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THE VALUE OF INFORMATION IN THE CONTEXT OF MOBILE NETWORK MANAGEMENT

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Dedication

I dedicate this work and give special thanks to my wife Patrícia and my wonderful son Afonso for being there for me throughout the entire doctorate program. Both of you have been my anchor.

I also dedicate my dissertation work to my family specially to my grandparents (their love is always with me). A special feeling of gratitude to my loving parents, António and Delmira whose words of encouragement and push for tenacity ring in my ears. To my brother Gabriel, who never left my side and is very special.

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Sou um guardador de rebanhos.

O rebanho é os meus pensamentos

E os meus pensamentos são todos sensações…

Alberto Caeiro

Resumo

A indústria de telecomunicações usa informação de forma intensiva e lidera a transformação do mundo, tanto a nível social como empresarial. As atividades de gestão das redes de telecomunicações estão no centro da atividade de qualquer fornecedor de serviços de comunicação e enfrentam desafios crescentes na gestão de informação e de dados, exigindo, portanto, decisões recorrentes de investimento que podem beneficiar do conhecimento do valor da informação (VoI) objeto de gestão. Há evidências abundantes do uso de paradigmas de VoI embebidos em tecnologias e processos de engenharia, desenvolvidos no âmbito das telecomunicações e, ainda assim, a quantificação financeira e uso de VoI nos processos de decisão humana relacionados com as atividades de gestão de rede são escassos.

Esta investigação representa os primeiros passos na tentativa de estimar o VoI relativo às atividades de monitorização da rede num contexto de comunicações móveis (com a possibilidade de combinar informações internas com informações obtidas a partir dos dispositivos dos utilizadores do serviço). As nossas contribuições incluem a abordagem conceptual para enfrentar o desafio de medir o VoI e os instrumentos práticos (*software* e métodos) para desenvolver experiências e apresentar a nossa estimativa de VoI para casos de uso específicos.

Foram desenvolvidas experiências para estimar o valor da informação perfeita (VoPI) usada na gestão de rede móvel no caso de avarias que resultem em falhas de serviço, explorando duas perspetivas distintas: (i) como o VoPI evolui quando a taxa de avarias que afeta a infraestrutura de rede muda e (ii) como o VoPI evolui quando os critérios de decisão mudam. Realizamos exercícios extrapolativos, adotando planos de serviço do mundo real, a fim de estimar o VoI por milhão de utilizadores, dando assim uma visão mais tangível para a gestão. Mesmo com baixas taxas de falha afetando a rede, o valor da informação atinge facilmente quantias de milhões de Euros numa base anual (por milhão de clientes).

Também avaliamos o uso de informação imperfeita usada no processo de tomada de decisão operacional em atividades de monitorização da rede. Consideramos a etapa de ‘identificação do problema’ como o momento central do processo e desenvolvemos experiências para entender o impacto do uso de informação imperfeita, antes (*ex ante*) e depois (*ex post*) desse ponto crucial. Os resultados indicam que a informação imperfeita *ex ante* pode ainda agregar valor, mesmo se for muito imprecisa, enquanto o valor da informação imperfeita *ex post* cai rapidamente (e fica inútil com cerca de 50% de magnitude da imperfeição).

Além disso, é demonstrado e medido o valor agregado da informação proveniente dos utilizadores, usada como complemento da informação de monitorização de rede, junto com o impacto de ter diferentes segmentos de preços (e nível de serviço) na população de utilizadores.

Esperamos que estas indicações forneçam aos gestores referências úteis para as suas atividades de gestão de dados, informação e iniciativas analíticas (ou dos sistemas que podem considerar comprar para gerir essas iniciativas), colocando o valor da informação no centro das decisões de investimento.

Palavras chave: Valor da Informação; Tomada de Decisão; Redes de Telecomunicações Móveis; Telecomunicações; Simulação.

Abstract

The telecommunications industry is information intensive and is also leading the world's transformation both at social and business levels. The network management activities are at the core of any communications service provider and face growing information and data challenges, thus requiring recurring investment decisions related to information management initiatives, which benefit from Value of Information (VoI) inputs to management processes. There is abundant evidence of the use of VoI paradigms in engineering processes and in technologies developed within the broad scope of telecommunications, and yet the VoI quantification and usage as input to human decision processes related to network management activities is scarce.

This research represents a first step towards the attempt to measure the financial value of information used within the network monitoring activities in a mobile communications setting (with the possibility of combining internal information with information obtained from service users' devices, to deliver higher performance and higher customer experience). Our contributions include the conceptual approach to tackle the challenge of measuring VoI in the network monitoring setting (including the user sourced information) and the practical instruments (software and methods) to develop experiments as well as actually putting forward our estimate for specific use cases.

Experiments were conducted to estimate the Value of Perfect Information (VoPI) used in mobile network management in the case of failures resulting in service denial by exploring two distinct perspectives: (i) how VoPI evolves when the fault rate affecting the network infrastructure changes and (ii) how VoPI evolves when the decision thresholds change. We undertake an extrapolative exercise, adopting real world service plans, to estimate VoI per million users, thus giving more tangible insights for management. Even with low fault rates affecting the network, the value of information easily reaches into the millions of euros on an annual basis per million customers.

Imperfect information used in the operational decision-making process at the network monitoring activities is also evaluated. We considered the 'problem identification' step as the pivotal moment of the operational decision-making process and developed experiments to understand the impact of imperfect information emerging before (*ex ante*) and after (*ex post*) this moment. The results indicate that *ex ante* imperfect information might still add value even if it is severely inaccurate, while the value of *ex post* imperfect information rapidly falls as the magnitude of imperfection increases, and actually such information becomes useless (roughly at 50% imperfection magnitude).

Additionally, the added value of the information from users' devices in the improvement of the operational decision-making process, on top of existing network monitoring information, is demonstrated and measured along with the impact from having different pricing segments in the population of users.

We hope these insights will give managers useful benchmarks for their daily activities such as evaluating data and analytics initiatives (or the systems and applications they might be considering buying to manage those initiatives) thereby putting the value of information at the core of the business case.

Keywords: Value of Information; Decision Making; Mobile Communications Networks; Telecommunications; Simulation.

List of Acronyms and Abbreviations

ABM	Agent-Based Modelling
AI	Artificial Intelligence
BS	Base Station
BSS	Business Support Systems
CSSR	Call Setup Success Rate
CDR	Call Drop Rate
DES	Discrete Event Simulation
Ec	Carried Traffic
Eo	Offered Traffic
IoT	Internet of Things
KPI	Key Performance Indicator
OSS	Operations Support Systems
Pb	Probability of Blocked Traffic
QoE	Quality of Experience
QoI	Quality of Information
QoS	Quality of Service
SA	Service Availability
UDI	User Device sourced Information
VoCI	Value of Combined Information
VoI	Value of Information
VoII	Value of Imperfect Information
WoS	Web of Science

1 Introduction

The value of information is a fascinating topic because every human has their own view on it. Despite all efforts and progress towards information creation and information control (by society, by science, by corporations, by individuals), the vast majority of information management activities are still based on qualitative assumptions instead of quantitative measurements. Value perceptions and argumentative persuasion on the value of information and information management initiatives prevail over efforts to measure and quantify value. This is the embarrassing reality gleaned from my own field experience of implementing management information systems, frequently in the form of dashboards, visual analytics and other information applications. This ‘elephant in the room’ was my motivation for developing the research presented in this thesis. Yes, we have made (huge) progress in the last decades. Yes, Value of Information (VoI) is expanding not only in terms of theoretical and applied research but also in practical applications in all industries and public governance. But still, using information value as a management decision input is far from being a general and routine practice, probably because in many situations it is difficult and cumbersome to attain (if viable at all) and might represent an overhead and an obstacle to information systems initiatives and innovation. However, at least in information intensive industries (like the telecommunications industry), the apparent void in literature regarding efforts to measure information value in financial terms and use of those inputs in management processes is quite surprising.

I chose the specific scope of this thesis (the VoI in the setting of mobile network management) from a combination of problem relevance and personal motivation: to develop applied research on VoI within an industry I know very well, and where I have access to practitioners who have shared interests in the research agenda and willingness to cooperate when needed. The problem relevance is apparent since (i) the telecommunications industry is information intensive and is also leading the world’s transformation and (ii) the network management activities are at the core of any communications service provider and face growing information and data challenges (in this case high volume, variety, and velocity of data used to manage and operate the network, but also to detect and overcome failures) thus requiring recurrent information management investment decisions which might benefit from VoI inputs.

We have conducted a literature review and concluded that (i) there is abundant evidence of VoI paradigms usage embedded in engineering processes and technologies developed within the broad scope of telecommunications and yet (ii) the VoI quantification and usage as input to human decision processes related to network management activities is scarce.

Specifically, our structured literature review (Chapter 2) showed that no method has been presented to estimate the VoI used within the network management activities. The network management activities that we have in mind are those aimed at operating the network, which means monitoring performance and making decisions based on the information gathered. Those decisions essentially concern choosing alternative courses of action based on the performance observed, and eventually taking actions that changes the network status and operating conditions, such as correcting failures, changing configurations and settings, thereby improving the system's performance according to top management guidelines on service grade goals, for example. The information used in those processes is costly to gather, costly to manage and costly to transform into actionable insights (either from a technological or a human point of view). To attain integrated technical and economic optimization of the network management activities, we find it imperative to evaluate information value and use this input in the information management (human driven) decision processes.

Thus, the objective of our research was to provide management level contributions (model, tools, procedures to estimate information value) to make it feasible for practitioners to include VoI-driven paradigms in their management practice to attain integrated technical and economic optimization of the network management activities.

In more practical terms, our research goals and objectives were:

a) to estimate the VoI used in mobile network management, specifically the information required to act on correcting or preventing network failures resulting in service denial

b) to understand and quantify how VoI is impacted by management options concerning the desired service level and by parameters that define the technical setting

c) to differentiate the VoI collected from network infrastructure with respect to information collected from end users (specifically that information that could be collected from the user's devices).

The research questions used as guidance to drive the experiments were:

Q1: What is the VoI required to act on correcting or preventing a specific telecommunications network failure event?

Q2: How does the VoI change for different service level options from the management?

Q3: How does the VoI change with different operational conditions (e.g., different fault rates affecting the network equipment and functions)?

Q4: What is the VoI potentially provided by end users as complement to the VoI gathered through traditional methods (performance from the network standpoint)?

Our actual contributions are summarized as follows:

i) We developed a simulation-based model of the essentials of the mobile communications service delivery that incorporates the information produced and used to manage this delivery;

ii) We put forward a procedure to estimate the VoI in the setting of mobile network management which isolates and measures (in financial terms) the information contribution to the network management efforts;

iii) The model was instantiated through a software development thus creating a tool to perform tailored simulations according to the procedures necessary to isolate information contribution to the network management activities;

iv) The model (and the software implementation) distinguishes the VoI gathered internally by traditional network monitoring versus the information coming from service end users;

v) We present results from a series of experiments conducted to estimate the value of perfect information used in mobile network management in the case of failures resulting in service denial. The experiments include different failure rates and different level of service strategies thus providing insights on the information's value implications from changes in operational settings;

vi) The value of imperfect information used in mobile network management at distinct moments of the decision process was also investigated;

vii) We demonstrate and measure the added value of the user device sourced information as input to the operational decision-making process, on top of existing network monitoring information, along with the impact from having different pricing segments in the population of users.

The model and the software created to instantiate the model are able to simulate various business scenarios as well as different information sources and different ways of using this information. As an example, we investigate the VoI gathered from the perspective of user experience as a complement of the information traditionally obtained from the network thus providing insights to the value contribution of each information source to more complex management strategies.

The model and the software developed in this work (described in Chapter 4) were presented in a conference and published in the conference proceedings (Mendes & Godinho, 2019). Two papers are being submitted to peer review journals. One manuscript is entitled "Estimating the value of information used in mobile network management using computational simulation – the case of failures resulting in service denial" (based in the experiments that consider perfect information, experiments A and B, presented in Section 5.2). The second paper is entitled "The value of imperfect information used in mobile network management both in *ex ante* and *ex post* problem identification in decision-making" (based in the experiments that consider imperfect information, experiments C and D presented in Section 5.3). There is a third paper in progress, dedicated to explore information value when network information and user sourced information are used in tandem to improve performance and customer experience (based in Section 5.4).

The dissertation is organized as follows. After this brief Introduction, Chapter 2 presents the VoI theoretical background along with a literature review focused on the VoI usage within the mobile network domain which exposes the research gap we have mentioned before. Chapter 3 presents the research strategy and the methodological approach used in the research. Chapter 4 presents the mobile communication setting, the modelling principles and simulation strategy followed in the implementation of the NIESIM (Network Information Economics SIMulation) software (model instantiation). Chapter 5 presents the VoI measurement procedure and the results obtained using NIESIM to support decisions concerning the grade of service, including scenario description and outcomes from the simulation process such as the network performance observed and the financial performance. Chapter 6 concludes the dissertation by presenting the main conclusions and future directions of the research.

2 Literature review

2.1 Information and Information Value: an Overview

2.1.1 Essential Concepts and Definitions

The term 'Information' plays a major role in a wide variety of scientific areas and human activities. There are multiple perspectives on the role of information in each domain, and as many definitions as the independence of those domains imposes. If we start with the broad range of information conveyed by the media and entertainment industries, such a definition would be "anything that can be encoded" (Shapiro & Varian, 1998), which is a comprehensive form of referring to any form of explicit knowledge.

