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Towards Acceptance of Virtual Validation: The Indirect Technology Acceptance Framework

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Abstract— **The development of autonomous and respective multi-agent systems creates both technological innovations and significant societal and regulatory challenges. Of particular note is the social acceptance of these systems once they are integrated into their usage environment. This is a critical factor that is typically limited to the end product, while the development process and the underlying technologies remain largely disregarded. However, there are indirect technologies like virtual testing, which are increasingly used in the respective product development, for which their potential effects on the acceptance among stakeholders are overlooked. To address this source of indirect skepticism, this paper introduces the Indirect Technology Acceptance Framework (iTAF) to investigate the practical applicability and acceptance dimensions using the example of virtual validation methods. The framework reveals specific implications for each framework layer: the technological layer requires procedural transparency; the institutional layer necessitates harmonized standards across jurisdictions; the societal layer highlights the influence of communication strategies and safety demonstrations; and the interactive layer emphasizes continuous stakeholder engagement throughout the development process. The model successfully integrates technical, regulatory, and societal dimensions, acknowledging the unique position of indirect users as critical stakeholders in societal legitimation and integration. It also offers a foundation to align development processes and especially system validation to the stakeholders' needs regarding the trustworthiness of the system of interest (SOI). To illustrate the iTAF, it is applied as a demonstrative example to the social acceptance of virtual validation in the presence of legal uncertainty.**

I. INTRODUCTION

The development of autonomous systems and their integration creates both technological innovations and significant societal and regulatory challenges. In particular, the acceptance of these systems represents a crucial and necessary requirement for their successful implementation in their usage environment [1], [2]. While numerous studies [2], [3] and research projects [4] have already examined the acceptance of agents and multi-agent systems like autonomous mobility solutions themselves, an increasingly critical aspect is often overseen: the role of indirect technologies like virtual validation as an indirect enabler for those systems.

Virtual testing and corresponding virtual validation are characterized by augmenting one or more physical elements with a simulation model to approximate reality. The most prominent methodologies within this framework encompass Model-in-the-Loop (MiL), Software-in-the-Loop (SiL), and Hardware-in-the-Loop (HiL). This is often cumulated with XiL [5]. As virtual testing and validation methods promise a more efficient, reproducible, and resource-conscious approach to ensure safety, they have steadily gained greater significance in the safety assessment of autonomous systems [6]. As an exemplary result, these methods are now explicitly considered for autonomous vehicles in European regulations such as EU (2019/2144) [7] and the associated (EU) 2022/1426 [8] to UNECE's World Forum for Harmonization of Vehicle Regulations (NATM-Guidelines) [9], where this topic is being discussed at an international level. Despite its numerous advantages, a limitation of virtual testing lies in the intrinsically limited fidelity of the models [9] despite systematic development and quality standards [10], [11]. Consequently, significant reservations persist regarding the exclusive or predominant use of virtual validation as a replacement for physical tests [12], which may influence the overall acceptance of the systems.

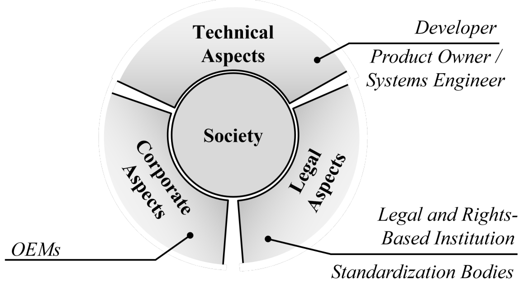

Fig. 1. Symbolization of the Effect of Society on All Adjacent Areas

This skepticism manifests on multiple levels, within academia, among manufacturers, regulatory bodies, and, not least, within society. It particularly includes concerns regarding the reliability of simulations, lack of transparency, and regulatory uncertainties. Given that systems that have been virtually validated will rarely be economically feasible without the acceptance of the relevant society and users, the latter appears to be the most critical stakeholder (cf. Fig. 1).

