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RESEARCH ARTICLE

A Multidisciplinary Model to Quantify Human Uncertainty in Human-Centric Cyber-Physical-Social Systems: A 5G Application Use Case

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ABSTRACT The emerging Human-Centric Networks (HCN) paradigm shifts the passive role of individuals to an active one, intertwining the uncertainty of network resource usage with human dynamics, which are difficult to analyze and predict. This phenomenon implies an increase in reciprocal interactions between Cyber-Physical-Social Systems (CPSS) and human activities, presenting the challenge of efficiently allocating network resources while taking into account qualitative human uncertainty. In this study, we propose a conceptual model that addresses and quantifies such uncertainties. The proposed model is characterized by its adaptability to various CPSS applications, facilitating its integration into existing applications and future innovations. The adaptability of the model is based on the application of the sociological concept of Boundary Objects (BO), which allows for the structuring of system components and the generation of a reference architecture that facilitates systematic problem solving. To evaluate the model, we propose a use case related to a Vehicle for Hire (VFH) application operating within a 5G network slice. The integration of the proposed model with the OMNET++ simulation framework has allowed to demonstrate the effectiveness of the model in intricate computational environments and have shown its capacity to incorporate previously overlooked elements that are essential for the optimal allocation of resources in CPSS. This study proposes a methodology for comprehending and mitigating the consequences of human uncertainty, emphasizing the significance of a multidisciplinary approach to resource allocation in sophisticated technological systems.

INDEX TERMS Cyber-physical-social systems, human-centric networks, human uncertainty modeling, network slicing.

I. INTRODUCTION

Cyber-Physical Systems (CPS) have been designed to intertwine cyberspace with the physical world. In this context, incorporating social networks into this CPS framework gives rise to a new paradigm called Cyber-Physical-Social Systems (CPSS). This evolution is mainly driven by two essential factors. On the one hand, there is a growing trend to adopt a Human-Centric Networks (HCN) approach to these systems [1]. On the other hand, technological acceleration in fields such as the Internet of Things (IoT), fifth-generation (5G) wireless communication networks, Software-Defined

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Networking (SDN), Network Functions Virtualized (NFV), Network Slicing (NS), Big Data and Artificial Intelligence (AI) has played an active role in this development [2].

However, this progress is not without its challenges. While uncertainty is inherent in all complex systems [3], in human-centric CPSS, where individuals are key players, these two essential factors add sources or causes that increase the degree of uncertainty [4], [5]. Uncertainties can be categorized as either quantitative or qualitative. Quantitative uncertainties are measurable and can be expressed in numerical terms, such as inaccuracies of sensors or delays in network transmission. On the other hand, qualitative uncertainty refers to subjective uncertainties that are difficult to measure or quantify, including human behavior, preferences, and social factors. In this study, we will particularly focus on considering only qualitative uncertainty generated by humans. It is therefore essential to address the challenges generated by human uncertainty in terms of the identified essential factors.

For a better understanding, it is important to note how these technological advances lead to hyperconnectivity and global coverage that, when combined with human-centric CPSS, generate challenges to overcome. First, the HCN approach entails incorporating uncertainty derived from human behavior into CPSS, which is a fundamental element for understanding both individual and collective dynamics, particularly when people generate and interact with data in social contexts [6], [7], [8]. Second, the hyper-connectivity of the technological factor introduces significant heterogeneity in CPSS components [9]. This diversity, which encompasses forms and standards of both technological and social communication, adds a layer of complexity to these systems, and challenges effective information interpretation and sharing [10], [11]. Consequently, uncertainty increases with the global coverage of these technologies, by widening the diversity in terms of cultures, laws and regulations existing in different countries and organizations. This could result in a wide spectrum of interpretations and responses to the available information, thus aggravating uncertainty in the system.

Therefore, to address these challenges, methods are needed that can deal with the subjectivity of the interpretations of the people in the system. Even more so, when the decisions people make in social contexts are inherently uncertain [12]. Moreover, these methods need to be flexible and adaptable to the diversity of both people and scenarios that can be addressed. The characteristics needed by these methods are found in the research domain that integrates computer science with disciplines oriented to the study of human behavior, indicating the need for a multidisciplinary approach [13], [14].

In this regard, among the multidisciplinary studies that have addressed these challenges from different perspectives, two main approaches stand out: the layered design approach and the consideration of human behavior in these systems.

A. LAYERED DESIGN APPROACH

The first approach involves partitioning the problem to handle the interaction between humans and the other components of the system. In this context, in [15] authors explore the layered architecture of CPSSs. They discuss layered integration from the perspective of network technologies and determine the requirements for enabling CPSS through wireless network virtualization. Similarly, in [16] authors propose a three-layer model for collaborative construction processes. They rely on the Petri net to optimize collaborative engineering design, placing particular emphasis on technical activities and coordination among stakeholders. Although both studies consider social elements, they overlook the interrelationship between institutional and organizational elements. On the other hand, in [17], authors present a three-level model to measure resilience in socio-technical systems. They extend the Functional Resonance Analysis Method (FRAM) with a quantitative version, the Q-FRAM, which allows quantifying key performance indicators, facilitating the passage from an exclusively qualitative analysis to a quantitative one.

B. INTEGRATING HUMAN BEHAVIOR INTO CPSS

In the second approach, research focuses on human behavior. In this regard, in [18], authors propose an incentive scheme for CPSS, based on specific human behaviors and applied in a collective collaboration framework. In their proposal, users are grouped into three categories: malicious, speculative and honest. However, this scheme is limited to focusing only on the observable behavior of individuals within social networks, neglecting the particular characteristics of each user. In contrast, [19] argues that end-user participation goes beyond incentives and is linked to satisfaction, cooperation, and social diffusion. Therefore, authors modeled an artificial demand-response society in a power system, incorporating individual, organizational and social influences to analyze and validate the social behavior of active consumers in a socio-technical context. However, one obstacle evident from these multidisciplinary works is that the theories and methods specific to each discipline employ a unique language, which can make it difficult for researchers from other areas to understand and apply them.

In this sense, the following studies are oriented to improve mutual understanding between different disciplines based on sociological concepts and theories. In [20], authors develop a solid explanation of how to implement Socio-Technical Grounded Theory to overcome difficulties in the process of gathering information and understanding system requirements through active and collaborative communication techniques between engineers and stakeholders, a process known as elicitation in software engineering. Although this method, derived from sociology, provides a qualitative understanding of the human and social aspects of the field, it lacks guidelines for measuring and weighing results. Another concept in sociology used in several studies is known as Boundary Objects (BO). For example, in [21] authors propose a participatory multi-modeling approach based on an ecology of BOs, showing that modeling the social world by integrating the organizational and institutional domains facilitates interactions and understanding among participants and between participants and their respective organizations. Similarly, in [22] authors present a BO on scale consisting of a three-dimensional framework. This approach can enhance interdisciplinary understanding of scale. By promoting deliberate consideration in the choice of scales, decision support systems can boost their credibility, prominence, and legitimacy. While both studies employ boundary objects to foster interdisciplinary comprehension by breaking down problems into layers or dimensions, they overlook the inherent factors of personal human experiences that could have an impact on problem-solving.

The present work builds on the results of two previous investigations. The first of these studies identified several situations within the IoT field where human uncertainty negatively impacted performance [23]. Based on this, a use case was developed for a Vehicle for Hire (VFH) application that operated on a 5G slice and demonstrated the negative effects of human uncertainty on telecommunication networks [24]. Building upon such previous findings, the aim of the present work is to create a model that captures human qualitative uncertainty and to evaluate it by implementing it in the previously mentioned use case, but in a more realistic environment using real data from the German city of Ingolstadt.

In this context, the contributions of the present study are: a) a conceptual model capable of capturing human uncertainty by integrating theories from sociology, psychology, and the computational sciences; b) the demonstration that the aforementioned conceptual model can be effectively integrated with computational systems; and c) the evaluation of the model in a scenario of current relevance, providing a new perspective for resource allocation in the NS of 5G networks and highlighting the importance of considering human uncertainty in such contexts.

C. SCOPE AND LIMITATIONS

This study focuses on developing and evaluating a conceptual model specifically designed to quantify human uncertainty in human-cenctric CPSS. The model integrates theories from sociology, psychology, and computational science, allowing us to capture the variabilities in human behavior and decisions within complex technological systems. Our main objective is to evaluate the model's ability to integrate and function effectively in advanced computational systems, providing a robust reference architecture for simulating and tuning processes in realistic environments. In addition, we will evaluate the applicability of the model through a concrete case study, which will enrich our theoretical and practical understanding of human interaction with technological systems and establish a solid methodological basis for future research aimed at integrating human components into state of the art technologies. This study, despite its rigor and interdisciplinary approach, faces several significant limitations that impact the full understanding of the scope and applicability of the findings. One of the main challenges arises from the integration of Myers-Briggs Type Indicator (MBTI) and BO models into a unified framework designed to model human uncertainty in CPSS. Although these models are widely supported in the academic literature, their application in our specific framework may not capture all variants of human behavior, which would limit the generalizability of our results. To mitigate this limitation, we have incorporated a weighting factor in the model with the aim of aligning the theories more precisely with observed reality. Additionally, the classification of the data used in this study reveals other methodological vulnerabilities. The primary data, which includes traffic data derived from a specific scenario, comes from consolidated databases and extensively validated literature. This source is crucial to ensure the reliability of our approach. However, the values assigned to the variables in the simulations, estimated from official data, introduce the risk of selection biases and the presence of incomplete information.

The remainder of the paper is organized as follows: Section II establishes the conceptual framework that underlies our research. This is followed by Section III, which introduces the conceptual model designed to address human uncertainty. Section IV details the proposed reference architecture, being illustrated through a use case. Section V explains the integration of this model into the simulation framework, specifying both the configurations and the methodology employed. The findings obtained are discussed in Section VI. Finally, in Section VII, we present our conclusions.

II. THEORETICAL FRAMEWORK

In this section, we address two essential components of our study, the BOs and the 5G infrastructure. We explore how these two elements are fundamental to both the design of our conceptual model and the construction of the use case employed in its evaluation, respectively.

A. BOUNDARY OBJECTS

In the context of human-centric CPSS applications, there is a wide spectrum of possible use scenarios. This highlights the importance of forming multidisciplinary work teams for their design, an aspect that becomes even more relevant, for example, when considering the service provider's perspective. The latter will need to quantify the uncertainty intrinsic to the human factor to determine its impact on the performance of the technological infrastructure. The complexity of this task lies in the intersection of multiple factors, especially those of a qualitative nature, which adds an additional difficulty to its measurement and weighting.