We wish to emphasize the close relationship between information and knowledge that is implicit in the previous definition, and also the broad range of contexts, from engineering to human and social interactions, where those knowledge processes take place. Amaral (2009) puts forward a distinctive characteristic of knowledge as a human process by which new messages are received and processed within the human brain, generating new knowledge.

The above notwithstanding, the concept of information is closely related to the concept of a message within a communication process. This definition is grounded in historical contributions to the communications theory of Shannon (1948). In a sense, information and knowledge are bound by communication processes. These have a dual nature, since any message comprises of a material nature (the bits that codify the actual information associated with the message) and of a semantic nature (the meaning of the information either from the sender's or the receiver's perspective).

Shannon (1948) suggested that semantic aspects are irrelevant for the engineering issue - the reproduction of a message sent from agent A to the reception point where agent B will receive it and interpret it. However, in this work, we rather focus our analysis on the social and economic usage of information and knowledge, which is semantic and content-centric. Shannon's approach to information is therefore not very helpful to our considerations, although some of the mathematical aspects he developed such as entropy (in close relation to chance and uncertainty), have been instrumental to quantitative approaches within information economics.

Although information is generally perceived as "objective evidence of the world", when information is consumed by humans, the interpretation and knowledge process changes the individual's beliefs about the world, generating new knowledge, related although distinct, and correlated to the received information/message (Hirshleifer & Riley, 1992). Hirshleifer and Riley emphasize that ultimately human decisions are based upon those subjective beliefs. In such a context, information can be interpreted as "a reduction of uncertainty" (Birchler & Butler 2007:16).

Decision making is another domain where information is critical, and where we can apply this paradigm, since any positivistic selection among alternative courses of action inherently demands a structured process of information search, gathering, processing and evaluation. Actually, a decision process is commonly associated with information processing of any kind. Within a business context, De Kuijper (2009) points out that information's usefulness derives from the ability to make a difference within our decision process, especially if a commercial transaction is at stake. Otherwise, one can barely differentiate information from raw data. Taking this exercise forward leads us to the field of control (and cybernetics), since decisions are instrumental in controlling efforts which are mastered by some sort of program that provides coherent decision criteria, assuring that the same input always results in the same decision output. The information flow, which requires a certain communication network, is central to any control activity. Information must be gathered and processed to influence the organization's direction towards a given end, which must be explicitly encoded in the program. Thus, programs control by determining decisions, and the concepts of control, decision, program and information are inherently related regardless of the biological, social or artificial nature of the organization (Beniger, 1986).

Beyond the material and semantic perspective, information is also regarded as an economic good in itself. As a good, it can be produced, stored, consumed, invested (used in production), or sold (Birchler & Butler 2007:16). The implications of this economic perspective towards information are tremendous since, as a good, it reveals distinctive characteristics (which are unmatched in other goods).

Birchler and Butler present a few examples:

- It can be sold without being given away;
- It is cheap to reproduce;
- It cannot be actively disposed of;
- It cannot be detected in a person;
- Often its dissemination cannot be prevented
- It often cannot be valued before it is known;
- It can be about facts or about other people's information.

Technical information is a defining characteristic of a company and enters the production function in a different way than other goods do. Typical goods have a constant return on use but information is used regardless of the scale of production and can generate extreme forms of increased returns (Arrow, 1996). Knowledge (explicit and implicit), in whatever form and carrier (machine code, work instructions, tacit knowledge), can be viewed as information. A business model itself consists of knowledge and information put to action and a growing number of companies, such as Google, Amazon, Facebook or Spotify, depend on algorithms (another form of explicit knowledge) as the core of their business models. Ultimately information is the key factor that makes a company unique and difficult to imitate.

The previous discussion unveils the key role of information from the basic level of communications to the ultimate layer of the corporate and economic edge, the competitive advantage. Shannon (1948), with his mathematical theory of communication, provided the concepts and tools to incorporate quantitative methods in the management of the information processed in communication's engineering activities. Shannon explicitly narrowed the scope of his efforts to the engineering problem of communication and excluded any semantic aspects of communication since those "*are irrelevant to the engineering problem*". Following this seminal distinction between the "*engineering problem of communication"* and the *"semantic aspects of communication*", Burgin (2003) suggested a unified vision called 'general theory of information' aiming for a common understanding of information as a natural, technological, and social phenomenon. According to the principles this general theory of information, new types of information are suggested (cognitive, conditioning, and regulative information). In the words of

Burgin, "*while in Shannon's theory quantity of information is an internal measure, value of information in the sense of the economic information theory is an external measure of information*".

2.1.2 Information as Means for Expressing Knowledge of the World

When we express knowledge of the world, we use information to describe the states of the world. To grasp a valuable usage of information and knowledge within the social and economic context, the scientific paradigm often suggests the adoption of models that resonate some aspect of the world to be studied along with a framework for a context-specific mathematical rationale. Samuelson (2004) presents a knowledge-modelling approach, after contributions from pioneers such as John Harsanyi, Leonard Savage and Robert Aumann, which is referred to in the literature as the "state-model approach". The basic idea is to accept that 'the world' (at least the slice one expects to model) can only have one state at any one time. Agents can list the possible states, meaning that a certain number of individuals (admitting those agents are people), each with a particular partition, are able to capture the overall world's possible states (states space), although each individual will act upon his usually limited knowledge of the world at any given time. Uncertainty is captured by assuming an agent does not know what the true state of the world is at a given time, although he is aware of which element of a partition contains the true state. Eventually agents receive signals that allow their prior beliefs to be updated and the decision or action by each agent can be simulated by combining this information interchange in the view of a certain context-specific framework.

The state-model is a tool which aim to describe not only what an individual knows (in terms of states of the world) but also what he knows about the knowledge of others, provided some axioms are accepted. Birchler and Butler (2007:149) present Samuelson's "*axioms of knowledge*" synthetically as:

- Awareness: We know the possible states of the world;
- Omniscience: We know all the implications of what we know;
- Knowledge: We can only know things that are true (events that have happened);
- Transparency: We cannot know something without knowing that we know it;
- Wisdom: We know what we do not know.

Although apparently simple, challenges and counter intuitive results have emerged from applying the state model to many practical contexts. Concepts like “common knowledge” and subsequent implications to trade (*“information does not give rise to trade”*, in Samuelson’s words) and to social behaviour (coordination problems, for example) provided room for the state-model becoming pervasive in the literature, as it allowed a multitude of analyses and developments in a myriad of domains (risk, markets, decision making, games, contract design, regulatory policies, innovation, etc.).

Nevertheless, Samuelson (2004) discusses some severe limitations of the state model, mainly the inability to “*accommodate unawareness*”, meaning that an agent cannot be surprised, which is far from realistic in many contexts. Another aspect uncovered by Samuelson and related to rationality and rational behaviour by agents, is that “*substantive assessments are readily made*” but “*procedural questions do not arise*” [within the state space model], although the “*procedural rationality is an important aspect of decision making*”. In more general terms Samuelson reinforces that “*much of the difficulty in studying knowledge arises in constructing the model*” and “*assumptions about knowledge and common knowledge can be demanding and can have surprising implications*”.

The very simple assumption of individuals acting on rational grounds is actually unrealistic in many scenarios. As Birchler and Butler (2007:404) describe it,

> *“economics was built around the useful abstraction of homo economicus. [...] He had one set of preferences from which he could derivate optimal rational choice [...]. Homo economicus was one single monolithic person and he either knew or believed something or he did not. Unfortunately, rational homo economicus failed to behave like a real human...”.*

2.1.3 Information Properties

Discussing information properties is important since those properties are key to the knowledge process and ultimately to the information's worth and to value analysis. Noteworthy is the fact that the interpretation of the message (and the states of the world it conveys) is context-based and the information's properties are the basic elements of that context, allowing the datum within any message to become a valid/acceptable semantic body of significance for a certain agent (the receptor) and thus an input in a knowledge process.

Let us recall the notion of information as part of a communication process where three elements participate in a knowledge transfer process: the agent emitting the message, the message itself, and the agent receiving the message. Information properties are characteristics (mostly qualitative in nature) associated with the message, built upon attributes directly measurable in the message or in their proxies (including the message's emission context).

Some of those characteristics (accuracy, trustworthiness, currency, etc.) are inherently related to information in the broad sense (news, institutional reports on societal and economic topics, market analyses, and so on) meaning that any real life usage of information is subject to scrutiny on some of those properties, although in many theoretical and analytical discussions they are absent, either for convenience and simplicity of the exposition or because they are presumed 'perfect', undisputable as far as that discussion is concerned.

Information attributes include the source of the message (at a company level this could be the system from which certain data have been extracted or the name of the author of a certain report), the context in which that message was produced (possibly following a structured, rule-compliant process), the context of disclosure and distribution of the message (having been released after some validation and approval process), the delivery medium (video, document, radio broadcasting, etc.), and many other elements. Those attributes are evaluated and combined with the contents and the format of the message at the reception time by the agent. A decision by the agent receiving the message on whether the message is worth processing and ultimately included in the knowledge process has to be made (we must recall that we receive many signals that we simply choose to ignore). These aspects, taken together, could suggest that the message is characteristically trustworthy, for example. The attributes (or their absence) establish the strength of each characteristic, although that strength is inherently subjective since it lies on the receptor's judgment and cannot be formally measured (as a rule).

Information properties are frequently discussed in the context of the quality assessment of a certain piece of information and Eppler (2006) presents an extensive list with examples of information quality criteria, but also a low-quality information definition as

> *"incomplete, inaccurate, obscure, useless, prolix (or wordy), inconsistent, false, obsolete, delivered in an inconvenient, late, undeterminable and rigid way, via an infrastructure that is inaccessible, exposed to manipulation and other security risks, cumbersome or costly to maintain, and slow"* (Eppler, 2006).

This definition is helpful in exemplifying characteristics that are frequently assessed by individuals when receiving a message, in this case contrasted with their opposites.

Information properties are also discussed in value assessment contexts where the Quality of Information (QoI) also plays a fundamental role. Zhao et al. (2007), in their effort to use information characteristics as a basis for information value assessment, suggested that seven characteristics (accessibility, usability, currency, accuracy, trust, relevance) are key to that endeavour. It is also usual to assess a certain characteristic by means of a certain combination of other characteristics (Zhao et al. consider that information quality is determined by accessibility, accuracy, currency, trustworthiness, usability). Moreover, there is an increasing use of sensor-derived information enabling fast-paced decisions in personal, social, business settings which demand frameworks to evaluate quality of information and the value of that information in a systematic and structured way. Bisdikian et al. (2013) introduced a framework for assessing VoI by weighting and aggregating its various attributes according to the analytic hierarchy process (AHP). The framework is based on a two-layer QoI/VoI definition, where the former relates to context-independent aspects and the latter to context-dependent aspects of an information product. In this framework, QoI is defined as

> *"the body of innate information properties that can be used to make judgments about the fitness-of-use and utility of information products"* . (Bisdikian et al., 2013)

which underlines that QoI, although intrinsic, might be relative to context of use (a piece of information might be of low quality for use case X and be of good quality for use case Y).

It is not our goal to discuss or provide definitions for each of those mentioned characteristics but we wish to illustrate the qualitative nature of many of those, and thus the definitions of Darlington et al. for several information characteristics provide enough evidence (Darlington et al., 2012):

- Accuracy: "*True or correct to a level of precision appropriate to the purpose*";
- Trustworthiness: "*The reliability of the information inferred from information about the source*";
- Usability: "*The extent to which the information can be used to achieve a person's intended goal(s) with effectiveness, efficiency or satisfaction*";
- Relevance: "*A measure of how pertinent, connected or applicable information is to fulfilling an informational need*";
- Currency: "*Applicable at the time of interest' where 'time of interest' is the operative term*".

Information properties cover a wide range of aspects from the mathematical to the semantic nature of information. The quality and value discussions, along with other perspectives of analysis, although semantic in nature, might include mathematical grounds and analytical perspectives in assigning characteristics to a certain piece of information that we wish to include in this overview of information properties.

Since the inception of the information theory in Shannon's paper, mathematical and other intrinsic formal properties and characteristics of information have been conceptualized, developed and used, mainly in the fields near the information economics domain and broadly applied in many industries (communications, insurance, banking, security, etc.). The paradigmatic example is entropy, which Shannon presents as "*a measure of information, choice and uncertainty*" (Shannon, 1948), about the states of the world.

The mathematical approach does not eliminate subjectivity, although it might be helpful in our effort to cope with it. For example, information quantity depends on the number of possible states of the world that are relevant for a certain individual (the message receptor). As a basic example, if you have bought a lottery ticket, the relevant information might simply be 'winner' or 'loser', ignoring the actual digit combination that was randomly selected as winner, but the quantity of information transmitted would be different in each case: communicating the complete lottery number versus the win/lose alternative. In many circumstances we choose to communicate only the outcome of a process to a certain targeted audience and thus we have to decide which subset of events is eligible and eventually included in our message. This is inherently a subjective process but the point here is to stress that, when we make those choices, we are adjusting the information structure which comprises direct impacts (limited information about the states of the world is encapsulated in the message) but also indirect impacts (the message receptor's ability to anticipate all the possible states of the world is conditioned by the information structure that we use in the communication process). Although in many situations the information structure is explicitly determined by the message's sender, this is not always the case. In many practical situations we have limited access to the states of the world (for technical or scientific reasons, for example) and the challenge might be to estimate or anticipate what those states might be, provided that a certain signal is received.