A systematic approach is imperative to overcome this skepticism in the usage environment and to cope with increasing regulations, like EU 2022/1426 [8] and other related standards, such as ISO 26262 [13]. To this end, the present paper establishes a foundation by introducing the Indirect Technology Acceptance Framework as a systematic model to face the aforementioned challenges. The model is designed to diverge from established models by centering the analysis on society as an indirectly impacted group. To streamline our subsequent discourse, our focus will be directed towards an inquiry into the domain of mobility as an exemplary system. Hence, the respective state of the

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art is presented in Section II. The subsequent Section III systematically identifies relevant stakeholder groups along a model use case. In Section IV, the framework is presented and applied in an exemplary manner. This framework is then discussed in Section V. Finally, Section VI summarizes the key facts briefly and provides an outlook on future work.

II. STATE OF THE ART

Despite the underrepresentation of the multi-agent and mobility sector in acceptance research [14], existing studies and approaches focusing on the acceptance of autonomous driving drew primarily from established theoretical models. These models include the Technology Acceptance Model (TAM) [15], the Unified Theory of Acceptance and Use of Technology (UTAUT) [16], and the Diffusion of Innovations Theory [17]. These frameworks have been adapted to the autonomous vehicles (AV) context, incorporating factors such as perceived safety, trust in technology, usefulness, ease of use, and perceived behavioral control [18], [19].

Research has demonstrated that acceptance is a prerequisite for the successful implementation of automated driving vehicles [20]. Yet, studies have also identified trust in automation as a pivotal factor in determining the adoption of automated systems and their appropriate utilization [21]. This element, in conjunction with other variables, exerts a substantial influence on individuals' inclination to utilize an automated vehicle [22]. Trust and acceptance are not only influenced by the system's ability of performing driving tasks but also by user experiences and the transparency of AV decision-making processes [23]. In addition, a reduced level of trust and acceptance is correlated to a lack of safety [24]. Furthermore, trust in manufacturers and regulatory oversight directly affects user willingness to relinquish control [25].

Consequently, several national and international initiatives have contributed empirical insights into public attitudes toward AVs. For instance, the European L3Pilot project, which involved large-scale testing of Level 3 automated functions in real traffic environments across multiple European countries, provided comprehensive data on user acceptance, behavioral adaptation, and societal impact [26]. A similar emphasis on safety validation and the establishment of trust-building through transparent safety criteria was observed in the German project PEGASUS [27].

While a significant portion of the literature focused on physical AV prototypes and real-world demonstrations [27], the increasing reliance on virtual testing and simulation environments introduces a new dimension to acceptance research. As AV development may become increasingly dependent on digital tools, the acceptance of virtual testing methods among stakeholders is necessary. The corresponding research draws from conceptual roots similar to technology acceptance, but is less mature and more fragmented [28], [29].

It has been determined that acceptance of virtual validation is divided into different perspectives. From a technical point of view, acceptance is influenced by factors such as trust in simulation accuracy, perceived reliability of virtual environments, and the extent to which virtual results correlate with real-world outcomes. In this context, Stocco et al. [28] highlighted the challenges in transferring results from virtual simulations to physical-world testing, emphasizing the importance of addressing the ”sim-to-real” gap to enhance stakeholder confidence.

Focusing on public acceptance, it is closely tied to perceptions of safety and reliability, which are influenced by the testing methods employed during development. The work of Clement et al. [29] investigated how virtual experiences using driving simulators may enhance trust in automated driving. Their findings suggest that exposure to virtual testing environments may positively impact user acceptance by demonstrating the capabilities and safety measures of AVs.

Furthermore, the regulatory landscape is evolving to incorporate virtual validation. The ISO 21448 (Safety of the Intended Functionality, SOTIF) [30], ISO 26262 [13] and ISO 34502 [31] standards emphasize the importance of simulation in the verification of AV safety. The National Highway Traffic Safety Administration (NHTSA) has also introduced frameworks like AV STEP [32] to evaluate and oversee autonomous vehicles, emphasizing the need for transparent data sharing and standardized testing protocols. But, trust in these standards and simulation results is contingent on transparent documentation, reproducibility, and traceability, as highlighted by the AV STEP program [23]. In systems engineering, traceability is considered essential for ensuring transparency, distinguishing between vertical and horizontal traceability [11]. In our context, vertical traceability means linking the system under test to the artifacts from the prior verification of its integrated system elements. Horizontal traceability, on the other hand, refers to the connection to requirements on the same level of abstraction. Furthermore, the EU 2022/1426 [8] even mandates traceability, albeit defined slightly differently as accurate documentation to ensure reproducibility.