From the perspective of the exact sciences, uncertainty quantification is based on laws and principles of a deterministic or metrological nature, allowing effective management even of components that require non-statistical quantification methods [26]. However, the quantification of human uncertainty demands a different approach due to its inherent subjectivity. This uncertainty can be modeled through various factors, such as perceptions, personality, and sociocultural context [27], [28]. The subjective essence of this phenomenon has been the subject of extensive analysis in the social sciences. Consequently, our study integrates an approach from this perspective to address the problem.

In the field of social sciences, there is a diversity of theories and methods oriented towards the management of human uncertainty. All of these can be incorporated into our model at any stage of its development. However, to address the problem posed, the concept of BO was chosen as the most appropriate instrument for the realization of this study.

BOs play a key role in problem modeling and, from this modeling, facilitate the recognition of interactions between model components to generate a reference architecture. In terms of their first role, BOs have suitable elements and characteristics that allow the problem to be accurately described, using a common language that promotes interdisciplinary collaboration and provides an abstract but comprehensive view of the problem context. Regarding its use as a reference architecture, this function facilitates the creation of diagrams or schemes that favor the programmability of the system, through the identification and connection between the elements of the model. To achieve this, the open nomenclature of the BOs will be used, which provides greater clarity for the participation of interdisciplinary teams, taking into account the wide range of services or applications that the model can cover.

The theoretical concept of BO facilitates the integration of diverse perspectives and stimulates learning at both the individual and collective levels [29]. In addition, it contributes significantly to conflict resolution and group decision-making concerning a given problem [30]. These properties are especially relevant in environments involving multidisciplinary teams, where it is necessary to work on the relationship between social and scientific aspects in conceptual models [31], [32]. Even, its usefulness extends to contexts where interactions between the physical and the digital occur, as it facilitates the understanding of how these interactions influence the respective positions within a shared framework [33], [34].

Initially introduced in a study of information practices at the Berkeley Museum of Vertebrate Zoology, the BO concept postulates that "Boundary Objects are plastic enough to adapt to the local needs and constraints of the various parties that employ them, but are also robust enough to maintain a common identity across different sites" [35].

These objects, which may be abstract or concrete, take a variety of forms ranging from technical artifacts to ideas, plans, and concepts [36]. In this context, the theory highlights two essential properties of BOs, their plasticity and their immutability. Plasticity refers to the ability of BOs to be interpreted and adapted differently by professionals from different fields, always according to their specific needs, while maintaining the advantages specific to their different backgrounds and perspectives [37], [38]. For example, in a scientific laboratory, an instrument such as a microscope can be adapted to study a wide range of samples, both biological and inorganic, according to the needs of the various scientists. Immutability, on the other hand, refers to the fundamental essence of the BO that preserves its identity and functionality despite its use in different contexts. In the case of the microscope, although it may be used to analyze different types of specimens, its primary function of magnification remains constant. Therefore, BOs possess a structure that is recognizable in different social contexts. This structure allows them to act as a means of translation, facilitating communication and cooperation between different communities. This ability to promote convergence of perspectives and objectives can be crucial for the success of projects involving multiple stakeholders with diverse interests [39], [40].

Finally, due to the above, the versatility of BOs has allowed it to be adopted and applied in multiple research contexts and disciplines, including several branches of applied sciences, from energy transition [42] and computer vision [43], to enterprise architecture [44] and systems intelligence [45]. In all these cases, BOs have proven to be a key tool for addressing complexity and interdisciplinarity, promoting better understanding and collaboration between different stakeholders involved in research and development projects.

B. 5G

The design of 5G is aimed at developing a flexible and scalable network infrastructure that enables unprecedented connectivity [46]. This innovation will facilitate the creation of new services and applications through the integration of technologies such as SDN, NFV, and NS [47].

These technologies facilitate network virtualization, a process that involves the segmentation of a single physical network into several virtual networks that share the same infrastructure. This logical segmentation enables the customization of different Service Level Requirements (SLRs), which can include factors such as throughput, latency and reliability, for each service or application, as well as their rapid deployment [48].

In this study, the concept of NS is of particular relevance. In order to fully understand its application and importance, it is essential to first dive into two key technologies that enable this capability, SDN and NFV.

SDN implements an approach that separates the data plane of the network, which is responsible for transmitting information, from the control plane, which is responsible for managing how that information is sent. In this approach, the logic of network device functions, such as a router, is removed from the data plane and transferred to the control plane, which takes over the routing and administrative functions [49].

This approach facilitates configuration and management, and increases flexibility and resiliency in communications networks, which are fundamental aspects for the development of NS [50].

As for NFV, it emerges as an attractive option that allows the reconfiguration of complex network functions, which have traditionally been implemented on dedicated hardware, into operational software instances in a virtualized environment [51]. This change not only reduces implementation costs by requiring less equipment and installation personnel, but also optimizes service deployment times. It should be emphasized that NFV and SDN are two complementary technologies that work together to achieve the level of abstraction and flexibility needed to meet the SLRs of specific applications [52], and their synergy is crucial for effective NS implementation.

NS is a technology, adopted in SDN architectures, for example in 5G, that enables the multiplexing of several independent, virtualized, logical networks into a single physical network infrastructure. Each 'slice' or network segment is an integral and isolated network, designed to specifically meet its own SLRs. Being built on the foundation of SDNs and NFV, the NS has the responsibility to properly select, allocate and manage compute, storage and network resources to meet the SLRs of each slice [53], [54].

From a business model perspective, NS for 5G provides a Network as a Service (NaaS). This model allows infrastructure providers to lease their physical resources to multiple Mobile Virtual Network Operators (MVNOs) [55]. In this scenario, each MVNO can efficiently deploy its own services and applications in distinct slices or segments within the same physical 5G network infrastructure, which they share with other MVNOs. However, this business model poses the challenge for infrastructure providers to efficiently manage the allocation of their resources to maximize their profits while maintaining a balance with the needs and demands of the different MVNOs.

The Handover (HO) process in 5G, which represents a particular resource allocation challenge, is essential to ensure call continuity and quality of service in mobile environments [56]. This process seeks the uninterrupted HO of an active call from one cell to another as a user moves within the coverage area. For this HO to be effective, it is crucial to have free frequencies available to assign to mobile devices entering a new cell. In the case of HO, frequencies represent a limited resource that must be efficiently allocated among all mobile devices to ensure optimal network performance. This allocation problem is of special interest in 5G because the characteristics of the scenarios will make the HO process difficult.

The unique characteristics of 5G scenarios, such as the progressive reduction in cell size to levels such as metrocells, microcells, picocells and femtocells, along with the increase in connection density to 10 million connections per km^2 and support for mobility speeds up to 500 km/h, make the HO resource allocation process especially critical in this environment [57].

III. LAYERED CONCEPTUAL MODEL

The design of the proposed conceptual model is oriented towards adaptability, a crucial feature for its implementation in any human-centric CPSS service or system. This versatility is specifically manifested in the ability to interchange and reconfigure factors and components across the different layers of the model. As a result, the system offers the possibility of incorporating multiple strategies, allowing it to be adapted to both existing applications and future emerging innovations.

BOs, as an essential theoretical tool in our research, were used in the structuring and organization of information within a conceptual model that considers three contexts, the natural, the social and the personal. These contexts, about the perspectives proposed in [21] and [22], represent multiple levels or dimensions that influence a decision. However, our model is distinguished by the specific characteristics assigned to each of these contexts, designed to encompass a broader spectrum.

For example, our natural context layer resembles the reality axis in [22], as it provides a time scale. However, we extend this concept to include location and environmental factors arising from the interaction between time and place. In the social context layer, we group institutional and organizational factors, similar to what was done in [21]. However, we incorporate an additional component: social networks. Finally, the personal context layer of our model considers personal information collected by technological devices, personal data and personality traits.

The proposed conceptual model places the human being at its core, surrounded by three interrelated layers. This proposal is transformed into a BO, aligning with the inherent complexity of HCN-focused CPSS. Figure 1 illustrates the structure of this model. Each context is differentiated by a unique geometric figure; the natural context is symbolized by a circle, the social context by an octagon, and the personal context by a rectangle.

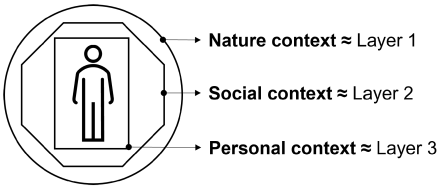

FIGURE 1. Proposed conceptual model.

As shown in Figure 2, when the interactions between the different layers and the elements of the scenario to be analyzed are defined, the model acquires a new dimension as a BO. In other words, the resulting diagram facilitates the understanding and analysis of the interaction between the components of the system under study.

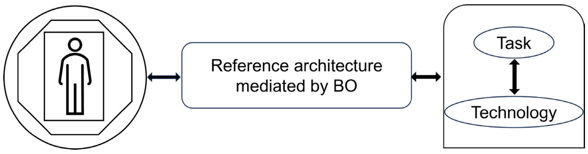

FIGURE 2. Definition of attributes in the CPSS through the support of BO.

The model in Figure 3 depicts the different scenarios that are possible as a result of this approach. Furthermore, the use of distinct colors within the figures indicates modifications to specific elements within each context, distinguishing them from other contexts of a similar nature.

First, with regard to Type 1, illustrated in Figure 3 a), we observe individuals with clearly defined roles, in this case as drivers, who, however, share the same social and natural context. This category also extends to those individuals who, although they do not have a specific role, are immersed in the same social and natural contexts.

Secondly, the Type 2 scenario, presented in Figure 3 b), refers to groups of people with roles, which can be both diverse and equal, who belong to different social contexts, but who are located in the same natural context.

Finally, Type 3 represents the combination of diverse natural and social contexts. This last type reflects the greatest complexity and diversity, including individuals with different roles coming from various social and natural contexts, as shown in the Figure 3 c).

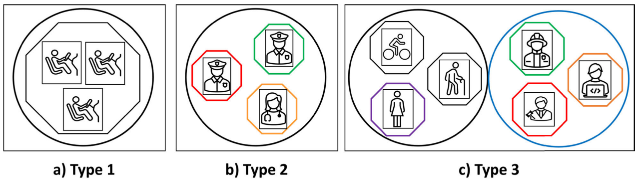
a) Type 1 b) Type 2 c) Type 3

FIGURE 3. Types of scenarios allowed by the proposed conceptual model.