Information properties related to the structure of the information and the way that the structure might vary between different agents receiving the information are extremely important aspects in many information economics and game theory domains. The concepts related to information structures are inextricably related to the state-model previously introduced as a methodology to express knowledge of the world, which is assumed to have a finite number of states (the state space).

Whenever we decide to split the state space into subsets (as the winner/loser of the lottery example or even/odd subsets of outcomes in a dice game) we are creating a so-called partition of the state space and the elements of a partition (like 'odd') are referred as events (or information sets, in game theory terminology).

A message telling an individual in which event (subset of the state space) the true state of nature lies (which event has occurred) is a signal, and signals, as we know, can be more or less informative. A signal with one value per each possible state (which corresponds to an information structure of subsets with only one element in each) would convey an exact state of the world and thus corresponds to a perfect signal. By contrast, any other alternative is an imperfect signal (which is the common situation in real life scenarios).

Information structures are useful tools to compare the type and amount of information of different agents. Birchler and Butler (2007) suggest the term 'homogenous information' for labelling information structures whose subsets do not overlap across individuals, while heterogeneous information refers to subsets which overlap across individuals. Different individuals might receive different, although non-overlapping, information structures (therefore, not heterogeneous), in which case the term asymmetric information is the most appropriate (since the agents are not in equal circumstances when it comes to interpret signals – one agent will have a finer information structure, which might also be interpreted as including private information).

A signal may be imperfect and additionally noisy. A noisy information structure is the one in which not only one signal can indicate several states, but also several signals can occur in the same state due to a mismatch between the answer an agent is seeking (for which it deals with a certain information structure) and the information structure implicit in the signal he receives (meaning that those information structures overlap and are heterogeneous).

Information is frequently used to forecast the states of the world. Thus, the accuracy of the forecast (the probability of the state of nature being equal to the signal) is an extremely relevant outcome of a signal interpretation directly related to the precision of the signal (the probability of state X leading to signal being X - in other words: the probability of the signal being X, when the true state is X).

Within this context (state-model), information quality is about one information structure being more informative than another and thus the fineness criteria are only valuable if we need to rank information structures that are homogeneous (when a structure with higher fineness is also a more informative one and thus of higher quality). Obviously, this fineness criteria are not useful when we have heterogeneous structures, in which case the precision criteria would be an alternative, among others.

Information properties are instrumental to any structured usage of information either in the scientific or business domains but the nature of the properties and the approach to tackle the difficulties in dealing with those properties might vary significantly depending on the particular context of usage.

2.1.4 Information Value Frameworks

As discussed in previous sections, information is inherent to the concept of knowledge as a human process by which new messages are received and processed within the human brain, generating new knowledge or at least new perceptions of the world. Previous knowledge is a condition to interpret and to acquire or generate new knowledge along with the ability to process new information and update beliefs. Information is central to this process and is therefore valuable. Thus, the understanding of knowledge processes and the human context behind those processes is a key element to reach a comprehensive understanding of information valuation strategies, methods and their implications to practice.

The information valuation process is inherently a subjective activity as long as we recognise that the source of value can have different natures. Depending on the circumstances of the evaluation's agent towards information as a good, one might recognize (i) the value of use or (ii) the value of exchange as two distinct value sources (Glazer, 1993). From a business point of view, Hubbard (2014) claims there can only be three reasons for information to have value: (i) information reduces uncertainty about decisions with economic consequences; (ii) information affects the behaviour of others, which has economic consequences and (iii) information has its own market value (exchange value). It is also possible to adopt a broader framework to encompass the complexities of human behaviour and consider a subset of human values as the source of value, as Holbrook (2006) did, suggesting economic, social, hedonic and altruist values as possible sources of value. New sources of value are being suggested to cope with challenges related to multiplicity of networked users and their mutual interactions in networked data and information environments giving rise to notions of connected and co-created value (Foster & Clough, 2018). Moreover, information experiences as sources of value are the subject of recent research. Rusho and Raban (2020) developed field experiments and concluded that value (of information) is dynamic and value perception increased after experiencing information, especially when people engaged in producing information instead of just consuming it. Finally, and before addressing specific valuation approaches, it is worth to observe that you cannot purchase a message but only a message service (Hirshleifer & Riley, 1992), thus the value of information frequently refers to the value of the information source.

All sources of value are potentially relevant from the management perspective, although ‘information as a guide to action’ is the pervasive way to use information within the specific scope of our research (the VoI in the mobile network management setting), as we show in the literature survey presented in the next section. Our aim is to quantify value in economic terms and use it as input to human-driven management processes. Thus, as far as this work is concerned, the source of value is a possible action an agent might undertake and we follow the valuation principle suggested by Birchler and Butler (2007), applicable to the context of information as a guide to action: “*value of information is the increase in utility an individual expects from receiving the information and from optimally reacting to it*”.

The overall idea is that, once the agent receives a piece of information, he is able to update his beliefs by means of probabilities, revised using Bayes’ theorem (Hirshleifer & Riley, 1992), thus allowing him to adopt an optimal action. Thus, a piece of information is meaningful as long as it allows probabilities to be revised. Ultimately, information is valuable because the revised probabilities have an influence on the optimal action (assuming the agent adopts a rational behaviour).

As a general rule, the pay-offs from alternative courses of action are fundamental inputs for computing the VoI. Using game theory language (and assuming an optimal reaction), the value of the information is equal to the difference between the value of the game (pay-offs) with and without information (Birchler & Butler, 2007). This is valid regardless of the quality of the signal and thus is widely adopted as a guiding principle for many use cases of information value computation.

If the problem under analysis is formulated using the utility paradigm, and the information is represented by a signal received by one agent and which he acts upon, then the value of that piece of information depends on the magnitude of the payoffs, the attitude of that agent towards risk (namely the degree of risk aversion), the prior uncertainty and the precision of the signal (Birchler & Butler, 2007). The absolute precision of the signal is usually referred as perfect information and is used to estimate the maximum expected value that information might deliver in a certain context. Thus, the value of perfect information provides a benchmark for the real imperfect signal you might have access to in a certain moment (for example, a signal may be useless unless its precision is improved), and also sets the upper bound for the value one should expect from the economic contribution of information.

Some counter-intuitive remarks should be added because reality is not as linear as one would expect: the degree of risk aversion does impact the VoI, but it does not always increase this value – it can actually reduce it (Hirshleifer & Riley, 1992); the VoI increases with the higher pay-offs but it is not always monotonic; it can have a peak, meaning that one should invest more in information gathering when facing indifference between alternatives (Birchler & Butler, 2007). Another aspect that affects utility is the preferences of individuals regarding the moment in time when the resolution of uncertainty is achieved (individuals that prefer an early resolution are called 'information-loving' and those who prefer a later resolution are called 'information-averse'). Finally, the precision of the signal is closely related to the measurements we have to put in place at a business level to make operational decisions. Hubbard (2014) claims that, when a model includes a substantial number of uncertainty variables, often the most valuable ones will obtain less attention from management, thus recommending the VoI quantification as a means to improve decision criteria on what should be measured and at what level of precision.

Another aspect Hubbard points out as critical to management is the timing of the decision (usually, delay means value loss) versus the availability of information (usually, gathering information or making measurements takes time). In many economic applications, valuing information is only part of the problem since costly information gathering rapidly imposes cost-benefit constraints; we therefore face an optimization problem: how much information is enough or adequate to maximize the agent's pay-offs? These optimization problems have interesting applications, such as determining the optimal precision of a forecast or the optimal sequential search, but many other applications exist.

Actually, part of the challenges in the network management setting are extensions of those challenges, since there is high volume of information available (and probably much of which with disputable value), the resources are limited and there are underlying costs of delays in decision making and actions towards network optimal operation.

2.2 Survey on the VoI in Mobile Network Management

The purpose this section is to provide a structured literature review on VoI in mobile network management thus describing the current state of research on the topic and setting the stage for our own contribution.

The network management activities we have in mind are those aimed at operating the network, which means monitoring performance and making decisions based on the information gathered. Those decisions essentially concern choosing alternative courses of action based on the observed performance, and eventually undertaking actions that changes the network status and operating conditions, such as correcting failures, changing configurations and settings, thereby improving the system's performance according to top management guidelines on service grade goals, for example.

Why is VoI so important in network management activities? Over the years, research evidence from different geographies and economic contexts has claimed that Quality of Experience (QoE) and Quality of Service (QoS), which require high-performing networks, are key drivers for customer loyalty (Edward et al., 2010), customer retention (Ruiz Díaz, 2017), behavioural intentions of the customer (Wang et al., 2004) and thus business success within the telecommunications industry. Calvo-Porral et al. (2017) emphasize this, recommending that "*company managers should use service quality as a mechanism for exit barriers that will retain present customers, considering the perceived service quality as a tool for customer retention*", which clearly indicates that network management activities are highly relevant to business success in this industry.

Notably, network management technologies and paradigms are among the top priority research topics (Hossain et al., 2019) and the relevance of these activities is grounded both in the technology wave and on business reasons, including a potential business model adaptation for mobile network operators that face increasing traffic growth on the one hand and declining revenues on the other (Oughton et al., 2018).

Modern mobile networks are highly complex systems and the next technology wave (5G) will be even more complex and data intensive both on the user and management side (Hossain et al., 2019), since many network functions and capabilities (traditionally hardware-based) are expected to be supported by virtual and software-based solutions in 5G (Suryaprakash et al., 2015). This technological context will increase the internal demand for computational power and computational resources which are expensive and require careful evaluation of their cost-benefit relation, not only as an alternative to assuming virtual network functions, but also for pure computation, in which case VoI is an effective criterion to optimize their usage (Bölöni & Turgut, 2017).

Data and information management are computationally intensive activities and it might be anticipated that the 5G technological wave (with a collateral higher demand on computing power) will prompt a higher level of scrutiny of information management within the network operations field which should follow tangible business value criteria as much as possible. Despite the growing complexity and volume of data required to manage any mobile network infrastructure (Dai et al., 2019), the value of the information used within these activities is, to the best of our knowledge, only barely addressed, if at all, in academic research.

2.2.1 Literature Review Methodology

The goal of this literature review is to explore the field of VoI usage in the mobile network management, to discover and summarize methodologies and approaches to related to modelling, usage and measurement of VoI in the mobile network management. Given the previous general goals, this literature research adopted the following primary research questions:

> RQ1: How has the VoI been modelled and measured in mobile network management?
>
> RQ2: How has the VoI been used within mobile network management?

The review process is based on the guidelines proposed by Kitchenham (2004) for the case of a single research but other studies played significant influence in the process namely Tranfield et al. (2003), Armitage and Keeble-Allen (2008) and Okoli (2015). Examples of literature reviews on VoI and related areas such as Keisler et al. (2014), Viet et al. (2018) and Collins et al. (2021) were also instrumental and inspired the reporting strategy. Overall, the activities undertaken were developed according to the following main steps:

a) Plan the review (developing the protocol, defining the research question, defining the search strategy, defining the data to be extracted from each primary study);

b) Locate and select studies (execute search, maintaining lists of included and excluded studies, assess if a study does actually address the review questions using a set of criteria);

c) Analysis and synthesis (read each study using the data synthesis framework to extract relevant data towards synthesis knowledge creation beyond reach for someone reading the individual studies in isolation);

d) Report (write the review report using the reporting guidelines according to the audience and dissemination strategy planned).

Next, we clarify how relevant studies were located and selected. Thereafter we present the data synthesis framework, which includes the dimensions used in analysing the selected literature. The results from the review are discussed in the subsequent section.

2.2.2 Article Search, Selection and Screening

A general outlook of the procedure followed during the search, selection and screening of the articles is presented in Figure 1. Those activities were executed in the presented sequence and will be explained in this section.