Notable drawbacks in the current discourse include the predominant user-centered paradigm based on established models such as TAM and UTAUT, as well as the missing integration-level consideration of all stakeholders and their interactions in the context of virtual testing acceptance. Consequently, an approach that focuses on users indirectly affected by technology, as is the case with virtual validation, and considers all relevant stakeholders, is still missing.

III. STAKEHOLDER-ANALYSIS

To access indirect user acceptance for virtual validation methods, first, all interested parties have to be identified. According to ISO 9001 [10], an interested party may be a stakeholder, person, or organization that may affect, may be affected by, or perceive itself to be affected by a decision or activity. In order to investigate the latter regarding the acceptance of virtual validation methods, an exemplary use case is analyzed. This deals with automated securing mechanisms for persons in wheelchairs within autonomous transport services. Such vehicles must integrate several complex systems: autonomous driving functions for navigation in city traffic, special boarding aids for wheelchair users, and automatic safety devices for passenger safety during the journey. The challenge lies not only in the individual systems, but in their seamless integration. Each system must function reliably under various operating conditions and be coordinated with the other systems in a multi-agent setup.

In a possible scenario, the user may request an autonomous specialized transport via a smartphone application by specifying the current location and desired destination. A vehicle arrives autonomously at the pickup location and positions itself at a suitable boarding point. Upon arrival, an integrated lifting mechanism is automatically activated, allowing the user to roll onto the lift. The boarding system must operate independently while maintaining awareness of the vehicle's status—ensuring the vehicle remains stationary and stable throughout the boarding process. Subsequently, the lift mechanism elevates the wheelchair to enter the vehicle without any manual intervention. This transition phase requires careful coordination between the mechanical function of the lifting mechanism and the vehicle's control systems to prevent movements that could endanger the passenger.

Thereafter, the user is identified and the securing process is initiated automatically. The system must determine the wheelchair type and dimensions in order to select suitable attachment points. To this end, a mechanical clamp is attached at a predefined anchor point located at the foot of the wheelchair to secure the wheelchair throughout the journey. Concurrently, an automatic belt system is implemented, enveloping the passenger's upper body and functioning as a conventional seat belt. These mechanical systems (the lifting mechanism, clamping system, and belt apparatus) operate as semi-autonomous robotic subsystems with dedicated sensors and control loops, requiring precise coordination to ensure passenger safety. The securing systems must achieve a delicate balance between safety during dynamic driving maneuvers and discomfort or anxiety for passengers who cannot adjust their position independently.

At this moment, the passenger becomes dependent on the automated systems. Following the successful completion of the securing measures, the autonomous vehicle navigates through the urban environment and reaches its destination without human intervention. The navigation system must continuously communicate vehicle dynamics to the securing subsystems, which adaptively adjust their parameters to maintain passenger stability during acceleration, deceleration, and turning maneuvers.

Upon arrival, the safety measures are automatically released, and the lifting mechanism lowers the wheelchair user back onto the road. The release sequence must be carefully orchestrated. Securing mechanisms cannot disengage until the vehicle is fully stopped and the lift platform is ready for deployment, while the lift cannot operate until all clamps and belts are safely retracted.

The need to coordinate these robotic subsystems reveals why virtual validation is essential. Physical testing of every possible interaction between lifting mechanisms, securing systems, and vehicle controls would require enormous time and resources. The interdependencies between these systems create a combinatorial explosion of test scenarios. Each system's failure modes can cascade through the integrated architecture, creating safety-critical scenarios that must be validated. Furthermore, the variety of wheelchair types, user conditions, and environmental circumstances multiplies these scenarios beyond what physical testing alone could reasonably cover. Virtual validation thus becomes indispensable for ensuring comprehensive safety coverage across this complex system-of-systems, making stakeholder acceptance of simulation-based testing methods crucial for the deployment of such accessibility-focused autonomous transport services.