Next, we describe and analyze each layer that constitutes our model.

A. LAYER 1, NATURAL CONTEXT

The purpose of this layer is to narrow down the context of the problem under analysis. For this purpose, factors such as temporal (t), ubication (u) and environmental (e) are incorporated into consideration. It should be emphasized that a BO, by its nature, is not capable of sustaining a continuous and indefinite state [42]. This characteristic stems from the fact that each BO undergoes a unique life cycle [32], modeled as a function of the interaction between Layer 1 and various factors corresponding to the other proposed layers. Moving forward in this analysis, as previously mentioned, the granularity of each element is determined according to the scenario we are analyzing. Therefore, the representation of this layer is expressed by Eq. (1).

$$Layer\ 1 = \{(t_1, t_2, \ldots, t_l), (u_1, u_2, \ldots, u_m), (e_1, e_2, \ldots, e_n)\} \tag{1}$$

To illustrate how these factors interact and can be addressed at different scales, consider, for example, the time factor. The scale can be addressed in terms of hours, minutes and seconds, or alternatively, it can be focused on a broader spectrum such as years, months and days. Similarly, geographic location can be defined through one or multiple elements, such as country, region and city. In addition, if it is decided to consider the environmental factor, it should be consistent with the combination of temporal and geographical factors.

B. LAYER 2, SOCIAL CONTEXT

Multiple social worlds exist, each with distinct entities. BOs facilitate interaction between these contexts by providing differentiated information to representatives of social groups seeking to interact with each other [44]. When considering the concept of BO in CPSS, it is a straightforward step to include social networks in the conceptual model. For these reasons, Layer 2 groups together social factors, such as social networks (s), as well as institutional (i) and organizational (o) factors.

Social networks are found in large numbers and for specific purposes. Not only do these platforms allow us to predict the behavioral trends of a collectivity in the face of particular events [58], [59], but they also can shape the individual behavior of users [60]. This dual influence of social networks, at the collective and individual levels, is essential in our analysis. For this reason, the concept of BO becomes a key tool for working with social networks [61], [62].

The institutional factor, which encompasses a number of elements, including legislative aspects, socio-cultural conditions and economic factors [63], delineates the viable options available for decision-making, as well as determines the flexibility inherent in the decisions [64].

The organizational factor is related to the processes, regulations and practices that govern an entity, usually the owner of the CPSS. This factor plays a crucial role in aligning the roles and interests of CPSS participants, thus ensuring the cohesion and effective functioning of the system [65]. Importantly, organizational processes, regulations, and practices can be significantly influenced by the institutional context [66], determining whether the purpose of the CPSS is maintained, modified, or even closed.

Upon the definition of the factors and elements of this layer, their representation is denoted in Eq.(2).

$$Layer\ 2 = \{(s_1, s_2, \ldots, s_u), (i_1, i_2, \ldots, i_v), (o_1, o_2, \ldots, o_w)\} \tag{2}$$

C. LAYER 3, PERSONAL CONTEXT

People do not always follow instructions or assigned tasks because of their innate ability to adapt to changing environments and develop creative solutions. It follows from this human capability that it is important to consider such characteristics in the design of CPSSs [15], in order to facilitate smooth interaction between humans and other components of the system.

In this context, in the proposed conceptual model, individuals play a dual role. First, they act as resources by providing information and services. Concomitantly, they also act as users by using these elements in the context of the CPSS.

This duality leads us to a deeper consideration of the integration of individual perspectives and modes of reasoning in the third layer of our model. To achieve this, elements are grouped into factors such as personal information collected through technological gadgets (g), personal data (d), and personality type (p). Therefore, Eq. (3) is composed as follows:

$$Layer\ 3=\{(g_1, g_2, \ldots, g_r), (d_1, d_2, \ldots, d_s), (p_1, p_2, \ldots, p_t)\} \tag{3}$$

These factors provide insight into how individuals interact with the CPSS. Current technological devices, including devices such as heart rate monitors, accelerometers, barometers, Global Positioning Systems (GPS), and pedometers, have driven a considerable transformation in terms of information acquisition, storage, and analysis. This technological revolution has cleared the way for access to an unparalleled volume of data, thereby enriching our understanding of how individuals interact with CPSS. More specifically, these advances make it possible to incorporate sensory variables as an additional factor in the analysis of the influence on human behavior.

On the other hand, personal data, such as age, gender, and other demographics, as well as the person's social role, play a crucial role in human behavior [67]. Consequently, by analyzing these elements, we can significantly increase the accuracy of human uncertainty weights, providing a human-centric approach to CPSS.

Regarding personality factors, it is necessary to select a model from the wide variety of psychological and psychoanalytic models recognized in the academic literature. The choice of the said model must be congruent with the specific objectives of the study or application under consideration.

We emphasize that the purpose of this work does not lie in the development or criticism of psychological models themselves, but in their application and adaptability in contemporary technological contexts. This distinction is essential to understand the scope and limitations of our research.

D. REFERENCE ARCHITECTURE FOR WEIGHTING HUMAN UNCERTAINTY

The conceptual model we propose provides a comprehensive framework designed for the inclusion of any CPSS application, placing the human being at its core, surrounded by three interrelated layers. However, we must point out that the interaction between these layers is not static. On the contrary, it is a dynamic process that may undergo variations depending on the application scenario under consideration. This fact translates into a diversity of factors present in each layer, which are affected by the inherent variability of the system. Furthermore, the granularity of each element in the layers is defined not only by its intrinsic magnitude but also by the specific scale of the analysis to be performed. This same criterion is applied to determine the weighting corresponding to each element.

To address the complex challenge of defining the multiple attributes of this system and the need to harmonize the various interests of the CPSS components, we propose the adoption of our reference architecture, illustrated in Figure 4. The proposal presented herein is based on a thorough analysis of the layered conceptual model presented, incorporating all the necessary components and features to effectively and coherently describe any situation within the CPSS.

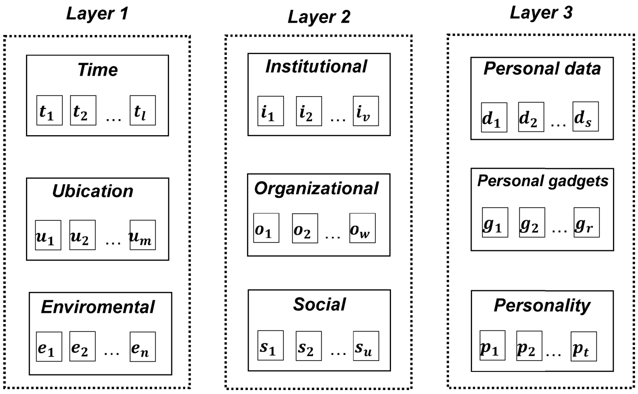

FIGURE 4. Reference architecture.

In this context, the proposed reference architecture serves as a tool to document the conceptual description of the problem, considering human uncertainty. For instance, this documentation can be utilized to produce specialized UML diagrams that aid engineers in programming by offering a clear visual depiction of the problem's structure and interactions.

In the framework of the present research, a sequential process based on boundary object–mediated negotiation has been adopted, as presented in [41]. This methodology serves as the basis on which the reference architecture can be applied to various scenarios within the CPSS. This sequential process is based on the following propositions:

- "Proposition 1: By drawing attention, boundary objects enable design-centered negotiation participants to focus on particular aspects of existing dispersed knowledge.
- Proposition 1.1: When design-centered negotiation participants across a national cultural boundary focus on particular aspects of existing dispersed knowledge, local knowledge can emerge.
- Proposition 2: By enabling clarification, boundary objects enable design-centered negotiation participants to clarify local knowledge.
- Proposition 2.1: When design-centered negotiation participants across a national cultural boundary clarify local knowledge, clarified knowledge can emerge.

- Proposition 3: By justifying outcomes, boundary objects assist design-centered negotiation participants to agree on the local clarified knowledge.
- Proposition 3.1: When design-centered negotiating individuals across a national cultural boundary agree on local clarified knowledge, common knowledge can emerge''.

Figure 5 illustrates the sequential process established to implement the reference architecture. This process is used to identify, define, and establish the intrinsic relationships of the fundamental attributes required to model the system accurately.

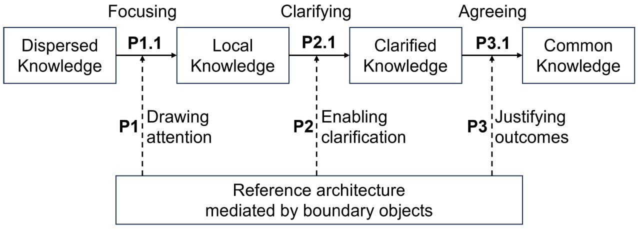

FIGURE 5. Reference architecture methodology. Adapted from [41].

With this, the reference architecture helps both the negotiation process between the parties and the joint definition by an interdisciplinary team of the selection of factors, elements, and interactions. This set of aspects contributes to the weighting of the uncertainty inherent to the human factor in our study.

In the next section, we detail the application of the reference architecture to the VFH application use case operating within a 5G NS.

IV. A USE CASE FOR A VFH APPLICATION ON A 5G NETWORK SLICE USING THE PROPOSED MODEL

VFH-type applications, such as Uber and Cabify, which utilize real-time connectivity between users and drivers via mobile devices to satisfy the need for transportation, has become increasingly popular. These applications enable users to select their destination and receive optimal routes; however, drivers can alter these routes, leading to uncertainty and negatively impacting the efficient distribution of resources and overall network performance.

This situation is especially pertinent for the use case of a VFH application operating within a 5G network slice, where deviations from predetermined routes have significant implications on the HO process. The optimal routes designed for this application are intended to guarantee the frequencies necessary for the HO process. Therefore, any alterations to the route may require additional frequencies, increasing the likelihood of call drops and affecting network efficiency.

For this use case, the city of Ingolstadt, Germany, was chosen as the scenario. The choice of this scenario is strategic, as it paves the way for future research using more detailed data sets, such as those obtained using the realistic traffic model known as the Ingolstadt Traffic Scenario for SUMO (InTAS) [70].

A. SELECTION OF FACTORS AND ELEMENTS FOR EACH LAYER

Considering the Ingolstadt City scenario as a context, factors and their elements were chosen for each layer of the reference architecture to capture the qualitative uncertainty that could induce a driver to alter the route defined by the VFH application.

