions and Power, Inflation, Environmental Conditions, Science and Technology, and Political and Cultural Situations". These higher-level sources, as external uncertainties, influence the development of systems and emergent creative solutions. In addition, there are also internal uncertainty sources encompassing system complexity, systems departments, SMEs, subsidiaries, manufacturers, operations, human error, machinery tolerance, models simplification, ignorance and assumptions, programming, computational implementations, and information exchange that affect the efficiency of the sustainability solutions. Considering all these sources of uncertainty, making resilient and reliable decisions for an enterprise's sustainability journey requires adopting a systematic non-deterministic approach like uncertainty-based design methodologies.

4.2. Uncertainty-Based Transdisciplinary Systems Optimization

The uncertainty-based systems design (UBSD) approach aims at addressing two issues encountering uncertainty from various sources: (1) to increase resilience by decreasing the system's sensitivity to static and dynamic variations (robust design optimization (RDO) methods); (2) to enhance a system's stability with a certain level of likelihood in the presence of extreme events increasing reliability and decreasing the probability of failure (reliability-based design optimization (RBDO) methods) [66]. These two perspectives can also be considered simultaneously in system design and development to improve performance in terms of robustness and reliability [68].

Considering the multidisciplinary nature of real-world problems and the role of interdisciplinary interaction in uncertainty analysis, a UMDO approach has been developed [68]. In the multidisciplinary problems, the impact of the uncertainties can be cross-propagated leading to unpredictable situations and activating new failure modes. Furthermore, global real-world issues like climate change inherently have many conflicting objectives and constraints, and the potential synergistic impact of the interconnected disciplines plays an important role in reaching a holistic, practical, and at the same time optimal solution to sustainability [36]. The UMDO approach organizes systematic communication between all the disciplines involved in a system by arranging them through a hierarchical sequence or a distributed concurrent network. Due to the sustainability problem's wide network beyond the boundaries of several connected systems, extending the UMDO from system-level design to the SoS level relying on TSE is vital to identify the challenging nodes and hotspots in the presence of uncertainties. Furthermore, the effect of changes and uncertainties on the higher-level needs and functional requirements must be traceable online. The online traceability of the impacts throughout the supply chain reveals the need for tools with cloud communication and simultaneous analysis of the entire life cycle which can be found in MBSE tools. The integration of UMDO, transdisciplinary engineering, and MBSE creates a UTSO approach which increases synergy in the sustainability network of each organization. UTSO can cover all steps of the product life cycle from needs and requirements to product disposal while simulating the system behavior in both deterministic and non-deterministic ways. Based on the UTSO approach, a sustainability assessment framework is proposed in the next section of the paper that enables organizations to draw a targeted resilient sustainability roadmap.

4.3. Two-Level Resilient Sustainable Framework

Despite significant efforts made in life cycle assessment focusing on sustainability, sustainable development is still in its infancy. On the one hand, ongoing assessments cover a few objectives such as carbon footprint, energy consumption, and waste management which have been done separately and in a deterministic form. On the other hand, assessments are general and not targeted without considering interconnections and uncertainties. In addition, although deterministic evaluations will present a snapshot of an organization toward some sustainability target, uncertainties and unclear/hidden interactions can change the derived results and analyses of what is reported.

To clarify the interactions among portfolio systems, involved disciplines must cooperate while following distinct or threshold-based targets. These communications must go broader than organizational internal interactions and should include the entire external network of the system. Implementing the UTSO approach offers detailed information on climate change issues across the entire portfolio. UTSO helps to perform the sustainability assessment in a targeted way and to consider resilience as a game changer for unpredictable future circumstances. In the UTSO approach, both deterministic and non-deterministic analyses should be considered in parallel. These two analyses are like two powerful arms for building a wing to fly over the sustainability tree and enable organizations to look at the big picture of this issue and cultivate strong roots by making resilient solutions. This concept is proposed through a two-level Resilient Sustainable Framework illustrated in Figure 8.