During the development stages and application of the described use case different interested parties arise. In the early stages of system development, societal needs and legal boundaries serve as the primary drivers of system requirements and reveal respective tests. *Society*, in this case particularly groups representing individuals with special needs, plays a pivotal role in ensuring that principles of usability, accessibility, and dignity are incorporated within the inception of the system. As shown by Harper et al. [33], autonomous vehicles possess the potential to increase travel for people with travel-restrictive medical conditions by up to 14% in annual vehicle miles traveled, highlighting the significance of developing such accessibility solutions. Representative bodies such as the European Disability Forum accompany the process by deliberative processes, advocating for inclusive standards. Concurrently, *legal and rights-based institutions*, including the European Commission and data protection agencies, ensure compliance with frameworks such as the General Data Protection Regulation (GDPR) and anti-discrimination laws. Simultaneously, *standardization bodies* (e.g., ISO, UNECE) and *associations* (e.g., SAE) delineate the fundamental requirements for safety, accessibility, and functionality, thereby establishing the foundation for virtual testing scenarios. As a result, four general groups of stakeholders have to be considered: (I) Society, (II) Legal and Rights-Based Institutions, (III) Standardization Bodies and (IV) Associations.

Within the subsequent system design process, the corresponding *Original Equipment Manufacturers (OEM)* in collaboration with the respective *product owner / systems engineer* determine the architecture of both the vehicle and the subsequent virtual validation pipeline. Here, decisions encompass engineering of the lift mechanism and the user recognition system, including respective digital models. These components must be aligned with standards such as ISO 26262 for functional safety and SAE J3016 for levels of vehicle autonomy. A critical aspect of this process involves the consideration of realistic use cases and edge scenarios, particularly those pertaining to vulnerable users. This stage is pivotal in defining the virtual test strategy and its role in either replacing or complementing physical tests. Thus, stakeholder groups (V) OEMs and (VI) Product Owner have to be highlighted.

In addition to the actual development and implementation of the product, *developers* of virtual test systems create the digital replicas of vehicles, the lift mechanism, urban environments, and user interactions in the next development stage to ensure that all functional elements are adequately prepared for virtual testing. The alignment with legal and standard-setting bodies ensures traceability between simulated results and regulatory expectations. In this context, the credibility of simulations necessitates the demonstration of a high degree of fidelity and reproducibility. Developers must demonstrate the equivalence of their simulations to physical test outcomes and account for rare but critical corner cases, as also emphasized by Stocco et al. [28] in their discussion of the sim-to-real gap. Since the latter marks the juncture from which social apprehensions emerge due to a lack of confidence in purely digital replicas, the stakeholder (VII) Developer has a prominent role in the acceptance of virtual testing. In the final validation and verification phase of the development process, the virtual testing system is utilized to assess safety, legal compliance and all other requirements. Regulatory bodies (e.g., UNECE, NHTSA) review simulation results as part of the type approval process. In addition, norming institutions (e.g., Euro NCAP) are progressively incorporating simulation into their safety assessments, particularly for AVs, thereby confirming the legitimacy of virtual testing.

Once finally brought to market, OEMs and product owners monitor the market introduction of the virtually tested system and the system's performance in real environments. This data may be fed into the simulation systems. From a provider's perspective, ensuring acceptance for the system and testing method is essential for successful market introduction and customer adoption. Therefore, societal stakeholders again play a pivotal role through public perception and purchasing behavior as well as their feedback and in-market surveillance.

As a result, we identify four stakeholder groups and perspectives: (1) *Legal Perspective* cumulating (II) Legal and Rights-Based Institutions and (III) Standardization Bodies, (2) *Social Perspective* including (I) Society and their technical representation by (IV) Associations, (3) *Corporate Perspective* representing (V) OEMs and (4) *Technical Perspective* containing (VI) Product Owner and (VII) Developer.