1) LAYER 1

In the first layer of the reference architecture, time and location parameters are defined, specifically 16:17 on a Thursday in November in Ingolstadt, Germany. In this specific study, the environmental component was not considered. However, if it had been, typical late autumn conditions would have been considered. Consequently, the first layer configuration is decomposed into the following elements: regarding the time factor, we have $t_1 = 16 : 47$, $t_2 =$ Thursday and $t_3 =$ November; regarding the location factor, $u_1 =$ Ingolstadt and $u_2 =$ Germany are specified.

2) LAYER 2

When moving towards Layer 2, it is essential that the chosen elements align with those of Layer 1. Thus, the selected traffic social network is Waze with the parameters of the selected city. Regarding the institutional factor, the traffic policies of Ingolstadt are incorporated,[1] such as speed limits and overtaking restrictions. Regarding the organizational factor, rules such as star rating[2] and differential rates[3] for services offered at specific times and zones, common features in VFH applications, are considered. Thus, the structure of the second layer is defined as follows: for the social factor, we have $s_1 =$ *Waze*; for the institutional factor, we set $i_1 =$ speed limits and $i_2 =$ overtaking restrictions; and for the organizational factor, we specify, $o_1 =$ star rating and $o_1 =$ differential rates.

3) LAYER 3

Finally, about the third layer, three main aspects are distinguished. First, there is the heart rate measured by a pulsometer, thus symbolizing the element of technological devices. With regard to personal information, three variables are taken into account: age, sex and the role of each individual. This last piece of information makes it possible to discern whether the person is the owner of the vehicle or an employee. Additionally, the four predominant personality characteristics previously explained are integrated.

In relation to the personality factor, the MBTI [69] method was chosen. The decision to use the MBTI was based on its well-established acceptance and validation, which has been demonstrated through numerous previous studies, making it a relevant tool for the objectives of this research. The MBTI's capacity to facilitate psychological profiling

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[1] https://www.ingolstadt.de/Rathaus/Verkehr

[2] https://www.uber.com/es/es-es/drive/basics/how-ratings-work

[3] lhttps://www.uber.com/es/es-es/drive/driver-app/how-surge-works/

using digital platforms such as LinkedIn showcases the potential for combining psychological theories with advanced technologies [68]. Therefore, this methodology confirms the appropriateness of the chosen model for research purposes.

MBTI method postulates that the personality type of individuals can be described by 4 dimensions:

- Extraversion-Introversion (EI), are two personality traits that indicate where a person gets their energy. Introverts are energized by solitude, while extraverts are energized by being around others.
- Sensing - Intuition (SN): This characteristic measures a person's information processing style. While intuitive relies on sensations, sensing people rely on their five senses.
- Thinking- Feeling (TF): This dimension evaluates a person's decision-making process. Decisions are made by thinkers using logic and reason, while feelers are guided by their ideals and emotions.
- Judging - Perceiving (JP): This aspect examines a person's way of life. Perceivers are more adaptive and spontaneous than judges, who want structure and order.

Thus, in the last layer, the personal gadget factor is represented by $g_1 =$ Pulsometer. In the personal data factor, $d_1 =$ Age, $d_2 =$ Sex and $d_3 =$ Role are identified and the personality factor (p) allows for the selection of one of four dominant personality trait types: EI, SN, TF, and JP.

B. RELATIONSHIPS BETWEEN LAYERS, FACTORS AND ELEMENTS

After establishing the relevant attributes of the problem, the subsequent step is to discern the patterns, correlations, and relationships between these attributes. This stage is crucial because it sets the foundation for an analytical model that enables the calculation of a weighted numerical result. The weighted numerical result is the decisive criterion in simulations to determine whether the driver opts to follow the route proposed by the VFH application.

The layer 1 of our model is designed to recognize the crucial elements that establish the foundation for institutional policies and organizational regulations. Moreover, this contextual layer functions as the starting point for implementing the Waze social traffic network, thereby facilitating the effective distribution of traffic-related information.

The factors identified in the second layer provide critical information that will be weighed by the drivers. Each of them, depending on their specific role and individual objectives, will evaluate these variables to determine whether to follow the route proposed by the VFH application. For example, the Waze social network may suggest whether to opt for an alternate route based on traffic conditions. However, recognizing that not all drivers resort to this type of resource, this factor is set up as optional in the model. This allows for a more nuanced representation of the diversity of behaviors and preferences among drivers.

In contrast to the optional factor mentioned above, the next two factors, institutional policies and organizational norms, are considered universal and thus mandatory in the reference architecture. These factors affect all drivers, but the degree to which they are affected will depend on their individual roles. Additionally, in our model, it is assumed that the elements of each of these factors will be evaluated in terms of their joint probability, i.e., the probability that both sets of elements simultaneously influence the driver's decision-making.

Thus, institutional policies, such as speed limits or overtaking restrictions, can act as constraints on the decision to alter a route, since non-compliance could result in penalties or increase travel time. On the other hand, organizational rules introduce an additional layer of complexity in decision-making. The relevance of these rules may fluctuate depending on the specific role of the driver. For example, consideration of dynamic fares may add an economic dimension to the decision, while the impact on the driver's reputation could be a crucial factor for those with a long-term view on the platform.

The third layer of the model focuses on factors intrinsic to the driver that may influence and determine driving decision-making. For example, for the technology device factor, a heart rate monitor that detects an increase in heart rate could serve as an indicator of elevated stress levels. Depending on the driver's personal characteristics, this emotional state could positively or negatively affect his or her driving behavior. It is important to note that since not all drivers have these technological devices, we have chosen to consider this factor as optional within our reference architecture.

For the personal data factor, different behaviors have been predicted based on demographic variables. For example, for the age variable, some age ranges tend to show greater boldness, while other age ranges tend to be more cautious. From a statistical perspective, gender also constitutes an element that can affect driving behavior, as statistics[4] indicate that women tend to adopt a more cautious driving posture. In the reference architecture, these demographic elements will be evaluated in terms of their joint probability to provide a more comprehensive view of how these factors may interact in driving decision-making.

Additionally, the driver role factor is considered to understand the objectives being pursued, whether they are economic or for the purpose of improving service quality. Depending on the specific role of the driver, these objectives will have a variable impact on the interpretation of information derived from social networks, as well as on the relevant institutional and organizational conditions. Finally, four personality dimensions are considered, selecting the most predominant one for each driver.

After defining the factors and elements corresponding to each layer and establishing their interactions and

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[4] https://www-genesis.destatis.de/genesis//online?operation=table&code=46241-0007&bypass=true&levelindex=0&levelid=1699889773069#abreadcrumb

relationships, these principles are implemented in the reference architecture. In this way, a reference architecture is developed that is specifically tailored to the proposed use case. This architecture is detailed in Figure 6, where the interactions and correlations between the factors and elements of the three layers of the conceptual model are highlighted.

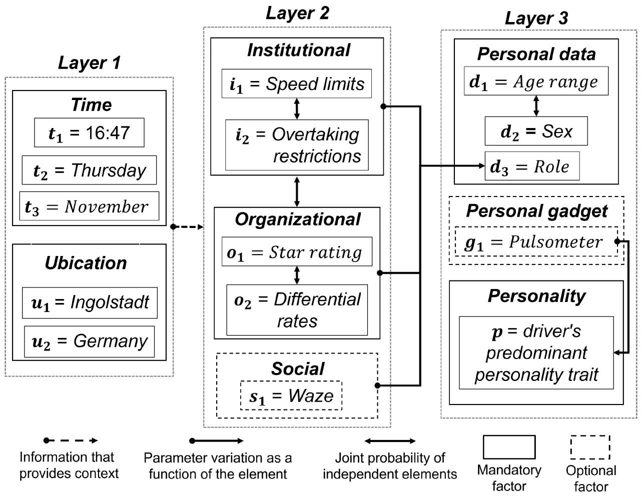

FIGURE 6. **Reference architecture applied to the 5G VFH use case evaluated.**

C. ANALYTICAL MODEL TO QUANTIFY HUMAN QUALITATIVE UNCERTAINTY

Building on the reference architecture and interelement relationships outlined in Figure 6, this section is devoted to the development of an analytical model to quantify the qualitative uncertainties inherent in driver behavior within the context of VFH applications. The connections and interdependencies identified earlier will now be translated into a mathematical framework that will allow for the quantitative assessment of these qualitative elements.

To this goal, we rely on the definitions provided in [71]. According to probability theory, a set is defined as a collection of elements, which can be both tangible and intangible. These sets usually represent the sample space, for instance, the total possible outcomes of a random experiment. An event, in this context, is a subset of the sample space that possesses probabilities of specific interest for our study. On the other hand, the union of events involves the combination of two or more distinct events to form a new event. The probability associated with the union of these events is calculated by determining the occurrence of at least one of the events in the union. If we have two events A and B, the probability of $(A \cup B)$ is given by: $P(A \cup B) = P(A) + P(B) - P(A \cap B)$.

In the case under study we assume that $(A \cap B) = \emptyset$ and the probability of $(A \cup B)$, is simply given by: $(A \cup B) = P(A) + P(B)$.

Therefore, Eq. (4) introduces an analytical model for determining (ρ_i), which represents the probability of a particular driver opting for an alternative route instead of the one suggested by the VFH application. These probabilities are computed based on the contributions from disjoint sets of events, each representing a different nature:

$$\rho_i = pPP + pDS + pRF \tag{4}$$

It is important to mention that, although this formula admits future optimizations, it is the one currently used in the simulations. The components are as follows:

- Psychophysiology (pPP): this component quantifies the probability of change of route related to the driver's predominant personality trait and the probability that the heart rate influences his/her behavior. In this work we assume that for each personality trait the probability of changing a pre-defined route is uniformly distributed in a range of values. This probability is represented by pp. Furthermore, for each personality trait there is an additive contribution to the probability of changing a pre-defined route given by the awareness of the heart rate. This probability is represented by pg. So, the formula $pPP = (pp + pg)$ is used to evaluate the contribution of psychophysical factors to the change of route.
- Demographic Segment (pDS): this component quantifies the probability of change of route related to two demographic variables, the driver's age and gender. In this work we assume that the contribution to the probability of change of route due to the driver's age can be inferred from the probability distribution of car accidents as function of the driver's age. This probability is represented by pd_1. On the other hand, the contribution to the probability of change of route due to gender is assumed that can be inferred from the probability of males and females involved in car accidents. This probability is represented by pd_2. It is also assumed that the contributions due to age and gender are independent. Therefore, (pDS) is given by $pDS = (pd_1 \cdot pd_2)$.
- Role Fit (pRF): this component quantifies the probability of change of route related to the influence of the driver's role, i.e., owner or employee, on his/her behavior taking into account the reaction to information from social networks s_1, his/her response to institutional (i_1, i_2) and organizational (o_1, o_2) factors. It is assumed that the reaction to information from social networks and the response to institutional and organizational factors are disjoint events. The contribution to the probability of change of route due to information from social networks is represented by $ps1$. On the other hand, the probability of change of route due to institution and organizational factors is given by the joint probability $p(i_1, i_2, o_1, o_2)$. It is assumed that the driver's response to each of the factors is independent from the other factors. Thus, $p\,(i_1, i_2, o_1, o_2)$ is given by $p\,(i_1, i_2, o_1, o_2) = [(pi_1 \cdot pi_2) \cdot (po_1 \cdot po_2)]$.