1. Prepare Queries
2. Search SCOPUS and WoS and Retrieve Primary Results
3. Eliminate Duplicates
4. Classify Articles using Title, Abstract and Keyword Information
5. Screen Articles
6. Initial List of Eligible Articles

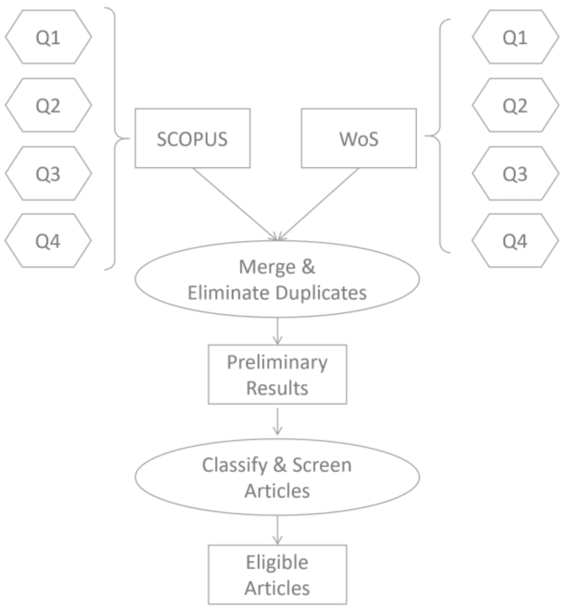

Figure 1 - Procedure followed during the search, selection and initial screening of the articles

Our goal was to identify as much of the relevant literature as possible on “how VoI has been modelled, measured and used within the mobile network management area”. Our initial plan was to consider only articles published in scientific journals. Given this general goal, we created a sequence of queries to use in two worldwide scientific repositories: SCOPUS and Web of Science (WoS). The sequence of queries starts with a narrow perspective and becomes more flexible (with higher probability of retrieving irrelevant articles). The first query is completely aligned with our goal (‘value of information’ and (mobile networks)) but we decided to consider the use of acronyms (the second query uses VOI instead of Value of Information) and alternative words to express similar concepts (the third query uses telecommunication (Telco) networks instead of mobile networks) or even expand the concept scope to capture extensions or variants of the concept (the last query uses networks instead of mobile networks). For all queries, the search is performed on title, abstract and keywords:

Q1: [(‘value of information’ and (mobile networks)) in (title, abstract, keywords)]

Q2: [(‘VOI’ and (mobile networks)) in (title, abstract, keywords)]

Q3: [(‘value of information’ and (telecommunication networks)) in (title, abstract, keywords)]

Q4: [(‘value of information’ and (networks)) in (title, abstract, keywords)]

We tested one additional query considering value and related synonyms (using ((information) and (value or profit or cost or benefit or saving or surplus)) instead of value of information) but the retrieved number of articles (32507, just in one search engine) was very high and we decided to keep just the presented four queries. The last query retrieved more than 3000 articles and we decided to exclude journals with minimum association with telecommunication networks (e.g., Environmental Sciences, Medicine, Agricultural and Biological Sciences) to avoid a significant number of preliminary results that were out of scope for obvious reasons (appendix I includes examples of tailored queries for each search engine and all the filters used). After excluding those categories, the number of retrieved articles was reduced significantly, and we decided not to impose restrictions on the time dimension.

In Table 1, we present the quantitative description of the search results (as explained before, only journal articles included and without duplicate exclusion for fair treatment of both engines). Given these 1016 records, we proceeded to eliminate duplicates (we found 177 duplicates, corresponding to 17 % of the records), ending up with 839 articles as preliminary results.

Table 1
List of journal articles retrieved from SCOPUS and WoS (duplicates included)

Engine	**Query**	**Number of articles**
SCOPUS	Q1	26
	Q2	2
	Q3	25
	Q4	866
Subtotal SCOPUS		919
WoS	Q1	8
	Q2	4
	Q3	0
	Q4	85
Subtotal WoS		97
Total Articles (both engines)		**1016**

After this step, we reviewed all article's title, abstract and keywords with the goal of identifying those articles that affirmatively address the goal of our literature review: explore the field of VoI usage in the mobile network management or telecommunication networks. We classified the articles into the following categories:

- those which explore the field of VoI usage in the mobile network management (VoI & Mobile Networks)
- those which explore the field of VoI usage in the telecommunication's domain (VoI & Telco Networks)
- those which explore the field of VoI usage but outside telecommunication's domain (VoI Not Telco Networks)
- those which do not explore the field of VoI usage explicitly (Not VoI)

In Table 2 we present the quantitative summary of this screening process. We assumed a broad interpretation of 'Telco domain', including not only any type of contexts related to networks and communication's technologies but also domains that nowadays are reasonably related with the field, such as sensor networks, cloud computing and the Internet of Things (IoT).

We conclude that 70.8% of the articles obtained from the queries on SCOPUS and WoS are not explicitly exploring VoI usage and another 21.3% of the articles, although exploring VoI related topics, are clearly unrelated with the telecommunications field. In conclusion only 7.8% of the articles (66 out of 839) are suited for deep analysis. This high number of articles retrieved by the search engines that turned out excluded after the detailed review was surprising but after all understandable due the fact that the words ‘information’ and ‘value’ are used independently across multiple scientific domains and clearly the search engines therefore retrieve many of those independent usages and thus generate a very high percentage of ‘false positives’.

Table 2

Summary of classified journal articles retrieved from SCOPUS and WoS (duplicates excluded)

Query	VoI & Mobile Networks	VoI & Telco Networks	VoI Not Telco Networks	Not VoI
Q1		10	5	14
Q2		0	1	0
Q3		3	3	18
Q4	2	51	170	562
Total	**2**	**64**	**179**	**594**

There are also situations in which those concepts are used in a general way, either in the title or in the abstract, but without material relevance in the actual content of the research reported in the articles thus becoming irrelevant for our analysis and in those situations, we therefore decided to exclude them even in later stages of the process.

Since this initial list of eligible papers was quantitatively below our expectations, and that we had access to examples of interesting conference papers, we decided to extend our study and repeat the previously explained steps targeting only conference papers but keeping the focus on mobile and telecommunication networks (in other words, query Q4 was not used). We retrieved 170 primary results from this procedure and after the classification and screening we added 63 new eligible papers. Finally, after comparing the eligible list with pre-available articles that we considered relevant, we concluded that several related articles were not detected by our queries and we decided to include those papers clearly aligned with the focus of this review (12 from journals and 14 from conferences).

We proceeded towards gathering the full papers on the eligible list and read each study. The thorough reading of the articles led to additional article exclusion due to several reasons: language (4 non-English articles); full paper unreachable (7 papers); VoI usage not confirmed (44 papers) and finally relation with telecommunication networks was absent (22 papers).

Thus, the complete process is summarized here:

1. Prepare Queries
2. Search SCOPUS and WoS and Retrieve Primary Results
3. Eliminate Duplicates
4. Classify articles using title, abstract and keywords information
5. Screen articles (VoI&Telco affiliated only)
6. Initial list of eligible journal articles (n=66 out of 839)
7. Initial list of eligible conference articles (n=63 out of 170)
8. Merge with previously available articles related to the subject (12 from journals and 14 from conferences)
9. Read each study using the data synthesis framework (n=155)
10. Screen articles (VoI confirmed usage in telecommunications only)
11. Final list of articles under review (n=78 out of 155)

So, in the last two decades (2000-2020), the scientific production under review has significantly increased during the first decade, went through a declining period and has recovered the growth from 2015 to 2020, as shown in Figure 2.

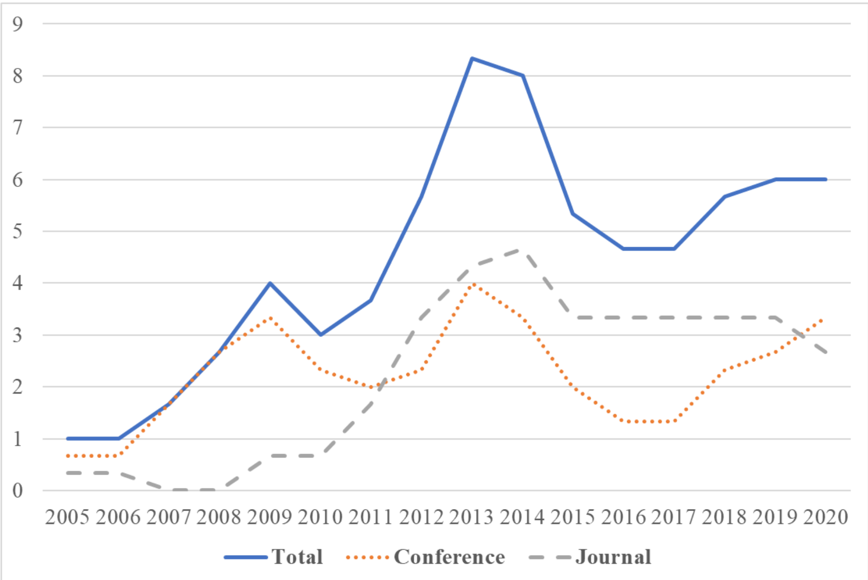

Figure 2. Time distribution of reviewed articles (moving average for a 3 years period ending in the year presented in the x-axis)

We have used a moving average of three-year periods to capture more of a trend than the specific number of articles per year. So, the value presented for 2005 is the average number of articles per year for the 2003-2005 period, the 2006 value is the average for 2004-2006, and so on. Also note that, in the final list, we have articles from 2003 until 2021 (the search that was used as input to the review was done in April 2021), but the number of collected articles published in 2021 are not representative of a full year, thus our historical analysis ended by 2020.

Thus, it is safe to conclude that VoI (and related concepts) have been adopted and consistently used by the telecommunication networks researchers for more than a decade. In Table 3, we present the list of Journals where the articles under review have been published which reveals a significant spread of the VoI topic through many different scientific domains and scientific audiences.

Table 3
Number of papers by Journal

Journal	**Articles**
Sensors	3
ACM Transactions on Sensor Networks	2
Future Generation Computer Systems	2
IEEE Communications Magazine	2
IEEE Transactions on Automatic Control	2
Performance Evaluation	2
Annales des Telecommunications/Annals of Telecommunications	1
Automatica	1
Computers and Geosciences	1
Expert Systems with Applications	1
IEEE Internet of Things Journal	1
IEEE Journal on Selected Areas in Communications	1
IEEE Network	1
IEEE Systems Journal	1
IEEE Transactions	1
IEEE Transactions on Industrial Informatics	1
IEEE Transactions on Multimedia	1
IEEE Transactions on Parallel and Distributed Systems	1
IEEE Transactions on Signal Processing	1
Information Sciences	1
International Journal of Business Analytics	1
International Journal of Communication Systems	1
International Journal of Computational Intelligence Systems	1

Journal of Multiple-Valued Logic and Soft Computing	1
Optimization Letters	1
Peer-to-Peer Networking and Applications	1
Pervasive and Mobile Computing	1
Physical Communication	1
Robotics and Autonomous Systems	1
Systems and Control Letters	1
Telecommunication Systems	1
Wireless Personal Communications	1

2.2.3 Data Synthesis Framework

The goal of this literature review is "to explore the field of VoI usage in the mobile network management", which is a fairly narrow scope considering that VoI may potentially be used in all functional areas of the telecommunications industry. After a thorough review of a subset of the articles, we concluded that the way VoI was modelled, measured and used depended fundamentally on (i) the type of network; (ii) the theoretical foundation; (iii) the research paradigm. Thus, regarding the type of network, with decided to adopt three classification categories:

- **Mobile Networks:** articles covering VoI applications related to the traditional communication services;
- **Sensor Networks:** articles covering VoI applications related to emerging paradigms of wireless sensors combined with communication infrastructure and information gathering, deployed to capture environmental data (from physical security threats to biological or climate observations, for example);
- **Cloud Networks:** articles covering VoI applications related to emerging paradigms in the telecommunications industry, such as cloud computing and the IoT.

Although our focus was on the first category (mobile networks), the diversity of articles retrieved and accepted into the review process recommended the use of articles of related categories, to avoid lack of generalization. Therefore, this classification was used.

Considering the diversity of theoretical foundations that we detected in an initial subset of articles, we also decided to evaluate each article considering the theoretical background used to model information (and compute information metrics or value), since two main schools of thought are recognized in the literature.

On one hand we have quantitative information theory (following Shannon's historical contributions) and on the other hand we have other approaches dedicated to the economic value or utility of information, usually considered as qualitative information theory, as discussed in Moskowitz and Russell (2018).

Since other articles discuss the need for combined approaches (e.g., M. Chen et al. (2019)), three categories were considered:

- **Quantitative** – backed on Shannon's information theory;
- **Qualitative** – backed on utility or value captured by information usage, exchange and other forms of value perception with economic externalities;
- **Hybrid** – quantitative and qualitative perspectives combined into one model or method to use the VoI to achieve higher performance or economic results.

The articles' research paradigm is also a very important classification criterion because it only makes sense to adopt coherent analytic conclusions by comparing and evaluating articles with compatible research paradigms. The following subcategories encapsulate the key dimensions of common research paradigms used in VoI-related studies:

- **Information Concept**
- **Decision Framework**
- **Performance Goal**

The analysis of the research paradigm was based on the framework depicted in Figure 3. The way information is modelled and measured, which is present in the first research question, is addressed by the dimension 'Information Concept'. The dimensions 'Decision Framework' and 'Performance Goal' are related to the way information is used in the articles and are also key aspects of any use of information as a guide to action.

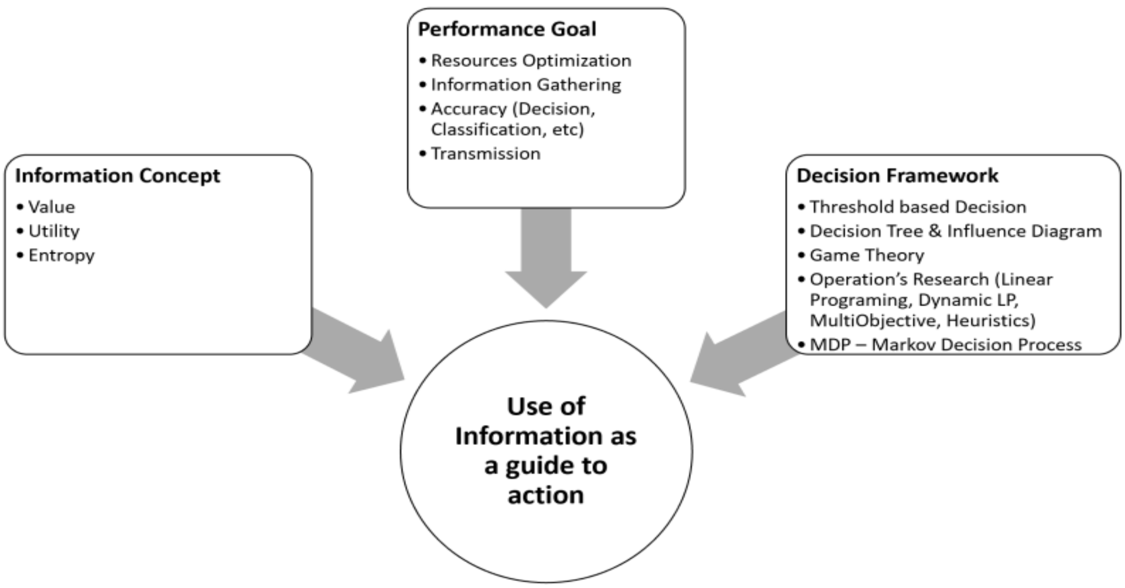

Figure 3 – Framework for the analysis of the 'Research Paradigm'.