IV. INDIRECT TECHNOLOGY ACCEPTANCE FRAMEWORK

Based on the identified stakeholders, we propose the Indirect Technology Acceptance Framework (iTAF) for the acceptance of indirect technologies, like virtual validation methods as part of the development of autonomous systems. As shown in the use case, the general public does not engage with virtual validation directly. However, the legitimacy and long-term societal endorsement of such technologies depend on public perceptions of their credibility, transparency, and normative adequacy. The iTAF responds to this requirement of understanding how technologies, not directly utilized by individuals, may achieve acceptance at a societal level. This transition marks a shift from a user-centered paradigm to a properly centered approach that emphasizes indirect acceptance behaviors, thereby underscoring the need to explore the broader societal impacts of virtual validation and to develop a comprehensive understanding of societal acceptance.

A. Overview

The iTAF, visualized in Figure 2, extends beyond classical user-centered acceptance models by incorporating multi-level properties that affect the societal legitimization and regulatory feasibility of such technologies. It differentiates between four interdependent layers: (1) the technological layer, which targets the functional adequacy, transparency, and explainability of validation procedures (e.g., SiL, MiL, HiL); (2) the institutional layer, which focuses on trust in regulatory authorities, perceived legitimacy of normative frameworks, and international coherence of technical standards; (3) the societal layer, which reflects public and individual perception of risk, ethical concerns, and cultural receptiveness to simulation-based approaches; and (4) the interactive layer, which emphasizes the role of information accessibility, stakeholder participation, and discursive engagement in shaping public understanding and acceptance.

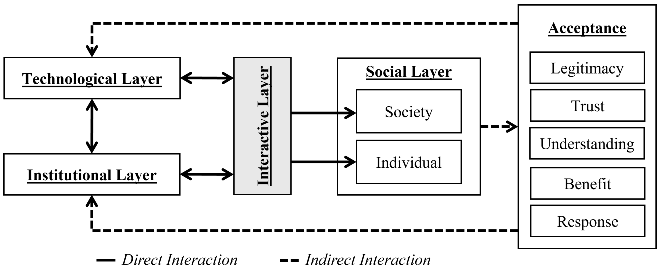

Fig. 2. The Indirect Technology Acceptance Framework

Each layer is associated with specific acceptance properties, such as cognitive understanding, affective trust, normative legitimacy, perceived benefit, and behavioral response. These factors jointly influence how virtual validation is perceived by different stakeholder groups. The model is inherently relational, admitting that acceptance is not merely an outcome of technical performance, but the result of communicative and institutional processes across the entire socio-technical ecosystem.

The four layers of the iTAF correspond to specific stakeholder groups previously identified in the development and validation process. At first, the technological layer involves those directly responsible for the technical implementation of virtual validation, namely the Product Owner (VI), Developer (VII), and OEMs (V). The institutional layer comprises Legal and Rights-Based Institutions (II) as well as Standardization Bodies (III), which ensure legal compliance, normative legitimacy, and alignment with international standards. The societal layer includes Society (I), sub-groups of these, such as individuals or their advocates, namely Associations (IV), who articulate ethical concerns and user needs. Lastly, the interactive layer emphasizes participatory and discursive engagement, involving Society (I) and Associations (IV) in shaping public narratives and fostering trust. These groupings reflect the layered and relational nature of societal acceptance, as outlined in the preceding section. At the same time, it allows a generic description through the possibility to define the affected groups according to the application.

By providing a structured lens, the iTAF allows for the identification of specific acceptance barriers and enablers. It also offers a foundation for developing targeted strategies, such as regulatory transparency, standardization alignment, and risk communication, based on derived stakeholder requirements aimed at improving acceptance properties of virtual validation as a robust and legally viable element in the development of autonomous systems. This includes methodologies from control theory through the model formalization.