In conclusion, $pRF = ps1 + p(i1, i2, o1, o2)$, i.e., $pRF = ps_1 + [(pi_1 \cdot pi_2) \cdot (po_1 \cdot po_2)]$.

Some of the assumptions made above are dictated by common sense and may not represent the most correct model. However, such "correct" model does not exist so far. It is important to emphasize that the objective of the work is to propose a reference architecture that can capture and quantify the intricacies of the human behavior. Whenever a better model for the evaluation of pPP, pDS and pRF is available it can be plugged into the architecture and more accurate results can be obtained.

Eq. (5) expands all terms the terms explained above for the condensed Eq. (4):

$$\rho_i = (pp + pg) + (pd_1 \cdot pd_2) + ps_1 + [(pi_1 \cdot pi_2) \cdot (po_1 \cdot po_2)] \tag{5}$$

D. ASSIGNMENT OF VALUES TO MODEL COMPONENTS

This section provides a comprehensive breakdown of the values attributed to the individual components of Eq. (5). Each component's assigned value is meticulously detailed, laying the foundation for a thorough understanding of its roles and interactions within the model.

To begin with, a total of 64 different driver profiles have been created to represent the factors corresponding to the third layer of the reference architecture. These profiles are derived from the combination of factors detailed in Table 1.

TABLE 1. Combinations of personality characteristic and personal data for driver profiles.

Predominant personality characteristic	Age ranges	Sex	Role
EI	18-35	M	Owner
SN	36-48	F	Employee
TF	49-65		
JP	66-85		

Starting with the personality variable, Table 2 presents the probability intervals associated with each personality category, providing an indication of the potential variations in behavior that correspond to the value of the pp variable in Eq. (5). The intervals assigned to each predominant personality characteristic were based on the results of a previous publication [68], in which the characterization was carried out based on data published on the social network LinkedIn, which we consider a valid example for this research. It is important to note that the aim of the present work is not the exhaustive construction of a personality model. However, due to the need to incorporate this factor in the analysis, a more simplified approach has been chosen. In this approach, it is adopted that the individual's behavior is determined by his or her predominant personality trait, identified by the maximum value among the four traits considered. From this predominant trait, a probability assignment is made that guides the individual's behavior in path-change situations. This method is open to future refinements, which could include more complex weighting systems to encompass the set of characteristics that define the personality type.

TABLE 2. Probability interval for decision changes based on personality type.

Predominant personality characteristic	Probability interval
EI	ppEI = 0.45 – 0.55
SN	ppSN = 0.43 – 0.57
TF	ppTF = 0.33 – 0.67
JP	ppJP = 0.49 – 0.51

The value ranges presented in Tables 3 and 4 are derived from official statistics provided by relevant authorities, which facilitate the deduction of data distribution and identification of key parameters. Utilizing these ranges, we established initial conditions and model parameters to ensure a grounded basis for our analysis. In the concluding phase, we conducted simulations to explore various scenarios, meticulously adjusting all the necessary parameters to maintain the resulting probabilities within the interval (0, 1).

Regarding age ranges established are directly correlated with road accident rates, based on official statistics from Germany.[5] Based on these data, specific values are assigned for each age range, as illustrated in Table 3. These values of accident probabilities vary across age ranges and are associated with higher levels of reckless driving. This recklessness, in turn, correlates with a greater tendency for drivers to deviate from routes suggested by navigation applications and make alternative route decisions. For this reason, it is adopted that the probability of accidents is reflected as a probability of route change.

TABLE 3. Incidence of road accidents according to age group.

Age ranges	Id	Accident probability
18-35	A	pA = 0.25
36-48	B	pB = 0.30
49-65	C	pC = 0.28
66-85	D	pD = 0.17

Furthermore, Table 4 presents the assigned values for an additional probability of changing route factor, which is based on the sex of the driver, and represents the pd_2 value in the Eq (5). These values were derived from official German traffic accident statistics,[6] which indicate that male drivers tend to make more impulsive decisions than female drivers. This difference in driving behavior between the sexes is reflected in the stipulated values.

Rounding out the Layer 3 components, we come across the Gadget factor. In this specific scenario, the gadget is a heart rate monitor that monitors heart rate. The relevance of this factor lies in how the variation in heart rate can be

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[5] https://www.destatis.de/EN/Themes/Society-Environment/Traffic-Accidents/_node.html

[6] https://www-genesis.destatis.de/genesis//online?operation=table&code=46241-0007&bypass=true&levelindex=0&levelid=1699889773069#abreadcrumb

TABLE 4. **Additional probabilities of changing route according to sex.**

Sex	Additional probability of changing route (pd_2)
Male	0.07
Female	0.02

correlated with the personality type of the individual being analyzed. In this way, we get a more complete and nuanced view of possible reactions to different driving circumstances. The weighting values for this factor are presented in Table 5. The values assigned to the variable ps_1 are arbitrary; however, they are intended to reflect the intensity of each personality type in response to fluctuations in cardiac signals, which helps explain variations in individual behavior. This correlation has been incorporated as an additional probability for path change in the analysis.

TABLE 5. **Weighting values for heart rate influence on predominant personalities.**

Predominant personality characteristic	Probability values associated with predominant personality
EI	pgEI = 0.02
SN	pgSN = 0.05
TF	pgTF = 0.08
JP	pgJP = 0.12

Regarding the weighting of the elements of Layer 2 of the conceptual model, a correlation was established, as previously mentioned, with the variable $d_3 = role$ played by the driver of the vehicle. In more specific terms, such roles can be classified as owners or employees of the vehicle. The values assigned to the variables (i_1, i_2, o_1, o_2) are arbitrary; however, it is always established that one role has a greater weight compared to another, in order to reflect the fact that the objectives of each role are different. In the scenario where the driver is the owner, numerical values within specific intervals are randomly generated for the social (s_u), institutional (i_v) and organizational (o_w) factors. These numbers help to accurately simulate the possible behaviors that an owner might exhibit under various traffic conditions.

Conversely, if the driver's role corresponds to that of an employee, random numerical values are generated, but within a different range of intervals. This approach allows for capturing potential differences in behavior between employees and owners in similar traffic situations.

Although d_3 is not explicitly included in Eq (5), its indirect impact is considerable and contributes to the parameterization of the second model layer factors in the final equation.

Thus, these considerations make it possible to create a more accurate simulation of the decisions made by different types of drivers in road environments. According to this methodology, the weighted values assigned are presented in Table 6.

V. MATERIALS AND METHODS

The proposed scenario is based on the principle of the use case previously analyzed in [24], where it was evidenced that human uncertainty has a negative impact on the quality of service of a 5G network. However, the scenario for this research has a larger amount of data and a simulation environment closer to reality. The scenario poses a VFH application, running on a 5G NS, with the objective of guaranteeing a specific Call Drop Rate (CDR) level with minimal resource usage. Consequently, failures in the HO process will be analyzed, specifically those related to the lack of frequencies in the cellular sectors. To carry out this scenario, certain vehicles are labeled as VFH type that will work within an NS, to guarantee the availability of the minimum frequencies necessary to carry out the HO in the different sectors along the vehicles' paths.

TABLE 6. **Weighting of the social elements in relation to the driver's role.**

	Owner	Employee
s_1	0.01 – 0.80	0.08 – 0.10
i_1	0.05 – 0.20	0.15 – 0.25
i_2	0.01 – 0.02	0.10 – 0.20
o_1	0.05 – 0.10	0.01 – 0.03
o_2	0.10 – 0.20	0.40 – 0.70

A. SIMULATION FRAMEWORKS

For this study, the Artery-C framework was used, which is based on the SimuLTE simulation framework. The difference is in the introduction of additional functionalities such as control and data planes, a dedicated side-link interface with a specific focus on dynamic mode switching, and some advanced features of 5G mobile networks. Furthermore, Artery-C integrates seamlessly with other simulation frameworks, such as Artery and SUMO. These allow, respectively, the simulation of standardized V2X messages and the modeling of vehicle movement and behavior on roads.

For the particular case of the scenario that was evaluated, additional integration between Artery-C and other components was necessary, as shown in Figure 7.

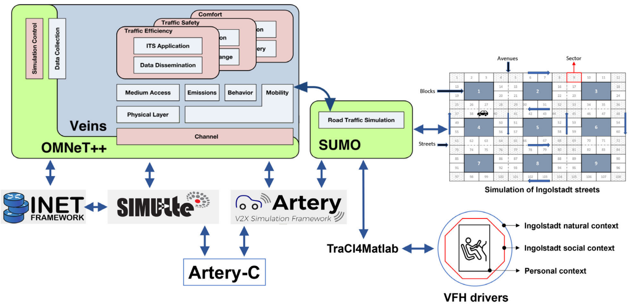

FIGURE 7. **Integration of the model with the simulation framework.**

The SimuLTE, Artery, SUMO and Artery-C simulation frameworks are integrated with OMNeT++, which provides a simulation environment distinguished by its modularity and component-based architecture. This structure has the advantage of allowing the programming of modules in C++, which, in turn, can be assembled to form larger models thanks to the use of the high-level language NED. This particularity favors the reusability of the models. Furthermore, its modular design facilitates the incorporation of the simulation kernel and models into existing applications.