The categories included within each dimension (e.g., Value, Utility and Entropy used within 'Information Concept') were initially defined according to our knowledge and expectations (as an initial reading guide) but eventually updated and adjusted according to the actual content and research reported in the articles. These categories are not intended to cover all the possibilities (that one could find in the VoI field) but solely the spectrum of research reported in the articles retrieved in our search and screening process.

To summarize the framework, we include in Figure 4 a diagram with all possible paths of analysis based on which we extracted knowledge from the thorough reading and interpretation of the articles included in the last step of the review.

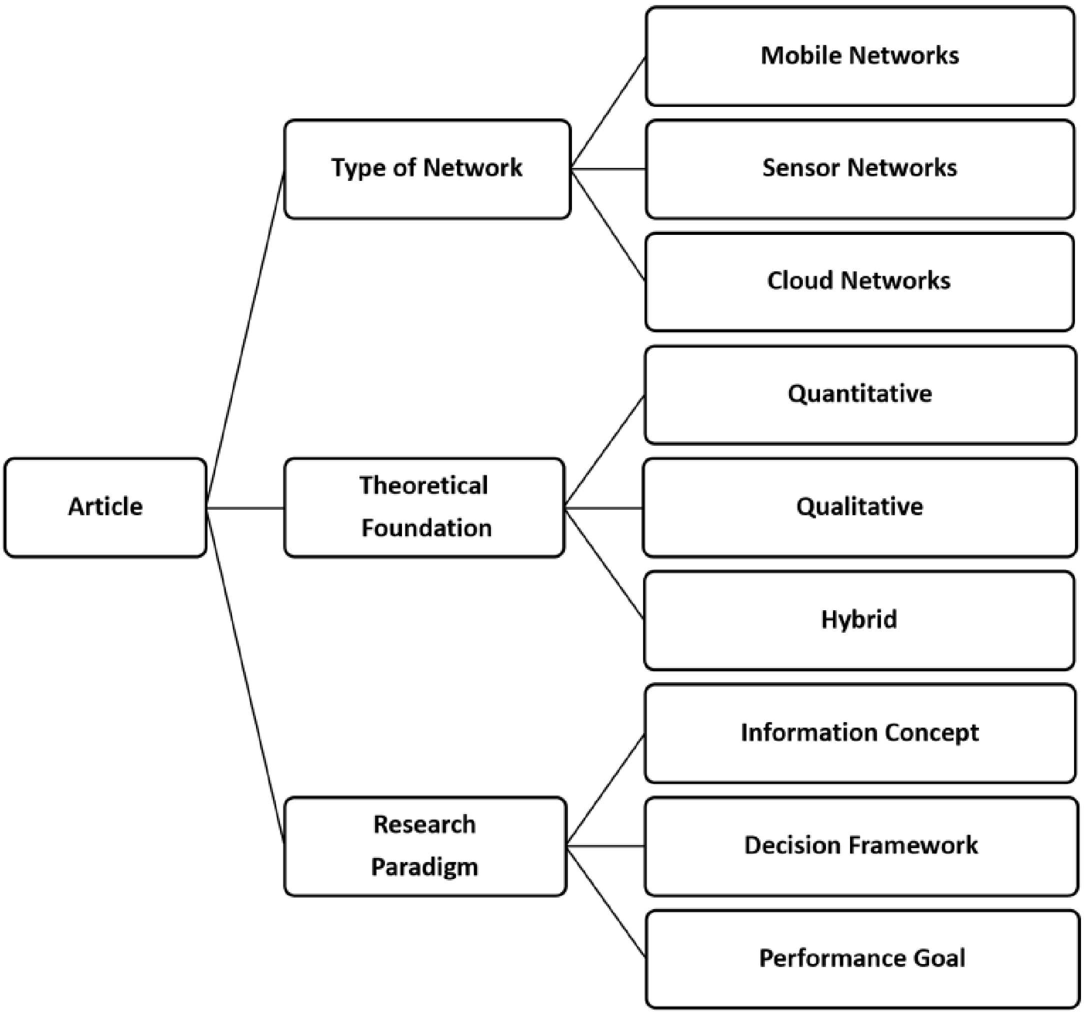

Figure 4 – General framework used to extract knowledge from the articles included in this literature review

In the following sections we will present the data and analytic conclusions according to the framework structure presented in Figure 4.

2.2.4 Results

This section presents the results from the analysis of the final list of articles under review (n= 78) based on the data synthesis framework. The articles mentioned or referenced in this section are listed in Appendix II with the complete list of articles retrieved after the screening process adopted in this review and may not be part of the references of the theses. First, we present a quantitative overview of each dimension of analysis (‘Type of Network’; ‘Theoretical Foundation’; ‘Research Paradigm’) and afterwards we provide a more qualitative discussion on the ‘Research Paradigm’ dimension. On the ‘Type of Network’ dimension, Figure 5 presents the main quantitative results. Thus, despite our special interest in the ‘Mobile Networks’ category, we accepted a significant diversity of articles in the review process (to avoid lack of generalization), which allows us to reach the following conclusions: (i) The most important type of networks considered in VoI application are ‘Sensor Networks’; (ii) a significant number of articles are within ‘Mobile Networks’, our initial target (23 out of 78), which means that VoI application in this domain is relevant. We acknowledge that our queries were not designed (nor extended) to capture the full extension of literature on the ‘Cloud Networks’ category thus we consider it wise to be careful when reading this category’s numbers.

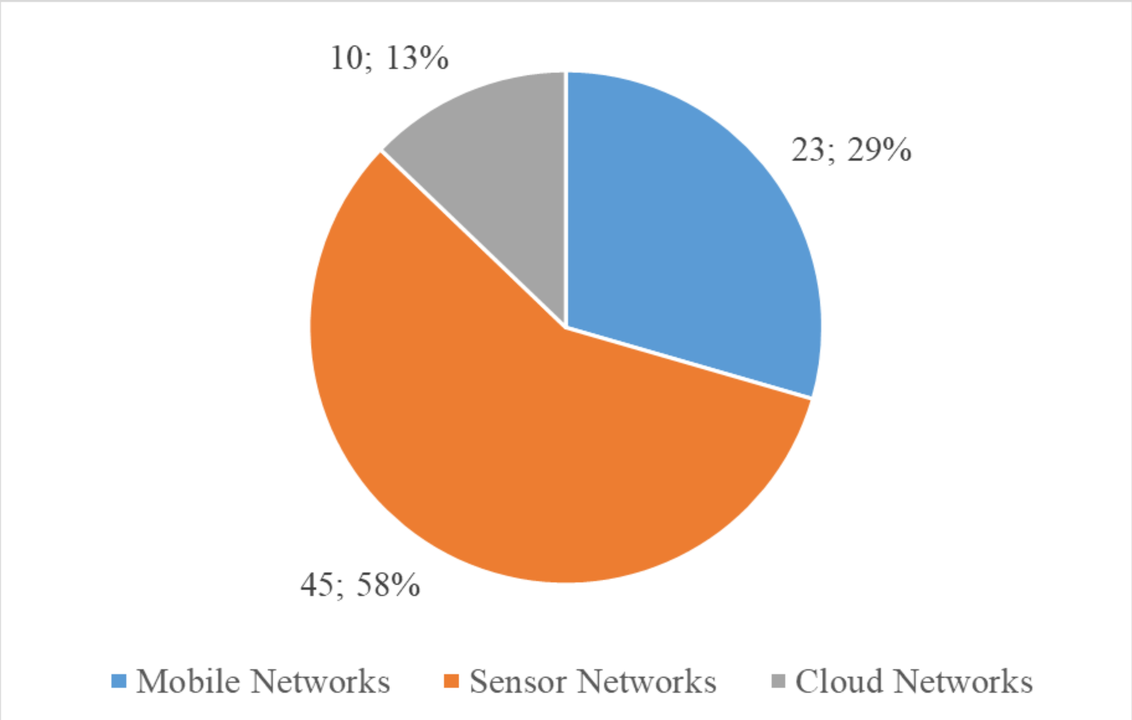

Figure 5. Quantitative distribution of reviewed articles among the analytic categories within the ‘Type of Network’ dimension.

In Figure 6, we present a timeline along the recent years of articles included in this review (moving average of 3 years) which allows some additional observations: (i) the VoI application within the 'Mobile Networks' category has a steady presence in the literature over the years; and (ii) the application of VoI paradigms in the 'Sensor Networks' category went through a hype of academic research and still has higher presence in the current scientific production, when compared to the remaining categories. Finally, the scientific production on both categories, 'Mobile Networks' and 'Sensor Networks', seems to be in a growing period in recent years (from 2017 to 2020).

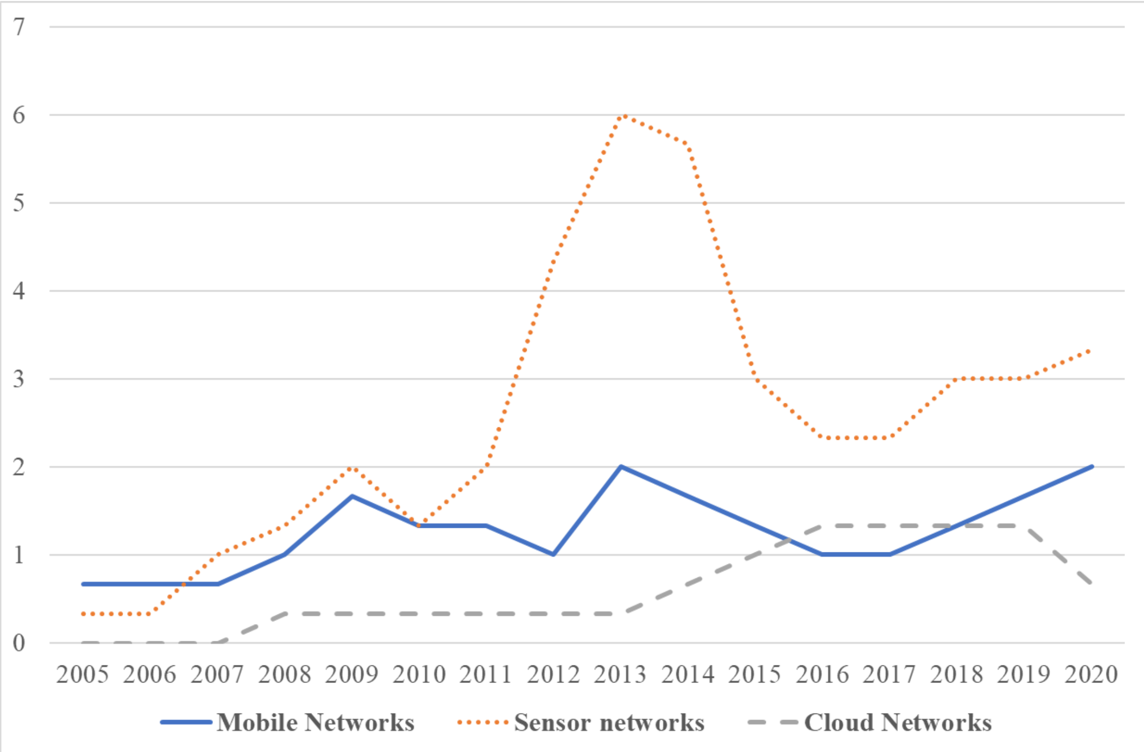

Figure 6 - Time distribution of reviewed articles among the analytic categories within the 'Type of Network' dimension (moving average for a 3 years period ending in the year presented in the x-axis)

In Figure 7 we present the basic statistics on the articles' 'Theoretical Foundation', showing that (i) the majority of articles are based on utility or value captured by information usage, exchange and other forms of value perception with economic externalities (our 'Qualitative' category), while (ii) near one third of the articles are based on Shannon's information theory (and subsequent developments), thus receiving the classification of 'Quantitative'. Finally, only a small number of articles discuss and put forward suggestions for combining both theoretical foundations (quantitative and qualitative perspectives) into one model or method to use VoI to achieve higher performance or economic results (our 'Hybrid' category).