B. Formalization

From a system-theoretical point of view, the framework operates through a system-input-output-feedback logic. Inputs such as validation methodologies, regulatory requirements, and societal expectations are processed through interactions among the four layers. Attitudes, behavior and level of knowledge form possible states. The output is the observed level of indirect acceptance by stakeholders, including regulators, industry actors, and the public. Feedback mechanisms allow for informing and reshaping validation practices, governance strategies, and communication approaches.

Consequently, we may define the social layer as a system $\Sigma : \mathcal{U} \rightarrow \mathcal{Y}$ to be controlled, described by a nonlinear stochastic differential equation:

$$\dot{\mathbf{x}}(t) = f(\mathbf{x}(t), \mathbf{u}(t)) + g(\mathbf{x}(t), \mathbf{u}(t))W(t, \cdot), \quad (1)$$

$$\mathbf{x}(0) = \mathbf{x}_0, \quad \mathbf{u}(\cdot) \in \mathcal{U}, \quad t \geq 0 \quad (2)$$

$$\mathbf{y}(t) = h(\mathbf{x}(t), \mathbf{u}(t)) \quad (3)$$

Here, $\mathbf{x}(\cdot)$, $\mathbf{u}(\cdot)$, and $\mathbf{y}(\cdot)$ represent state, input, and output of the system. The symbol $\mathcal{U}$ denotes a set of admissible inputs that may be applied to the system coming from the Interactive Layer. Simultaneously, $\mathcal{X}$ denotes a set of states and $\mathcal{Y}$ denotes a set of admissible outputs. Here, the former represents social states formed by attitudes, behaviors and the level of knowledge and the latter component represents acceptance, a subset of acceptance as well as effects or feedback to the influenced Technological or Institutional Layer. $\mathbf{x}_0$ represents the initial state of the system, and $W(t, \cdot)$ is defined as a d-dimensional Brownian motion process. For every $t \geq 0$, the random variables $\mathbf{x}(t)$, $\mathbf{u}(t)$, and $\mathbf{y}(t)$ assume values in the state space $\mathbb{R}^n$, the control space $\mathbb{R}^m$, and the output space $\mathbb{R}^p$, respectively. The mappings $f : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^n, g : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^{n \times d}, h : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^p$ are the system drift, diffusion, and output functions.

As a result, we may employ system theoretical approaches to structurally analyze acceptance. For instance, to ascertain the impacts of actions at the Interactive Layer, emanating from the Technological or Institutional Layer, on outputs a sensitivity analysis would be suitable. In addition, the intricacies and diversities of society and its constituent subgroups may be delineated. This includes the understanding that only a reasonable subset of manipulable states is controllable.

Hence, there exist controllable and uncontrollable subspaces of $\mathcal{X}$. The latter being unalterable by inputs and dynamics. Broadly speaking, not all parts of society or a social group may be influenced directly or indirectly. In a similar vein, it is noteworthy that in the majority of cases, the measurement of acceptance is limited to a specific subset. Here, the concept of observability may be utilized to split the society into measurable and non-measurable subspaces.

Consequently, control and system theoretical approaches may be applied to structurally analyze acceptance for virtual validation and define and tune control inputs.

C. Exemplary Application

To illustrate the operational logic of the iTAF, a hypothetical scenario is outlined for the social acceptance of virtual validation in the occurrence of legal uncertainty. It is postulated that a survey has been conducted in which certain sections of the public have expressed reservations about virtual validation, which forms the state $\mathbf{x}$, due to fears of legal uncertainty $W(\cdot)$. This uncertainty stemmed, for instance, from a deficiency in understanding of the pertinent regulatory instruments due to an absence of transparency on the part of state bodies as well as companies and is represented by the dynamics f and g. Additionally, there was an absence of readily identifiable indicators of compliance, such as publicly visible certification marks, which are part of $\mathbf{u}$. In the aforementioned scenario, the absence of acceptance is correlated with the acceptance properties of "legitimacy, trust, and response" in $\mathbf{y}$.