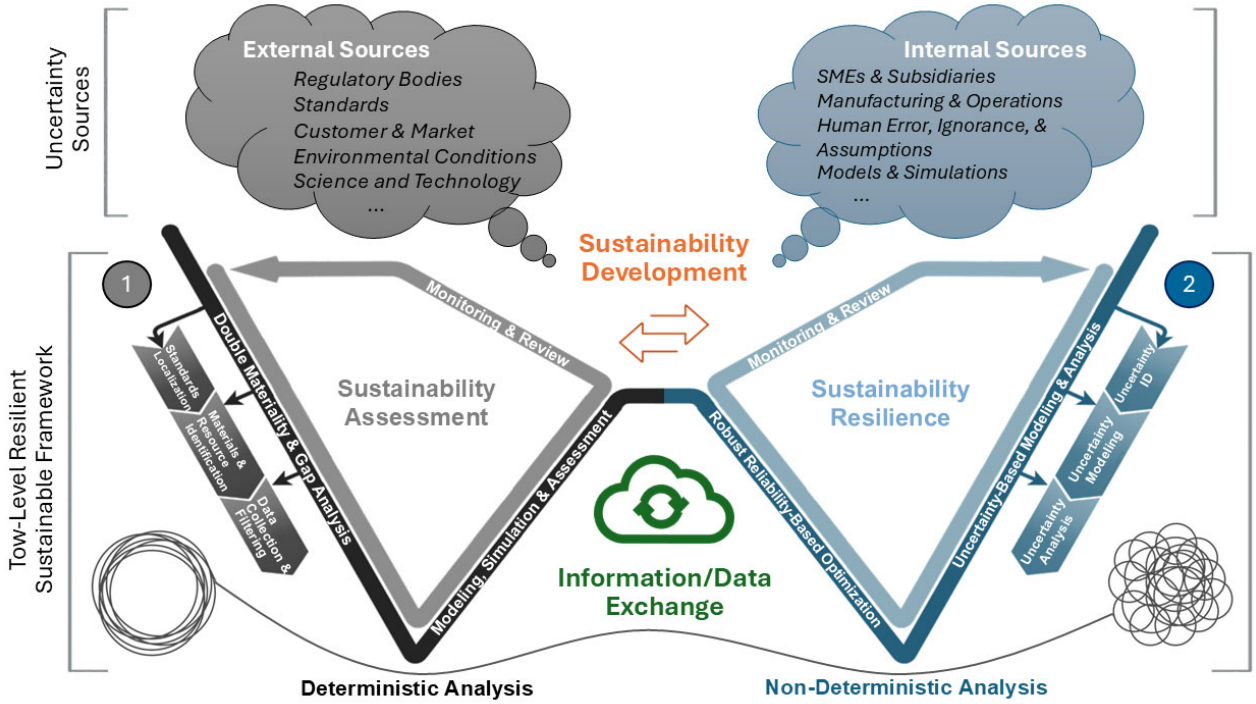

Figure 8. Two-level resilient sustainable framework.

Figure 8 presents the sustainability development in a W form including two Vs for sustainability assessment (SA) and sustainability resilience (SR). Starting at the top-left (indicated by 1 in Figure 8) with sustainability standards localization and scoping, the SA begins to lay the groundwork for evaluation on the left-hand part of the V by doing DMA, gap analysis, and collecting the required data. Then, this information transfers to modeling and simulation by going up from the right-hand part of the V to assess the chosen sustainability metrics. In contrast and starting at the top-right (indicated by 2 in Figure 8), the SR starts with identifying the uncertainty sources and proceeds by going down the right-hand side of the V to uncertainty modeling and analysis. Afterward, the sustainability modeling will carry over to the optimization by going up from the right-hand part of the V to look for robust and reliable solutions in the presence of uncertainties. In each V, continuous monitoring and technical review will be done through exchanging information and communication with responsible disciplines. The information and data exchange can be conducted through a secure cloud to accelerate the procedure. In addition, to identify, categorize, and analyze extracted data and transfer them to related parts, process automation relying on AI and data mining tools can be applied. To ensure the consistency between SA and SR, an online interface management process is required. Since MBSE tools relying on cloud-based information exchange have all the necessary features in

one place, it is better to advance both sides of the analysis together within the context of an MBSE tool. The decisions resulting from such an integrated framework, considering both deterministic and non-deterministic sustainability analysis, enhance the resilience of organizations' roadmaps and close the gap between sustainability in research and what it is in practice.