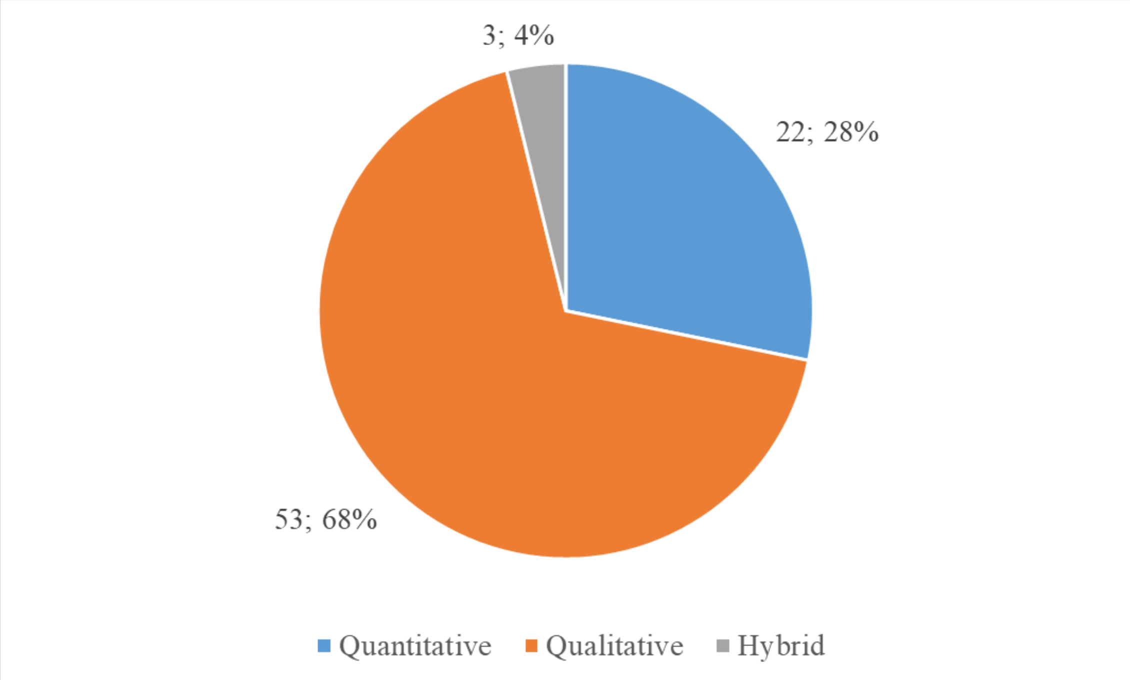

Figure 7 - Quantitative distribution of reviewed articles among the analytic categories within the 'Theoretical Foundation' dimension.

Regarding the research paradigm, articles are classified according to all three dimensions. Nevertheless, we notice that a few articles (8 out of 78, which corresponds to 10%) were difficult to classify in all the dimensions, so we decided to analyse those with special care and they are not included in this quantitative analysis.

In Figure 8 we present the quantitative perspective of the 'Information Concept' used in the articles, showing that Value is the highest represented category. The detailed data is presented in Table 4 and it is worth mentioning that (i) some articles were classified according to our interpretation of the prevalent concept used (not necessarily exclusive) and (ii) we decided to add a column ('Observations') with information concepts used in those articles that differ significantly from the reference designations used for classification purposes.

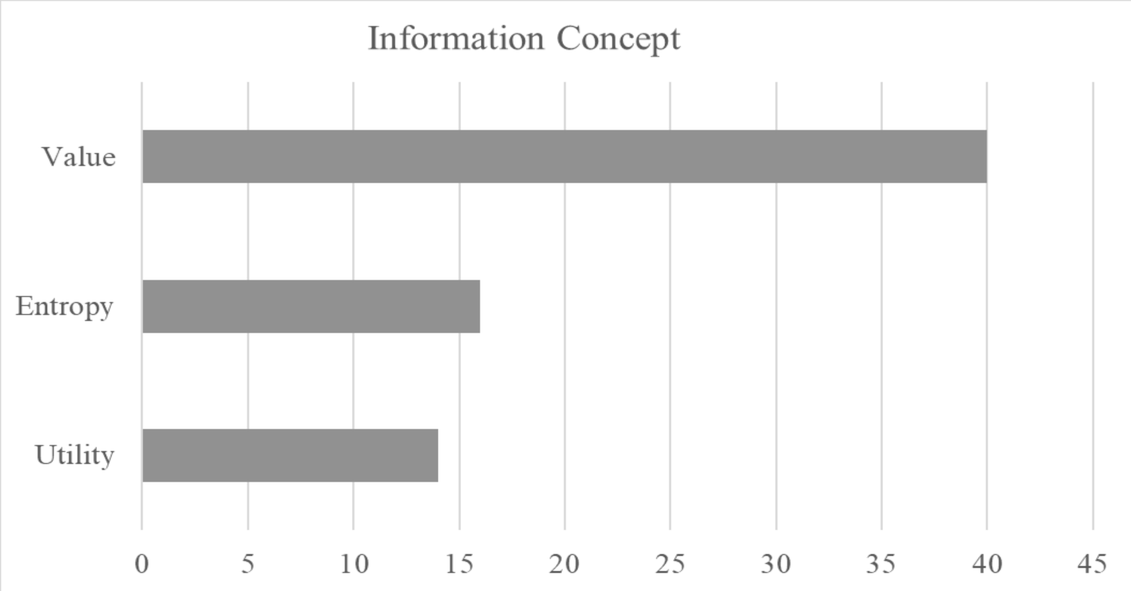

Figure 8 - Quantitative distribution of reviewed articles among the categories of the "Theoretical foundation" dimension.

The next dimension of research paradigm we have evaluated is the 'Decision Frameworks', for which we found several alternatives like 'Threshold-based', 'Decision Tree', 'Game Theory', 'Linear Programming' or 'Markov Decision Process', just to mention some examples. We included in the 'Threshold-based' category all the articles which report any variation of the linear decision principle based on adopting a reference performance indicator and defining a threshold of performance as decision criteria to take action (below and up until the threshold value of the performance indicator the action might be X and above that reference value the action would be Y). On overall, this category received the highest number of articles as discussed in the forthcoming analysis. For the quantitative analysis, we decided to collapse those multiple approaches into five groups (Figure 9): 'Threshold-based', 'Operations Research' (which includes LP - Linear Programming, Dynamic LP, Multi-Objective, Heuristics, etc.), 'Game Theory', 'MDP - Markov Decision Process' and 'Other', which includes the remaining cases (each alternative included in the 'Other' category did not account for more than two articles). A preliminary analysis of this dimension shows that there is a diversity of options regarding the 'Decision Framework' (Table 5), but the majority of works use 'Threshold-based' frameworks.

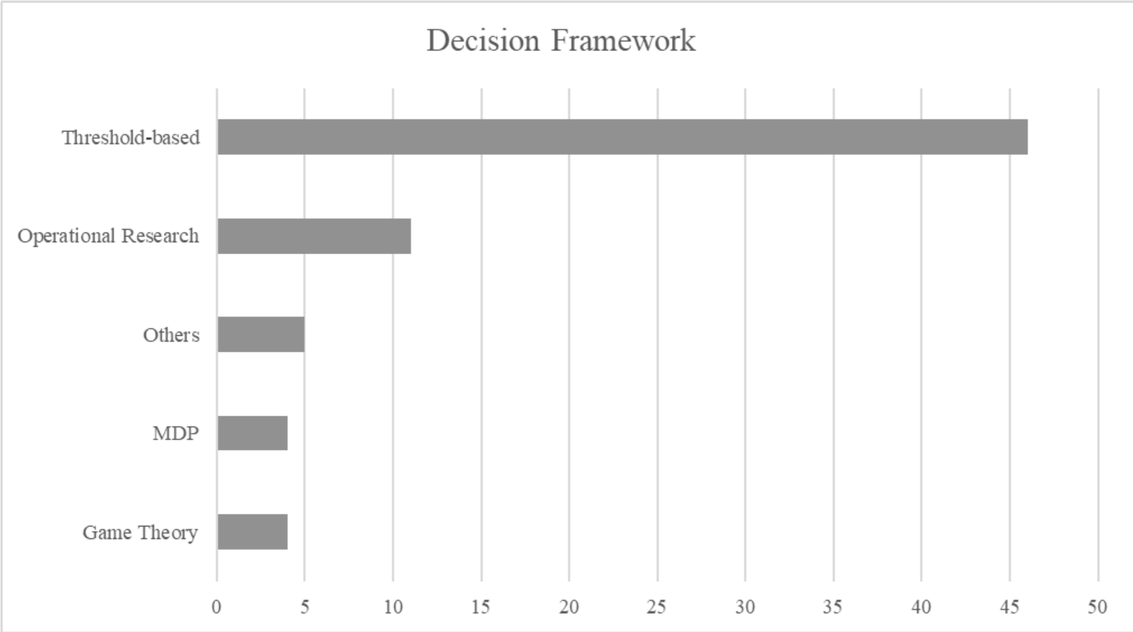

Figure 9 – Quantitative perspective of the 'Decision Framework' used in the articles.

Finally, regarding the 'Performance Goal' behind the research reported in each article, we considered the three categories presented in Figure 10. The correspondence of each article to this category is presented in Table 4 and there are a few cases where multiple goals were described in the same article (and that is why the total of the bars is higher than 70).

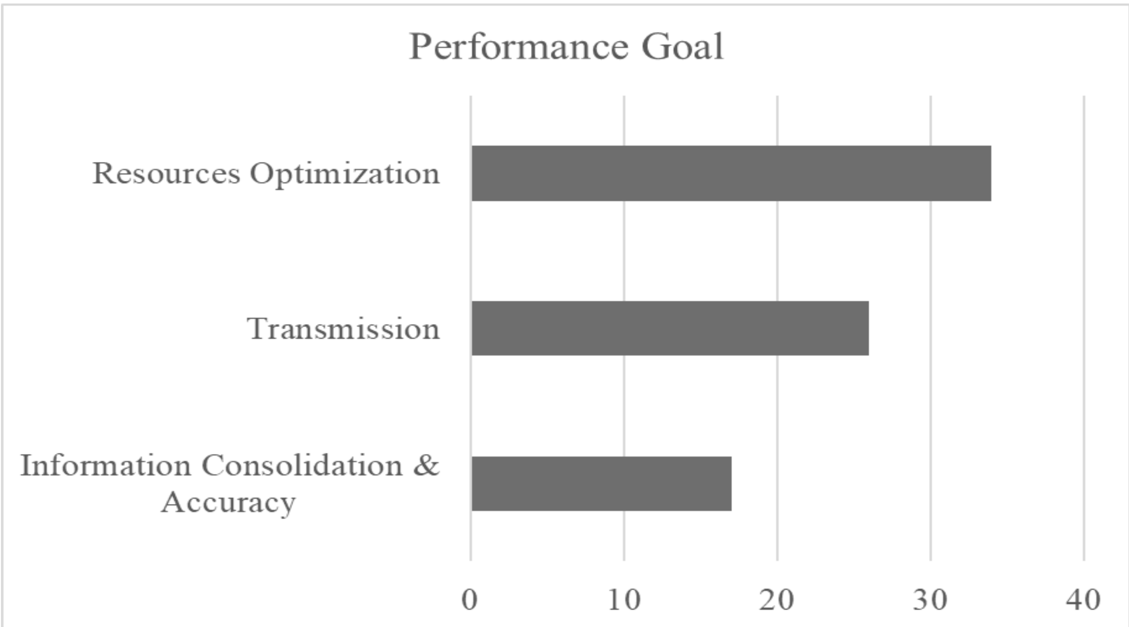

Figure 10 – Quantitative analysis of different 'Performance Goals' adopted in the articles.

The category 'Transmission' is assigned to the article when information is used to optimize the communication process at the engineering level, while the 'Information Consolidation & Accuracy' is applied to articles reporting research related to information coming from distinct sources (usually sensors) that requires some sort of merging and consolidation process where information metrics are used to optimize this process. In those articles this information coming from distinct sources has to be combined to provide accurate observations of the world and thus information metrics are used to optimize the accuracy of this observation (thus explaining our option to the name category). Nevertheless, the majority of the articles report research efforts to optimize resources including energy, bandwidth and network resources.

2.2.5 VoI 'Research Paradigm' Dimension – a Closer Look

In this section we review the article's 'Research Paradigm' considering three dimensions previously introduced (Figure 3): 'Information Concept', 'Performance Goal' and 'Decision Framework'. We start with the articles that are easily classified across the three dimensions (70 out of 78) and by the end of this section we analyse a handful of articles that require distinctive treatment because their classification is not straightforward.

In Table 4 we present a general list of the articles with our classification of each one regarding the 'Information Concept' used and the 'Performance Goal'. This is a simplified form of presenting many different ways to interpret and make use of information. For example, the category 'Value' (adopted as umbrella term for different forms of expressing the value of information) actually maps to different meanings in the articles, such as: fuzzy expected value of perfect information and fuzzy value of stochastic solution (Turan et al., 2016), value of stochastic solution (Turan, Hasan Huseyin et al., 2013), expected value of sample information (Faied, 2015), value of resource-discovery information (Wolfson et al., 2005), environmental value of information (Doctori-Blass & Geyer, 2008), global expected value of information of the points for decision making (de Bruin et al., 2012), switching option value (Geyik et al., 2012), conditional VoI (Boloni et al., 2013), value of coordination and delayed queue information (Gopalan et al., 2013), value of sensitive information, (Moitra, 2014), value of sensing information (Ranjeeth et al., 2020), value of sensed information (Al-Turjman et al., 2017). Some articles incorporate the timing of the information as a critical aspect to determine the value of information and, actually, the age of information metric is suggested and used in some articles (Ayan et al., 2019; Duan et al., 2020). Moreover, there are articles adopting concepts that are (at the most) proxies to the value of information (e.g., 'index value of the channel' or 'imperfect channel state information') but sure do not qualify neither as utility nor as entropy use cases. This diversity of qualitative nature of information being managed and used (despite the narrow scope of our search) should alert us for the plethora of opportunities in this field.