If limited acceptance of virtual validation is, at least partially, attributed to perceived legal uncertainty and consequently to the dynamics g, the concerns need to be addressed at the institutional level, as defined by the iTAF. At this layer, appropriate measures (inputs $\mathbf{u}$) may be implemented to counteract legal ambiguity, to strengthen public trust in regulatory authorities and their operations, and thereby to promote acceptance or potentially enable its full realization. More formal, to influence $\mathbf{x}$ by $\mathbf{u}$ in f and g.

In cases where relevant legal provisions, technical standards, or certification procedures for virtual validation already exist, efforts should focus on increasing public awareness and visibility of these frameworks. Consequently, the output $\mathbf{y}$, represented by the user experience, should be addressed. This may be achieved through targeted communication strategies as inputs $\mathbf{u}$. These may include the use of recognizable labels, certification schemes, or quality seals aligned with established value systems and brand identities, thus enhancing perceived legitimacy and transparency in $\mathbf{y}$.

Conversely, in situations where legal provisions are lacking, or where legal uncertainties $W(\cdot)$ persist, it is imperative to develop appropriate regulatory instruments. These may involve the enactment of regulatory measures, the development or refinement of technical norms and standards, or the publication of dedicated guidance documents as inputs $\mathbf{u}$. Where neither applicable requirements nor new developments are present, it remains essential to communicate any existing measures to the public as input $\mathbf{u}$ in a manner that is both transparent and appropriate for the dynamic g. Even in situations where no new regulatory developments are planned, proactive communication of the existing safeguards and assessment mechanisms remains essential. Such transparency fosters public trust, signals institutional accountability, and supports the societal legitimization of virtual validation methods.

The impact of measures implemented in this domain is contingent upon the specific institutional layer, with consequences that extend beyond the immediate social sphere. The emergence of novel norms, standards, and/or guidelines necessitates their consideration within the technological layer and subsequent implementation. Actors in the technological layer must then employ suitable marketing measures as inputs $\mathbf{u}$ to inform society appropriately and transparently about their adequate consideration and implementation.

In the context of communication between actors of the technological or institutional layer with those forming the social layer, it is imperative to situate these interactions as input $\mathbf{u}$ within the interactive layer.

The efficacy of the implemented measures and the new state $\mathbf{x}$ should be evaluated against the desired state through subsequent empirical studies, for example, via follow-up surveys or longitudinal assessments of stakeholder attitudes.

V. DISCUSSION

The Indirect Technology Acceptance Framework is a multidisciplinary approach that integrates elements of social sciences and system theory to elucidate the phenomenon of acceptance using the showcase of virtual validation methods.

The iTAF's provision of this structured lens facilitates the identification of both acceptance barriers and strategic enablers. It establishes the foundation for targeted measures, including regulatory transparency, alignment of international standards, and proactive risk communication, which may foster societal endorsement. The model reveals specific implications for each layer: the technological layer requires procedural transparency to address the "black box" nature of simulations; the institutional layer necessitates harmonized standards across jurisdictions; the societal layer highlights the influence of communication strategies and safety demonstrations; and the interactive layer emphasizes continuous stakeholder engagement throughout the development process.

From a systems engineering point of view, the iTAF depicts a way to qualify and later even quantify the trustworthiness of the virtual system validation as part of the SOI's development process. This trustworthiness contributes to the SOI's overall credibility, being a measure of effectiveness that corresponds to the stakeholder need for a minimum level of trust in the SOI (cf. [11]). Assessing and aligning this credibility contribution might be crucial to the success of systems like autonomous vehicles, as the comparison between stakeholder need and perceived overall credibility, a comparison that unavoidably takes place when the SOI is integrated into its usage environment, decides about the overall acceptance of the AV technology. Unmet expectations not only jeopardize the specific product but also threaten the technology as a whole.

While iTAF shares conceptual roots with well-established models such as TAM [15] and UTAUT [16], it addresses a fundamentally different use case. The iTAF focuses on the indirect societal acceptance of technologies that are not directly operated by individuals. TAM and UTAUT are user-centric, focusing on behavioral intention driven by perceived usefulness or ease of use. However, these frameworks are limited when applied to contexts involving collective stakeholders and non-user-facing technologies. iTAF advances beyond this limitation by offering a multi-layered, relational framework that incorporates institutional legitimacy, discursive engagement, and normative alignment as core mechanisms rather than peripheral moderators. Unlike TAM and UTAUT, which focus on individual adoption decisions, iTAF structurally embeds systemic constructs such as transparency, trust, and standardization within its four interdependent layers.