The selection of OMNeT++ as a network simulation tool is grounded in its acceptance by the scientific community specializing in this field, which demonstrates its suitability for the present study. Furthermore, the evaluation of the data corresponding to Ingolstadt, chosen as the analysis scenario within the frameworks that OMNeT++ integrates, has enabled not only the verification of information previously documented in the literature, but also the development of a more detailed and complete model. While other potentially applicable simulators are available, we consider that the choice of OMNeT++ aligns with the specific objectives of this study.

Additionally, the frameworks used benefit from the use of the INET library. This library provides comprehensive support for all aspects of the network layer in the OMNeT++ simulation environment. INET, being an open-source project, has been designed around the concept of modules that interact through the exchange of messages. As a consequence, network agents and protocols are represented by components that can be flexibly combined, allowing the creation of hosts, routers, switches and other network devices. Finally, the model proposed in this research was developed in Matlab. For an efficient interaction with the simulations, the model was integrated with the Artery-C simulation framework through the TraCI4Matlab library. This library acts as a bridge between Matlab and the SUMO traffic simulator, allowing the implementation and evaluation of the model in the simulated environment. In this process, TraCI4Matlab plays a fundamental role by introducing the model parameters, which are evaluated at each time instant during the simulation. This adjustment ensures an accurate and dynamic representation of the systems under study, allowing a detailed and precise evaluation of their behavior under different conditions.

The following is an explanation of each of the components integrated to make the evaluations of the proposed model.

1) ARTERY–C

Artery-C is an extension of the OMNeT++-based simulation framework Artery. This framework, which provides a clear separation between the facilities, application layer and vehicular scenarios, becomes an ideal basis for Cellular V2X simulations. To model the LTE Radio Access Network (RAN) and Evolved Packet Core (EPC) data plane functionalities, the user plane of the SimuLTE simulation framework was used and extended, integrating it into Artery. This process was fundamental to the development of Artery-C. In this context, Artery-C supports three modes in a common simulation framework: uplink/downlink with RAN and EPC, network-assisted sidelink, and out-of-coverage sidelink with distributed resource allocation and management. In addition to simultaneously supporting these three modes, Artery-C allows dynamic switching between them as part of the simulation scenario. This mode-switching capability therefore allows more complex scenarios to be modeled and V2X applications to be studied under more realistic conditions. In addition, "Artery-C integrates transparently into the Artery framework and facilitates the use of microscopic SUMO mobility models, as well as simulation of the full Cooperative Intelligent Transportation Systems (C-ITS) protocol, which includes ad hoc networks, facilities, security and others" [72].

2) SIMULTE

SimuLTE is a simulation framework for LTE networks, used to model and evaluate the performance of LTE systems. It allows testing different scenarios and configurations, and analyzing system behavior under different conditions. SimuLTE is based on the OMNeT++ simulation framework, and includes models for the LTE protocol stack, as well as for the physical layer, the MAC layer and the RLC layer. It also includes models for network topology, user mobility and traffic patterns. SimuLTE can be used to study different aspects of LTE networks, such as throughput, delay, packet loss, handover, and interference.

3) SIMULATION OF URBAN MOBILITY

Simulation of Urban MObility (SUMO) is an open-source tool that provides detailed microscopic modeling of traffic flow, allowing the simulation of individual vehicle and pedestrian behavior. This functionality enables the simulation of various types of traffic, which facilitates the representation of complex urban mobility scenarios. Given its extensibility, SUMO can be modified and extended by researchers and developers, which ensures that the tool keeps up with the latest advances in traffic management and simulation. On the other hand, SUMO has the ability to simulate large-scale traffic scenarios, covering entire cities or regions. This feature is useful for studying the impact of traffic management strategies or infrastructure changes. SUMO also allows calibration and validation of simulations using real data, which improves the accuracy and reliability of simulation results. Regarding pedestrian simulation, SUMO provides configurable models that allow the representation of pedestrian behavior and their interactions with vehicles. This tool can be integrated with other simulation tools to study the interaction between traffic and communication networks, which is useful in the study of vehicular communication systems or intelligent traffic management systems.

B. METHODS

In this study, in order to evaluate the proposed model, the simulation scenario previously examined in [24] is taken as a reference. However, in order to obtain more accurate results that reflect reality, the aforementioned scenario is replicated using the frameworks integrated in this research. In addition, we include different variables associated with the vehicles in the simulations to more accurately capture common traffic conditions. These variables include pauses at intersections to respect traffic lights or yield, as well as initial speeds for both acceleration and braking. Additional vehicles are even incorporated which, although not linked to the VFH application, simulate general traffic conditions.

To establish the vehicle load associated with the VFH application in the scenario that all these vehicles will follow the predefined routes, simulations contemplated a range of vehicle loads fluctuating between 1 and 30 units, always adding 15 vehicles that do not use NS resources. A maximum admissible CDR equal to 3% has been considered,[7] in line with previous work cited above. In each scenario, Dijkstra's algorithm was used to determine the optimal routes, which are the paths suggested by the VFH application to the drivers. Additionally, five alternative routes were generated for each optimal route, with equal or greater lengths, to simulate the uncertainty factor that is introduced when a driver chooses to modify his or her trajectory. In the simulations, the selection of an alternative route was randomly selected from the five available options.

In order to determine the highest possible loading per sector to ensure that the CDR does not exceed the 3% limit using specific frequencies, simulations were performed for various loading scenarios ranging from five to 30 vehicles and frequencies of two, three and four. By averaging the results of 30 simulations, a more accurate assessment was obtained, which provided empirical support for the optimal vehicle loading per scenario. The simulations also included data from scenarios in which drivers altered their routes.

In Figure 8, the results are presented with two frequencies, where it is evident that at that frequency, they do not achieve a CDR of 3%.

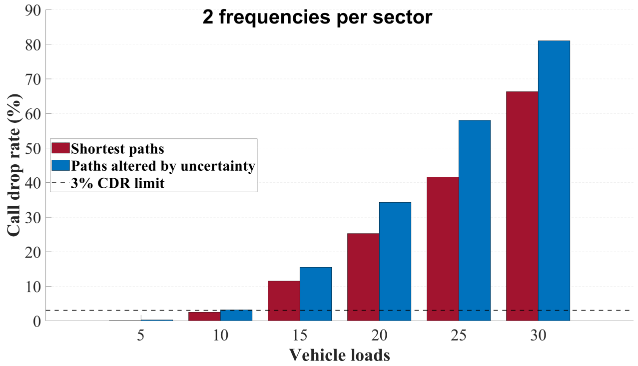

FIGURE 8. Comparative analysis of CDR for different vehicle loads with 2 frequencies per sector.

Figure 9 shows that with the load of 25 vehicles and 3 frequencies for the optimal routes provided by the application, an average value of 2.9% CDR is obtained. Therefore these are the parameters established for the simulations.

Figure 10 illustrates that with four frequencies the CDR is met for most of the loads but with very high resource usage in all sectors.

With the vehicle load already established, simulations are started, integrating the model with the previously configured

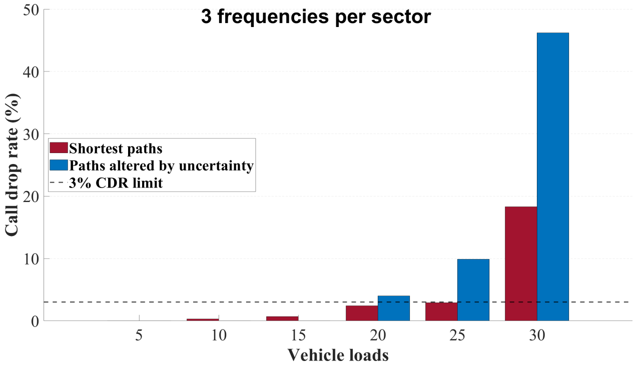

FIGURE 9. Comparative analysis of CDR for different vehicle loads with 3 frequencies per sector.

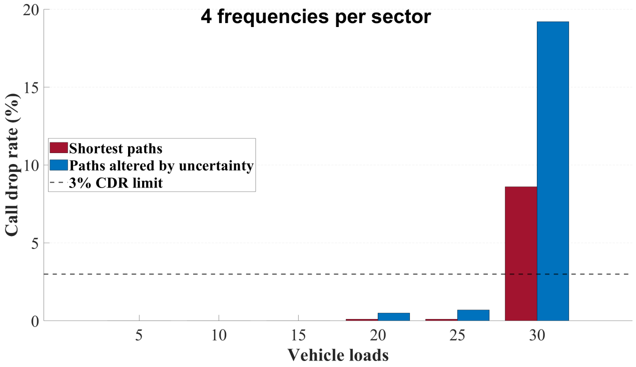

FIGURE 10. Comparative analysis of CDR for different vehicle loads with 4 frequencies per sector.

scenario. The objective of these simulations is to compare the CDR results when using optimal routes calculated by the VFH application, which are free of uncertainty, with those obtained when following alternative routes that incorporate uncertainty factors. The analysis was performed according to the procedures specified in Algorithm 1 in Appendix B to determine whether each vehicle must modify its route periodically.

Table 7 presents a concise summary of the parameters utilized in the simulations.

TABLE 7. Summary of simulation parameters.

Parameter	Value
Vehicles associated with the VFH application	25
Vehicles not associated with the VFH application	15
Simulation time	1800 s
CDR	3%
Frequencies allocated per sector	3
Number of alternative routes for each route	5

VI. SIMULATION RESULTS

All the simulations conducted for gathering the data presented in this section share two essential characteristics. Firstly, they are performed with a maximum vehicle load of 25 units, all connected to the VFH application as detailed in Section V-B. Secondly, the evaluation is designed around two distinct scenarios: one simulates

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[7] Recommendation ITU-T E.807, Section 7.4.5, (02/2014)

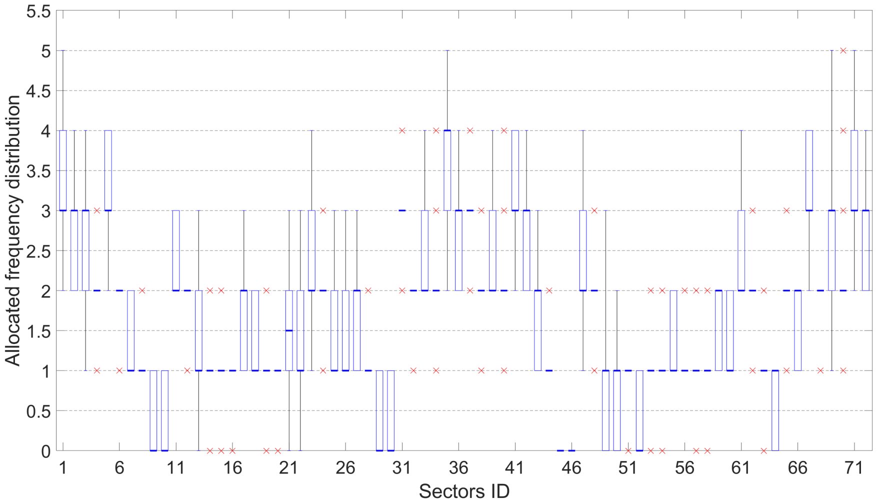

FIGURE 11. Multi-simulation analysis of the frequency utilization in the different network sectors when using predefined routes.