5. Concluding Remarks and Future Perspectives

As indicated by Capra et al. [53] "We never will find solutions to our current challenges using the old maps and to do more than reducing negative symptoms we have to change our worldview". To comprehend the complex interconnectedness of complex real-world problems developing comprehensive analysis models using a transdisciplinarity approach is vital [50–53]. Since sustainability is a complex multi-agent multidisciplinary SoS problem with the potential for disaster in the presence of inevitable uncertainties, we argue that deterministic analysis will provide us with temporary solutions, and moving towards non-deterministic systemic analysis is a must to achieve optimal, feasible, and, at the same time, resilient solutions. To build a targeted sustainability assessment along the transdisciplinary approach discussed in this paper the principles of systems thinking, system-of-systems engineering, and uncertainty-based design must be perceived. The following subsections explain the main contribution of this study and limitations and future needs for research.

5.1. Study Contribution

Since in sustainability development, a desired or unwilling tendency towards each of the pillars due to uncertainties takes us away from its main objectives, sustainability assessment practices require a resilient framework. This paper looks at the sustainability problem from a transdisciplinary system-of-systems perspective focusing on developing a comprehensive robust sustainability assessment framework. To this end, first, the sustainability regulations are reviewed, and challenges and needs are highlighted. Then, the concept of transdisciplinary systems engineering and its application for sustainability analysis is introduced. The steps required to be followed for prioritizing the key attributes and their related disciplines are explained. In realizing sustainability in the true sense, a comprehensive analysis is required that considers the uncertainties that may arise from various sources. In addition, in the portfolio of the climate change problem, many actors are involved. These actors are guided by humans and their interactions with technology and science. Therefore, a two-level resilient sustainable framework covering both deterministic and non-deterministic sustainability assessment is proposed in this study. This framework requires an online technical review for both sustainability assessment and sustainability resilience sides to review and confirm data and metrics interactions based on the experts' knowledge. Model-based systems engineering tools can facilitate and accelerate the framework's implementation.

5.2. Limitations and Future Needs

Although different life-cycle assessment tools and integrated frameworks have been developed for addressing and facilitating sustainability reporting, none of the existing tools are adequate to provide a holistic deterministic sustainability assessment and do not consider uncertainties in the assessment process. Sustainability development needs new uncertainty-based sustainability assessment tools to visualize a realistic view of the companies' situation towards sustainability. The proposed systematic framework presented in this research is an initiative toward tackling climate change issues by finding resilient sustainability solutions. Despite the holisticity of the presented framework, the accuracy of data, unclear quantitative impact of metrics on each other, and quantifying the uncertainties are some of the leading limitations in its implementation. These limitations play key roles in assessments and influence the final feasible set of solutions resulting from applying the framework. By moving toward Industry 4.0 and Industry 5.0, some companies already have collected a lot of data. Most of this data is unstructured and overlaps with others

that cannot be used for evaluating sustainability metrics accurately. Unstructured data itself is a source of uncertainty and creates ambiguities in result interpretation which could mislead the organizations from the correct orientation. Therefore, clarifying the inter-related interactions between disciplines as well as the collected data is crucial in achieving correct basic data for assessment and preventing the creation of further uncertainties. However, identifying the key attributes in the presence of uncertainties and making solid decisions through assessment tools is a challenging problem because of the multifunctional nature and direct and indirect impacts sustainability decisions have on other disciplines. New non-deterministic many-criteria decision-making and many-optimization methods approaches should be developed to address the sustainability optimization problem. Therefore, in envisioning future sustainability assessment tools from a transdisciplinary viewpoint, emerging new MBSE tools that rely on cloud communication to facilitate the sustainability indicators' traceability and online decision making could be a game changer.

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