Next in line, the 'Utility' category is also widely used on this list of articles, actually representing diverse technical and economic aspects of the modelled problem such as: service quality (e.g., video quality) in multimedia applications (Park & van der Schaar, 2008); contribution of information to compute the probability of an event (a rear-end collision is the given example) (Frank et al., 2011); location accuracy of the intruder, and error of the path reconstruction (Turgut & Boloni 2012); network throughput (Parag et al., 2011); amount of allocated bandwidth (M. A. Khan et al., 2009).

Finally, some articles are grounded on Shannon's theory of information (that we have classified as quantitative) and use 'Entropy' (or a related metric) to attain their information driven performance goal. Actually, there are several information concepts derived from entropy (see observations column in Table 4) and one that is frequently used is mutual information. Entropy is a measure of uncertainty and conditional entropy H(x|y) represents the amount of uncertainty remaining about x after y has been observed. In this context, mutual information is a measure of uncertainty that is resolved by observing y, thus, mutual information is a metric that enables sensor segregation (e.g., determine that sensor 1 provide better information than sensor 2) and is interpreted as VoI in some contexts (Kadambe & Daniell, 2003). Other information metrics that we found multiple times in these articles include the Fisher information metric and the Kullback–Leibler (KL) divergence. In some applications, the information is about the estimated position of a target which is represented as a multidimensional probability distribution, and the Fisher information metric is used to quantify the uncertainty represented by this distribution (Kho et al., 2009). The Kullback–Leibler (KL) divergence is used to address challenges related to multiple probability distributions which are common within distributed sensing networks' applications and metrics such as the Renyi divergence; the Chernoff distance; f-divergence and others are explained and used in (Mu et al., 2014).

Table 4

General list of the articles with classification regarding 'Information Concept' used and the 'Performance Goal'.

	Information Concept Used				Performance Goal		
Article	Value	Utility	Entropy	Observations	Transmission	Information Consolidation & Accuracy	Resources Optimization
(Kadambe & Daniell, 2003)			X	Mutual Information		X	
(Das et al., 2004)		X					X
(Wolfson et al., 2005)	X						X
(Guha & Sarkar, 2005)	X			Imperfect communication information	X		
(Antoniou & Pitsillides, 2007)		X			X		
(Haifeng & Zhen, 2007)	X			Collective Information Contribution		X	
(Olfati-Saber, 2007)			X	Fisher Information Metric		X	
(Marbukh & Sayrafian-Pour, 2008)		X				X	X
(Doctori-Blass & Geyer, 2008)	X						X
(Marbukh & Sayrafian-Pour, 2008)	X				X		
(Park & van der Schaar, 2008)		X					X
(Bradley, 2009)		X				X	X
(Khan et al., 2009)		X					X
(Kho et al., 2009)			X	Fisher Information Metric			X
(Park & van der Schaar, 2009)		X					X
(Frank et al., 2011)		X					X
(Hsiao et al., 2011)	X			Expected Load	X		
(Jacko, 2011)	X			Index value of the channel	X		
(Olfati-Saber & Jalalkamali, 2011)			X	Fisher Information Metric		X	
(Parag et al., 2011)		X			X		
(Szymanski et al., 2011)		X					X

(Ballari et al., 2012)	X					X	X
(de Bruin et al., 2012)	X					X	
(Cochran et al., 2012)			X			X	
(Geyik et al., 2012)		X			X		
(Jalalkamali & Olfati-Saber, 2012)			X	Fisher Information Metric		X	X
(Olfati-Saber & Jalalkamali, 2012)			X	Fisher Information Metric		X	X
(Rinehart & Dahleh, 2012)	X						X
(Turgut & Boloni, 2012)		X				X	
(X. Zhao et al., 2012)			X	Information Noise		X	
(Boloni et al., 2013)	X				X		X
(Cansever, 2013)			X	Mutual Information	X		
(Chamkhia & Hasna, 2013)	X			Imperfect Channel State Information (CSI)	X		
(Gopalan et al., 2013)	X				X		
(Turan, Hasan Huseyin et al., 2013)	X				X		
(Turgut & Boloni, 2013)	X						X
(Zoller et al., 2013)	X						X
(Anand et al., 2014)		X					X
(Ho-Van, 2014)	X			Imperfect Channel State Information (CSI)	X		
(F. A. Khan et al., 2014)	X						X
(Moitra, 2014)	X						X
(Mu et al., 2014)			X	Kullback–Leibler divergence; Renyi divergence; Chernoff distance; f-divergence; Varational; Matusita			X
(Faied, 2015)	X					X	
(Liu et al., 2015)			X		X		
(Suri et al., 2015)		X			X		

(F. A. Khan et al., 2016)	X					X
(Lazov, 2016)		X		X		
(Lore et al., 2016)	X				X	
(Tortonesi et al., 2016)	X			X		
(Turan et al., 2016)	X					X
(Zhang et al., 2016)		X	Kullback–Leibler (KL) divergence			X
(Bölöni & Turgut, 2017)	X					X
(Lazov, 2017)		X		X		
(Ranjeeth et al., 2020)	X			X		
(Soleymani et al., 2017)		X			X	
(Al-Turjman et al., 2017)	X					X
(Bidoki et al., 2018)	X					X
(Depizzol et al., 2018)		X	Mutual Information	X		
(F. Khan et al., 2018)	X					X
(Patil et al., 2018)	X			X		
(Ayan et al., 2019)	X		Age-of-Information (AoI)		X	
(J. Chen et al., 2019)	X					X
(Omri et al., 2019)	X		Imperfect Channel State Information (CSI)	X		
(Patil et al., 2019)	X					X
(Tortonesi et al., 2019)	X			X		
(Duan et al., 2020)	X		Age of Information (AoI)	X		X
(Xia et al., 2020)	X					X
(X. Chen et al., 2008)	X		Imperfect Channel State Information (CSI)	X		
(X. Chen et al., 2008)	X					X
(Wei et al., 2021)	X		Time Discounted Value of the Distributed Information	X		

Table 4 also classifies each article regarding the ‘Performance Goal’. We considered three generic categories (‘Transmission’, ‘Information Consolidation & Accuracy’, ‘Resources Optimization’) to provide some sort of synthesis. This synthesis implied sacrificing some details – for example, in the category ‘Resources Optimization’ we included completely different resources such as energy (Patil et al., 2019), bandwidth (Anand et al., 2014), and network resources (Das et al., 2004). In the category ‘Information Consolidation & Accuracy’ not only multiple forms of information consolidation are adopted (including data fusion (Kadambe & Daniell, 2003; Bradley, 2009; Lore et al., 2016) and data sampling (Ballari et al., 2012; de Bruin et al., 2012; Soleymani et al., 2017)) but usually the article is related to sensor networks and either decision accuracy (Ballari et al., 2012) or classification accuracy (Faied, 2015) are the ultimate performance goal. Finally, in the ‘Transmission’ category beyond the traditional optimization (e.g., bandwidth or spectrum utilization) we included also those articles that optimize transmission through filtering information, for example only transmitting data with a significantly high VoI (Boloni et al. 2013).

Note that in Table 4 we added an extra column ‘Observations’ (within ‘Information Concept’ dimension) used to highlight information concepts used within each article that stand out from the expected or mainstream concepts associated with the category’s designations (‘Value’, ‘Utility’ and ‘Entropy’).

The remaining component of our analysis is the ‘Decision Framework’ dimension. In most articles, we find some form of traditional ‘Threshold-based’ decision paradigm. The remaining articles are those included in Table 5, where we summarize distinctive decision frameworks commonly used within the information economics domain that were used in the mentioned articles. The diversity of identified frameworks means that there are plenty of viable options to consider as decision framework within the telecommunication’s engineering domain.

Concerning the ‘Research Paradigm’, Table 4 includes 70 items although we have identified 78 eligible articles in our screening process. Now, we will take a closer look at those missing articles that we have not been able to classify across all defined dimensions.

Two articles present contributions to the communication process: in one case following the quantitative background of Shannon information theory (specifically using the mutual information related to channel state information) to estimate outage probability and thus reduce communication outages (Asyhari & Guillén i Fàbregas, 2012); the other suggests the combination of quantitative and qualitative perspective in communication networks so that intelligent information transmission (one capable of selecting only useful information for transmission throughout the wireless network) becomes feasible and the author introduces the concept of cognitive information value and a method of measuring such information (M. Chen et al., 2019). Two other articles are related to sensor networks and present new concepts and theory combining intrinsic Quality of Information (QoI) with VoI. In one case, the goal is establishing the building principles for a quality of information specification for sensor information (Bisdikian et al., 2009) while the other article presents a two-layer QoI/VoI definition (Bisdikian et al., 2013). The fifth article presents a framework dedicated to controlling VoI during sharing of that information through a concept of 'obfuscation'. The 'obfuscation' framework is designed to protect aspects of information's producing infrastructure from being revealed (such as its sensing capabilities and sensor locations) or simply to protect certain inferences from being revealed to the information consumer (Chakraborty et al., 2012).

Table 5
Decision frameworks different from 'Threshold-based' used in the articles included in this review.

Decision Framework	**Articles**
Decision Tree & Influence Diagram	(Ballari et al., 2012) (de Bruin et al., 2012)
Game Theory	(Das et al., 2004) (Antoniou & Pitsillides, 2007) (M. A. Khan et al., 2009) (Anand et al., 2014)
Operation's Research (LP – Linear Programming, Dynamic LP, Multi-Objective, Heuristics, etc.)	(Guha & Sarkar, 2005) (Marbukh & Sayrafian-Pour, 2008) (Turan, Hasan Huseyin et al., 2013) (Turan et al., 2016) (Duan et al., 2020) (Jacko, 2011) (Soleymani et al., 2017) (Bidoki et al., 2018) (Duan et al., 2020) (de Bruin et al., 2012) (F. A. Khan et al., 2016)
Market Mechanisms (Switch Options & Auctions)	(Szymanski et al., 2011) (Geyik et al., 2012)
Coordination	(Gopalan et al., 2013)
MDP – Markov Decision Process	(Patil et al., 2018) (Patil et al., 2018) (Boloni et al., 2013) (Patil et al., 2019)

For all these five articles, identifying the ‘Information Concept’ used (or proposed) is feasible but assigning the ‘Decision Framework’ and the ‘Performance Goal’ is either not possible or does not make sense. Additionally, that is also the case when an article reports methods to estimate the VoI in financial terms without necessarily discussing the ways this information will be used by decision makers thus making it impossible to assign the ‘Decision Framework’ and the ‘Performance Goal’.

This is the case of Turgut and Boloni (2017) where the authors describe the importance of assessing VoI and cost of privacy in the context of the IoT, possible directions for their formalization, their relationships to regulatory trends and other related areas as well as future directions of the field. The central idea is that information and privacy have a quantifiable value and IoT’s business model will have to successfully address the hurdles of that quantification in a transparent way to all participants (including individual customers and users).

Another case is the article by Aly et al. (2018) where the authors investigate the intrinsic value of information (in this case location data) in the context of strong privacy, where location information is only available from end users via purchase. A method for computing the value of spatiotemporal data from the perspective of a buyer is presented and explored for two scenarios: the delivery of targeted ads specific to a user’s home location and the estimation of traffic. Aly et al. (2018) argue that this method is important because it calculates the expected monetary value of a user’s location coordinates, even when the detailed coordinates are unknown to the buyer beforehand thus filing a gap in the pricing of location data and in the methods available to help inform decisions by buyers and sellers of location data.

Finally, a third article by Moskowitz and Russell (2018) discusses the implications of IoT with intrinsic AI environment in terms of being itself intelligent, being itself able to elicit value and how these features might enable a dominant moderator of demand characteristic (e.g., self-adapting, self-operating, and self-protecting; controlling access). The paper identifies challenges of the existing VoI theory to address this ‘IoT with intrinsic AI environment’ and suggest improvements towards a guarantee of a minimal value of the information.

Closing remarks: (i) we are surprised by such a reduced number of articles related to or aiming to estimate the value of the information in financial terms (monetary quantification) in the telecommunications industry (including in areas outside the traditional core business such as IoT, value added services on top of communication’s services); (ii) none of those articles, dedicated to VoI in general, focuses on VoI estimation in financial terms in the mobile network setting.

2.2.6 Findings

This section presents the results from the analysis of the 78 articles with the lens of our research questions, which we reproduce here:

RQ1: How has the VoI been modelled and measured in mobile network management?

RQ2: How has the VoI been used within mobile network management?

These research questions were created with a specific application in mind: the application to mobile network management activities. Moreover, although value might be expressed and experienced in multiple forms, our goal is to estimate value in the financial perspective and expressed in monetary terms. We will now discuss each of these questions taking into account the literature review that was performed.

Only approximately one third (23 out of 78) of the reviewed articles are in the 'Mobile Networks' category and thus directly related to these questions. On this list, two articles are theoretical or conceptual contributions to improve information transmission, while the vast majority (21 out of 23) are dedicated to using information as a guide to action (frequently adopting information metrics rooted in entropy that are proxies of VoI but with no correspondence to monetary value).