Furthermore, the model is relational and process-oriented, conceptualizing acceptance not as a static end-state but as the dynamic outcome of communicative, institutional, and technical interactions within a broader socio-technical ecosystem. Acceptance is not solely achieved through high-performance technical functionality. Rather, legitimacy, accountability, and transparency across all relevant domains must be established. This efficacy stems from its adherence to a system-input-output-feedback logic. The corresponding inputs, including validation methodologies and regulatory requirements, are processed through an interaction layer that disseminates them to society as a system. The observed level of indirect acceptance by society or social subgroups is the output of this process. Feedback mechanisms allow responses to inform and reshape validation practices, governance strategies, and communication approaches.

In addition, the iTAF allows the formal modeling of indirect acceptance pathways as well as the analysis of interdependencies across stakeholder groups and provides actionable insights. For instance, it shows how institutional actions or communication strategies propagate through the system and influence public perceptions and acceptance. The system-theoretic formalization provides a structural foundation for modeling the dynamic, multi-layered nature of indirect technology acceptance. However, it must be acknowledged that, in its current form, the formal model remains largely conceptual and underdefined in terms of empirical instantiation. Specifically, the state, input, and output variables, as well as the functional mappings f, g, and h, have not yet been explicitly parameterized or linked to measurable indicators. This abstraction was a deliberate design choice to maintain generalization across varying application domains and stakeholder contexts.

However, we acknowledge the imperative to transcend the realm of theoretical modeling and attain practical applications. Subsequent endeavors will center on operationalizing the system's pivotal components. For instance, the input space $\mathcal{U}$ may be instantiated through quantifiable policy instruments, communication strategies, or technical disclosures aimed at stakeholder engagement. The state vector $\mathbf{x}$ can be defined via latent constructs such as public trust, perceived legitimacy, or cognitive understanding, estimated from longitudinal data sources including public opinion surveys, social media sentiment analysis, or structured stakeholder interviews. The outputs $\mathbf{y}$ may then be linked to observable proxies of societal acceptance, such as public compliance, institutional support, or shifts in regulatory posture.

However, further challenges also emerge. For instance, the conversion of qualitative system dynamics into actionable metrics is feasible, albeit potentially intricate. The structure of the system is feedback-driven, which complicates the process of causal inference and the identification of clear intervention points. Furthermore, the implementation of a model across diverse cultural or regulatory contexts may encounter resistance due to varying trust regimes. Moreover, this would be possible from a framework perspective.

Despite these limitations, the iTAF offers a comprehensive and adaptable instrument for navigating the intricacies of indirect societal acceptance. By integrating technical, institutional, and societal dimensions, the iTAF supports the strategic alignment of indirect technologies with broader legitimacy demands, offering a structured approach for transitioning from skepticism to social robustness.

VI. Conclusions and Outlook

In this paper, we introduced the Indirect Technology Acceptance Framework to assess social and overall acceptance of virtual validation methods. Built on a systematic stakeholder identification, we integrated technical, regulatory, and societal dimensions, acknowledging the unique position of indirect users as critical stakeholders in societal legitimation. The approach provides a foundation for developing targeted strategies that support positioning indirect technologies, such as virtual validation as a socially robust and viable element of the safety assurance landscape for autonomous systems. Therefore, it is applicable not only to the social sciences, but also to the engineering sciences.

Building on the framework, future work will focus on the application. To this end, an evidence-based identification of critical acceptance parameters will be conducted. Subsequently, applicable methods for filling the framework will be defined, and their effectiveness will be analyzed. As a result, the establishment of a comprehensive acceptance system for the indirect critical components, like virtual validation, serves as a pivotal aspect of the acceptance of autonomous systems.

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