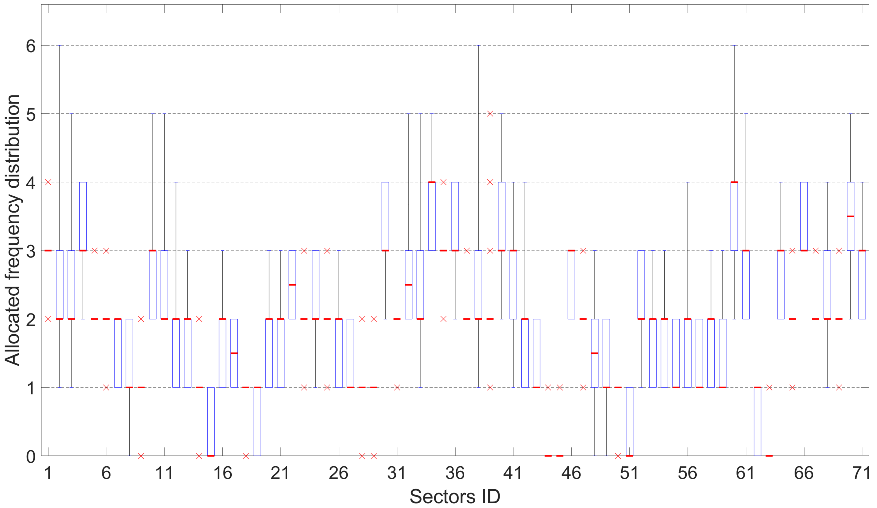

FIGURE 12. Multi-simulation analysis of the frequency utilization in the different network sectors when allowing driver route changes.

an environment without uncertainty, where drivers adhere strictly to predetermined trajectories by the VFH application, i.e. the shortest paths; and another scenario incorporates human uncertainty by modifying initially selected routes for vehicles.

A comparative analysis of the use of frequencies in the 72 sectors that make up the scenario studied is shown in Figures 11 and 12.

In relation to Figure 11, the data obtained when all drivers opt for the shortest route defined by the VFH application are shown. It is relevant to note that only in five sectors (1, 35, 69, 70 and 71) the use of five different frequencies is recorded. In addition, only sectors 45 and 46 do not show any frequency usage records. In an additional analysis, 30 sectors, equivalent to 40% of the total number of sectors evaluated, show low variability in the data, which confers a degree of certainty regarding the number of frequencies required for each of these sectors.

With respect to Figure 12, the data displayed show the repercussions derived from the changes in the routes chosen by drivers. It is necessary to emphasize that there is a notable increase in the maximum use of frequencies in certain sectors, reaching a total of six frequencies in sectors 1, 3, 39 and 61. Contrasting Figures 11 and 12, there is an increase in the number of sectors using five frequencies, from 5 to 12 sectors. In addition, three sectors now have no use of frequencies at all, compared to the two previously identified sectors that had no frequency use. In addition, there was a 33% decrease in the number of sectors with low data variability, from 30 to 20 sectors.

The variation in frequency usage across different sectors, as depicted in Figures 11 and 12, is closely connected to the presence of human uncertainty. In Figure 11, most sectors demonstrate a moderate utilization of frequencies. However, Figure 12 reveals an uptick in maximum frequency usage within specific sectors due to the implementation of new routes that impact these areas. This phenomenon also accounts for the slight increase in the number of sectors not utilizing frequencies, indicating a redistribution of demand towards other sectors. Henceforth, considering this variability caused by uncertainty, it becomes imperative for frequency allocation strategies to be adaptable and responsive to rapid shifts in demand.

Figure 13 illustrates the performance data for 5G slice under various utilizations of frequencies per sector, ranging from one to four, during peak load conditions with 25 vehicles connected to the VFH application. The evaluation metric used was the CDR. It should be noted that, regardless of the number of frequencies assigned, network performance is constantly compromised in the presence of uncertainty. Throughput degradation shows steady increases, with 1-frequency assignment leading to an 8.7% increase, while 2, 3, and 4-frequency assignments result in relative increases of 39.4%, 241%, and a notable 600% increase, respectively.

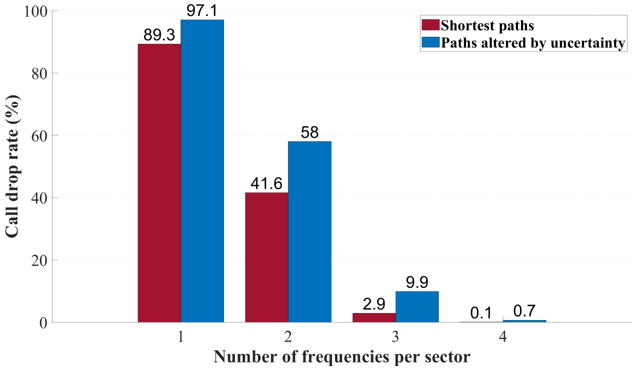

FIGURE 13. **Comparative analysis of CDR outcomes under deterministic and uncertain scenarios with varying fixed frequencies.**

Using the average number of frequencies (a real number) extracted from the results shown in Figures 11 and 12 it is possible to find the distribution of the number of sectors as function of the number of needed frequencies. The actual number of needed frequencies can be obtained by either rounding the average number of frequencies to the nearest integer or to the ceiling integer. Figure 14 shows the results when there is no uncertainty, whilst Figure 15 shows the results when the change of routes is allowed and therefore uncertainty is present.

As observed, the remarkable variability in frequency demand between different sectors underscores the ineffectiveness of a fixed resource allocation approach, in which each sector receives the same number of frequencies. In contrast, a dynamic frequency allocation, which adjusts in real time to the changing demands of each sector, could lead to more effective resource management and an improvement in overall system performance.

Besides, when comparing scenarios with and without uncertainty, variability in sector utilization was realized. This variability could be attributed to route modifications triggered by uncertainty. This finding highlights again the importance of considering flexibility in frequency allocation, so as to adapt to unpredictable fluctuations in the demand by sector.

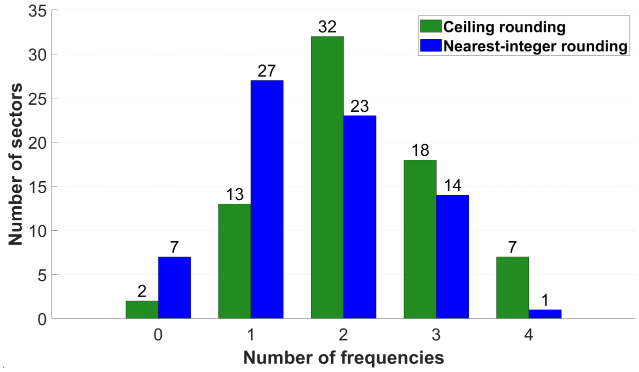

FIGURE 14. **Quantitative analysis of sector allocation variability in frequency rounding methods, without uncertainty.**

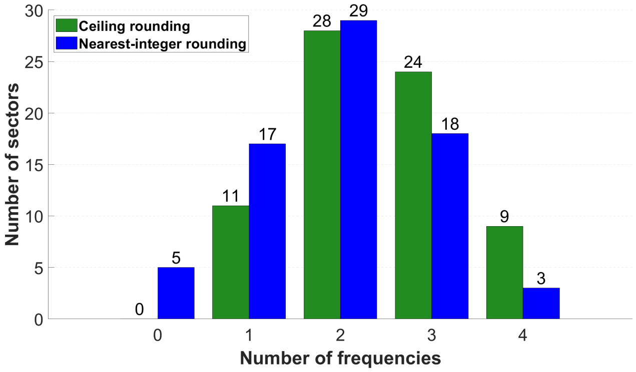

FIGURE 15. **Quantitative analysis of sector allocation variability in frequency rounding methods, with uncertainty.**

According to Figure 13, when 3 frequencies are used per sector, the CDR increases 7.0%, from 2.9% to 9.9%, when uncertainty is introduced in the scenario. Figure 16 illustrates the capture of the influence of pRF components, such as information from the Waze social network when considered, as well as the impact of the driver's role, differentiating between owners and employees. The values presented in each column indicate the percentage of its influence on the total CDR, presented in Figure 17, when using three fixed frequencies per sector and when routes are affected by human uncertainty. It is highlighted that, when incorporating the Waze social network element, it has a 1.4% impact on the CDR. During the simulations, labels were assigned to certain roads based on institutional and organizational policies, indicating that the owner role had an influence of 3.0%, and the employee role had an influence of 5.6% when these qualitative factors were taken into account. Therefore, the pRF component overall contribution to the 7% rise in CDR amounts to 10% of this increase. However small, such values are enough to make the total CDR increase above the established limit of 3%. In addition, it shows that the proposed model is able to capture such values that can impact significantly the performance of the network and allows to differentiate the influence of the Waze social network information and the owners and employees roles.

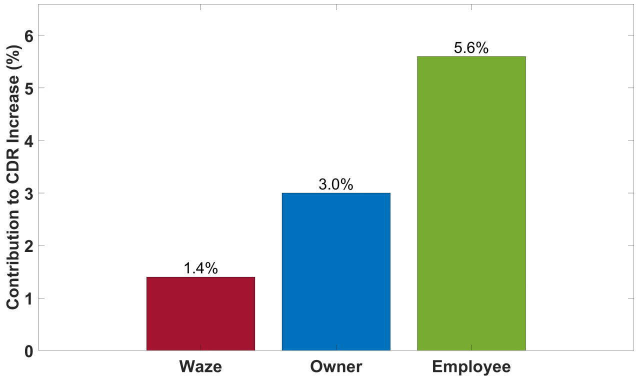

FIGURE 16. Quantitative analysis of the influence of pRF components on CDR.

Figure 17 illustrates the evaluation of the CDR in two scenarios: one with predetermined routes and one that considers uncertainty in route selection. The point of comparison is a CDR of 3.0% for routes without uncertainties, as explained in Section V-B. In both scenarios, the comparison is made when three fixed frequencies are assigned and when two different rounding methods are used for values between 3.0 and 3.9. The analysis of Figure 17 demonstrates that the presence of uncertainty negatively impacts the network performance once it exceeds the threshold of 3%. This holds true for both fixed allocation and rounding methods.

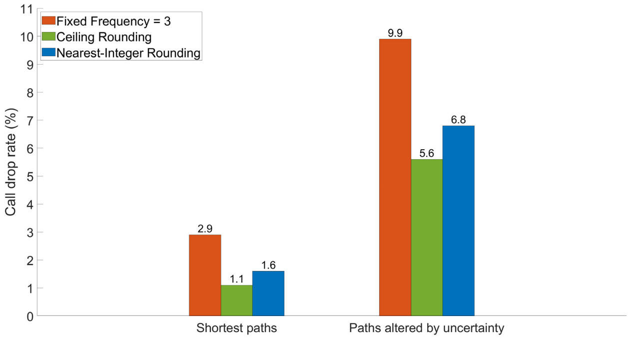

FIGURE 17. Evaluation of CDR based on rounding methods for deterministic and uncertain scenarios.

Figure 18 shows a uniform trend in the total number of frequencies required for both categories of routes, regardless of the allocation method used. However, it is observed that shortest paths and routes subject to uncertainty use a higher number of frequencies distributed over a larger number of sectors. More specifically, the presence of uncertainty uniquely alters the distribution and use of these frequencies. This implies that, despite general similarities in frequency requirements, the uncertainty variable introduces unique dynamics in their allocation and utilization. Based on an economic perspective, the data presented in Figure 18 suggests that rounding frequencies could be a cost-effective approach to reduce expenses, as long as it remains below the CDR threshold. However, for this specific case, it can be inferred that addressing uncertainty solely through rounding methods is insufficient.

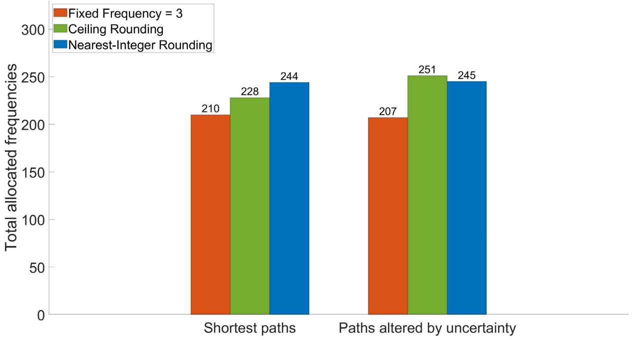

FIGURE 18. Quantitative evaluation of total frequency allocation through rounding methods in deterministic and uncertain scenarios.

VII. CONCLUSION AND FUTURE WORK

The present study has developed an interdisciplinary model that integrates sociological, psychological and computational elements to quantify the qualitative uncertainty derived from human interaction in Cyber-Physical-Social Systems. The effectiveness and versatility of the model were evaluated in a simulated scenario involving a Vehicle for Hire application operating in a slice of a 5G network. The findings confirm that the proposed layered model has the ability to capture and quantify the qualitative uncertainty inherent in humans. Furthermore, the results highlight uncertainty as a significant obstacle to the effective implementation of slicing in 5G networks, and suggest the need for a robust methodology in future research. This methodology should enable network operators to define metrics aligned with their strategic objectives and incorporate them into resource allocation strategies with the overall goal of optimizing operational efficiency and maximizing network performance.

After a detailed analysis of the results obtained, it is important to address certain limitations inherent to the proposed model and the data sources used in this study. The model has certain constraints that hinder a comprehensive understanding of the unpredictable elements and irrational behaviors observed within CPSS. This limitation stems from the intricate nature of human behavior, which introduces unforeseeable variables and scenarios beyond what can be fully captured by any theoretical framework. Therefore, we rely on incorporating a weighting factor in our model to mitigate the influence of uncertainty. In this study, it is important to note that the data sources used primarily consisted of official records. However, there were instances where certain data points had to be assigned based on arbitrary assumptions due to technological and legal limitations. This highlights the need for innovative methodologies in future data collection endeavors, which could involve interdisciplinary collaborations or legal agreements to ensure comprehensive access to relevant information.

In future research, we propose to evaluate the reference architecture in several use cases where human uncertainty impacts the domain of state-of-the-art technologies. These cases include those we have identified in [23].

In addition, it is proposed to examine the integration of different levels of human uncertainty in CPSS. This would include the use of data on the psycho-emotional stability of users, thus expanding the basis of the human uncertainty management model. In addition, it is suggested that physiological parameters such as blood pressure be incorporated to address critical situations such as heart attacks and strokes. It is also contemplated to explore the implementation of a light signaling system, both internal and external, to indicate uncertainty levels in CPSS, especially in driving contexts.

Another line of future work is the incorporation of the Human Digital Twin in human-centric CPSS. This technology, which allows simulating and analyzing human behavior in virtual environments, improves the understanding and prediction of human dynamics. Its integration into CPSS enhances the ability of these systems to adapt and respond to the complexity of human interactions, opening new avenues in the management of qualitative uncertainty.

APPENDIX A

See Table 8.

TABLE 8. List of main acronyms.

Acronym	Full Form
5G	Fifth Generation
AI	Artificial Intelligence
BO	Boundary Object
CDR	Call Drop Rate
C-ITS	Cooperative Intelligent Transportation Systems
CPSS	Cyber-Physical-Social Systems
EPC	Evolved Packet Core
FRAM	Functional Resonance Analysis Method
GPS	Global Positioning System
HCN	Human-Centric Networks
HO	Handover
InTAS	Ingolstadt Traffic Scenario for SUMO
IoT	Internet of Things
LTE	Long-Term Evolution
MBTI	Myers-Briggs Type Indicator
MVNO	Mobile Virtual Network Operator
NaaS	Network as a Service
NFV	Network Functions Virtualization
NS	Network Slicing
Q-FRAM	Quantitative Functional Resonance Analysis Method
QoS	Quality of Service
RAN	Radio Access Network
SDN	Software-Defined Networking
SLR	Service Level Requirement
SUMO	Simulation of Urban Mobility
UML	Unified Modeling Language
V2X	Vehicle-to-Everything
VFH	Vehicle for Hire

APPENDIX B

See Algorithm 1.

Algorithm 1 Driver Uncertainty Weighting

```
Require:
$VFH = \{Driver_1, Driver_2, \ldots, Driver_i\}$ where,   $Driver = [p, g_1, s_1, d_1, d_2, d_3]$   ▷ Composition of each VFH
$p \in \{EI, SN, TF, JP\}$   ▷ See Table 2, Probability interval for decision changes based on personality type
$g_1, s_1, d_2, d_3 \in \{0, 1\}$   ▷ For $g_1, s_1$ and $d_3$, see Tables 5, 6 and 6 respectively.
$d_1 \in \{A, B, C, D\}$   ▷ See Table 3
Ensure: $0 < \rho_i < 1$
Time steps to evaluate:
for $z = Sim_{\text{start}} to Sim_{\text{end}} step time slots$ do
    Uncertainty weighting of each driver:
    for $i = 1 to z$ do   ▷ $z$ = Number of vehicles active in VFH application
        $X \leftarrow VFH_{\text{i}}$   ▷ $X$ = Variable to hold all elements from the Driver vector
        Psycho-physiological component
        Extract predominant personality type
        $p \leftarrow X_1$   ▷ $p$ takes the first value of the vector X
        if $p == EI$ then   ▷ See Table 2
            $pp \leftarrow$ random $ppEI$
        else
            if $p == SN$ then
                $pp \leftarrow$ random $ppSN$
            else
                if $p == TF$ then
                    $pp \leftarrow$ random $ppTF$
                else
                    $pp \leftarrow$ random $ppJP$
                end if
            end if
        end if

        Assign values whether or not the gadget is considered:
        if $X_2 == 1$ then   ▷ Probability of route alteration based on the information from the gadget corresponding to each personality type
            if $p == EI$ then
                $pg \leftarrow pgEI$
            else
                if $p == SN$ then
                    $pg \leftarrow pgSN$
                else
                    if $p == TF$ then
                        $pg \leftarrow pgTF$
                    else
                        $pg \leftarrow pgJP$
                    end if
                end if
            end if
        else
            $pg \leftarrow 0$
        end if
        $pDS \leftarrow (pp + pg)$
        Demographic Segment component:
        Assign values according to age:
        if $X_4 == A$ then
            $pd_1 \leftarrow pA$
        else
            if $X_4 == B$ then
                $pd_1 \leftarrow pB$
            else
                if $X_4 == C$ then
                    $pd_1 \leftarrow pC$
                else
                    $pd_1 \leftarrow pD$
                end if
            end if
        end if
        Assign values according to sex:
        if $X_5 == 0$ then
            $pd_2 \leftarrow 0.07$
        else
            $pd_2 \leftarrow 0.02$
        end if
        $pDS \leftarrow (pd_1 \cdot pd_2)$
        Role fit component
        if $X_6 == 0$ then   ▷ Driver is Owner
            Generate Owner-specific random values:
            if $X_3 == 1$ then
                $ps_1 \leftarrow random[0.01, 0.8]$
            else
                $ps_1 \leftarrow 0$
            end if
            $pi_1 \leftarrow random[0.05, 0.2]$;   $pi_2 \leftarrow random[0.01, 0.02]$
            $po_1 \leftarrow random[0.05, 0.1]$;   $po_2 \leftarrow random[0.1, 0.2]$
        else   ▷ Driver is Employee
            Generate Employee-specific random values:
            if $X_3 == 1$ then
                $ps_1 \leftarrow random[0.08, 0.10]$
            else
                $ps_1 \leftarrow 0$
            end if
            $pi_1 \leftarrow random[0.15, 0.25]$;   $pi_2 \leftarrow random[0.1, 0.2]$
            $po_1 \leftarrow random[0.01, 0.03]$;   $po_2 \leftarrow random[0.4, 0.7]$
        end if
        $pRF \leftarrow (ps_1 + (po_1 \cdot po_2)(pi_1 \cdot pi_2))$
        Calculate the probability of $VFH_i$ changing route:
        $\rho_i = pPP + pDS + pRF$
    end for
end for
```

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