Thus, regarding the first question (How has the VoI been modelled and measured in mobile network management?), we conclude that the articles model different types of information and, albeit related to mobile networks, they are not related with the aim of our quest (information used to monitor and manage a mobile communications network). Examples of information modelled and measured in those articles are: information on network resources availability (Das et al., 2004), channel state information (Asyhari & Guillén i Fàbregas, 2012; Chamkhia & Hasna, 2013; Guha & Sarkar, 2005; Omri et al., 2019; X. Chen et al., 2008), Cognitive Information (M. Chen et al., 2019), entropy information on bandwidth (Lazov, 2016, 2017), information distribution process (Wei et al., 2021), information on bandwidth (Anand et al., 2014; M. A. Khan et al., 2009; Turan, Hasan Huseyin et al., 2013; Turan et al., 2016), mutual information (Depizzol et al., 2018), network configuration information (Marbukh & Sayrafian-Pour, 2008), network resources information (Parag et al., 2011; Park & van der Schaar, 2008, 2009), queue-length information (Gopalan et al., 2013), utility functions related to service QoS (Antoniou & Pitsillides, 2007).

This means that there is a literature gap underlying the results we have presented here (the absence of research dedicated to measure the VoI in the mobile network management setting and specifically the information used to manage and operate the network (neither using financial value nor using other information metrics). We have detected this gap during the initial phase of our research project and the updated literature review seems to indicate that our work is the first contribution to address this issue.

This is an interesting point since VoI estimation in financial terms is a very common application in many industries such as health care / medical, agriculture, environmental or energy (Keisler et al., 2014) but, surprisingly, the telecommunications industry is not on the list of top adopters and our data actually confirms this. In this review, as stated before, we retrieved only three articles (3 out of 78) devoted to information value quantification in financial terms while the vast majority of articles are devoted to the use of information (or information metrics) as a guide to action (70 out of 78).

As we reported, VoI applications in the telecommunications industry are frequently related to the use of information embedded in engineering algorithms and processes (information metrics are used as guide to automatic action), while in other industries the explicit quantification of potential benefits of additional information is more common (in industries like Health Care and Agriculture, for example) and information is used as part of management processes. This difference in applications (embedded versus explicit or automatic versus human processing) across different industries might have future interest as a research topic (why is the telecommunications industry not pursuing significant research on the quantification of VoI?).

Finally, on the second question (How has the VoI been used within mobile network management?) we present in Table 6 the information usage described in articles classified as 'Mobile Networks' in the 'Type of Network' criteria. We notice that information concepts are used as guide to action towards transmission or resources optimization and not a single article is dedicated to estimating VoI in financial terms.

In conclusion, concerning the topic "VoI in the mobile network management setting", we detect an absence of research related to VoI measurement in financial terms (and with the goal of use this as input to human management processes), although significant research exists dedicated to use of information value related concepts embedded within communication's engineering technologies.

Table 6

The information usage described in articles classified as 'Mobile Networks' in the 'Type of Network' criteria.

Performance Goal	**Type of Information**	**Articles**
Transmission	Channel State Information	(Guha & Sarkar, 2005) (Asyhari & Guillén i Fàbregas, 2012) (Chamkhia & Hasna, 2013) (Omri et al., 2019) (X. Chen et al., 2008)
	Cognitive Information	(M. Chen et al., 2019)
	Entropy Information on Bandwidth	(Lazov, 2016) (Lazov, 2017)
	Information Distribution Process	(Wei et al., 2021)
	Information on Bandwidth	(Turan, Hasan Huseyin et al., 2013)
	Mutual Information	(Depizzol et al., 2018)
	Network Configuration Information	(Marbukh & Sayrafian-Pour, 2008) (Parag et al., 2011)
	Queue-length Information	(Gopalan et al., 2013)
	Utility Functions Related to Service QoS	(Antoniou & Pitsillides, 2007)
	Transmission Scheduling Information	(Jacko, 2011)
	Spectrum Information	(Ranjeeth et al., 2020)
Resources	Information on Bandwidth	(M. A. Khan et al., 2009) (Anand et al., 2014), (Turan et al., 2016)
	Network Resources Information	(Das et al., 2004) (Park & van der Schaar, 2008)

3 Research Strategy and Methodology

3.1 Research Goal and Scope

Our research topic is the VoI in the mobile network management setting. The network management activities we have in mind are those aimed to operate the network, which means monitoring performance and making decisions based on the information gathered. Those decisions essentially concern choosing alternative courses of action based on the performance observed, and eventually taking action that changes the network status and operating conditions, such as correcting failures, changing configurations and settings, thereby improving the system's performance according to top management guidelines on service grade goals, for example. Thus, our primary goal is to measure the VoI used in network management activities (as described before) which requires modelling the business setting where this information is used.

Modelling is all about capturing the core elements that define a system (regardless of its nature) and thus simplification is both a matter of necessity (to reduce complexity and be able to solve the problem) and convenience (focus on the topics that really matter). In our case, the mobile communications setting is about individuals (population) using a mobile communication service (network infrastructure) provided by an entity that manages this process through infrastructure monitoring and corrective actions upon failures, thus using information to guide its actions according to business rules and management goals (service level adopted by provider). Thus, the main components of the model are (1) user population; (2) network infrastructure, and (3) information flows.

Regarding the population modelling, our option is to replicate the service usage by individual and independent users, thus assuming a preference for a representation of individual and autonomous actions over a generic statistical description of the behaviour of individuals. At the network infrastructure, we follow the same reasoning and define a representation aimed at modelling technical failures causing service denial to specific individual users. The information used in the process of network monitoring and management is modelled in the goal of reproducing a realistic organizational and technical context (KPI computation in the telecommunications industry and decisions regarding actions that aim at correcting failures) under certain constraints and business rules (e.g., service level goals and expected response times).

In summary, our preference is to adopt a simplified vision of the mobile communication service, focused on the major steps that are necessary to a successful delivery of that service in a user's perspective, with enough detail to achieve our goal of estimating information value (a management quest rather than an engineering one).

Finally, we chose to use simulation methods to perform experiments (towards VoI estimates), since it is a well-established research paradigm in the telecommunications industry and we did not find any alternatives that could be plausibly used.

3.2 Simulation Strategy

Computer simulation is the imitation of an existing system through a computational re-enactment of its behaviour according to a set of rules and constrains described in a model (than might include mathematical elements but also other types of rules). Simulating a system entails considering a limited number of key features, characteristics and behaviours within the physical or abstract system of interest, thus limiting the complexity and detail of the original system (Guizani et al., 2010) but ensuring the viability of the simulation in terms of implementation and also in terms of cost (including computation time and computation resources).

Given our general research goal (to study the VoI in the mobile network management setting through the simulation of the mobile communications setting and the information used to manage and operate the network), the simulation must consider entities that interact during the process of a mobile communications service in a certain time period. Individual users (from multiple locations) establish interactions with the network through call setup initiatives and the network responds (under certain conditions, which depend on network resources available at each time for each location) by establishing the call. Information comes to play when network failures produce service denial (along with revenue loss) and subsequently the management team uses network monitoring information to decide when to take action to ensure that the grade of service is compliant with the business goals (in the telecommunications industry. these goals may be attached to regulatory requirements).

At the first glance, the problem does have a natural representation as agents (individual users of the service) communicating with each other, thus agent-based modelling (ABM) might be a valid approach. On the other hand, each call has a natural representation as a (communication) event and thus the problem might alternatively resort to discrete event simulation (DES).

Siebers *et al.* (2010) compare the characteristics of DES and ABM in terms of the type of problem that is suited for each approach (see Table 7) and these guidelines helped us to clarify that DES is our best option. First, although each user should be treated independently (in terms of autonomous initiative to establish a call or in terms of geographical mobility), our goal is to model the system (and particularly the network as service provider enabler), not the users *per se*. The interactions between individual users (and potential influence on each other's behaviour) are not part of our modelling effort. Second, the thread of control must be centralized in the sense that network resources are the main restriction to the service delivery and individual users have no autonomy to control their own behaviour at each moment (in other words, individual users do not have initiative, do not perform individual decisions). Third, decision making is centralized in the management team responsible for network monitoring and network operation.

Table 7

Attributes that define the model type (Siebers et al., 2010)

DES Models	**ABM Models**
Process oriented (top-down modelling approach); focus is on modelling the system in detail, not the entities	Individual-based (bottom-up modelling approach); focus is on modelling the entities and interactions between them
Top-down modelling approach One thread of control (centralised)	Bottom-up modelling approach Each agent has its own thread of control (decentralised)
Passive entities, that is, something is done to the entities while they move through the system; intelligence (e.g., decision making) is modelled as part in the system	Active entities, that is, the entities themselves can take on the initiative to do something; intelligence is represented within each individual entity
Queues are a key element	No concept of queues
Flow of entities through a system; macro behaviour is modelled	No concept of flows; macro behaviour is not modelled, it emerges from the micro decisions of the individual agents
Input distributions are often based on collected/measured (objective) data	Input distributions are often based on theories or subjective data

Finally, the simulation of the mobile communications setting is compatible with the notion of a flow of entities (users) through a system in the sense that user's communication initiatives flow through the network, having a natural representation as sequences of events and, therefore, being compatible with the use of queues (since there is a flow of call attempts that are served by network resources). These sequences of communication events should be repeatable in the exact same terms with different system parameters (in our case, with and without information flowing and contributing to decision making), which is not compatible, for example, with a model based on the micro decisions of the users that entails some sort of randomness. Finally, we wish to provide input distributions based on real data collected from service providers related to the hourly service usage and also on the profile of call duration.

As far as our goals are concerned, we need to know if a certain person, at a given moment, is able to establish a call. Thus, the state of the service may only assume on/off values at the user level, and we can simplify and represent other aspects of the model following the same paradigm (for example, network usage and availability). From a time perspective, although people live in a continuous time mode, our simulation will still be close to the reality if we consider that calls only happen in discrete moments (we consider the second as the minimum time interval, which is aligned with the minimal time span used in billing by real service providers). Therefore, a discrete-state and discrete-time model where the individual entities (e.g., users and network) are represented directly and possess an internal state, and their evolution along the simulation period (the state of each entity is updated from one time step to the next) is governed by their own properties and characteristics (as characterized by Guizani *et al.* (2010)) is a good fit to address our simulation goals.

In conclusion, the DES approach is very much aligned with our problem and it is our choice, reinforced by previous examples of DES adoption to simulate VoI usage in the context of networks (Al-Turjman 2017; Hsiao et al. 2011; Khan et al. 2009) and recommendations from other complex systems such as supply chains (Viet et al., 2018), where DES is recognized as particularly appropriate to evaluate VoI in real cases, due to the ability to capture high complexity and uncertainty.

In telecommunication networks, simulation can be used to provide a safe and relatively cheap test bed to evaluate network designs (and their side effects) and network protocols, and to optimize the performance of the system, identify bottlenecks in a process and so on, thus dozens of network simulators have been developed and used for network optimization and design tasks as reported in several surveys, e.g., Kaushik and Shekhar (2014), Nayyar and Singh (2015). DES is a very popular simulation paradigm as documented in those surveys but, after preliminary evaluation of the available tools for simulation in the telecommunications, we concluded that: (i) there are dozens of simulation tools used within the context of the telecommunications industry, but (ii) they are primarily targeted at engineering problems related to communication networks, devices, communication protocols (from physical layers to applications layers) and many other engineering-related problems and (iii) we did not find evidence of any tool targeted at modelling information flows emerging from network management activities and estimating VoI in a financial perspective. Moreover, the learning curve of such tools is frequently long (Kaushik & Shekhar, 2014), and hypothetical customization of the tools (to include our requirement on information modelling) would require code development using programming languages like C, C++ or Java, with no guarantees of the viability of such an endeavour. For these reasons, we decided to develop a dedicated tool designed to model and simulate a mobile communications scenario and featured to isolate information flows and eventually compute the VoI used in mobile network management. Note that other researchers, adopting DES to explore VoI usage in network contexts, decided to develop their own simulation software, despite the abundance of simulation tools, e.g., Khan et al. (2009) and Hsiao et al. (2011).

3.3 Design Science Research Adoption and Application

Any science research initiative is hardly a linear endeavour and obstacles might require reconfigurations at the tactical level to achieve the strategic goals, thus the (re)configuration of a particular research method might be imposed by unexpected changes at the research subject and specific research objectives (Frank, 2018). In the previous sections, we have introduced our research goal and scope along with some research choices that where our starting point.

In Chapter 2 we presented the theoretical context of our research and the structured literature review that ended up showing not only a void in the literature regarding our research topic but also the absence of material instruments (models, constructs, instantiations) adequate to initiate the applied part of our research journey. We have identified the potential path of studying VoI in the mobile network management setting through the simulation of the mobile communications setting and the information used to manage and operate the network. Nevertheless, the available alternatives (network simulators) were not fitted to pursue that path and we ended up reconfiguring our research objectives to include (i) the development of a mobile communications model designed to reproduce the essentials of the mobile communications service delivery and the information produced and used to manage the service delivery and subsequently (ii) develop an instantiation of that model through a software development, thus creating a tool to perform tailored simulations according to the procedures necessary to isolate information contribution to the network management activities.

The research method should provide concepts to structure research projects as well as a process that guides the execution and documentation of a project. From a methodological perspective, Design Science Research emerged as the most appropriate path to follow, since we seek to create and evaluate artefacts expected to improve the management ability to address organizational and business challenges, as recommended by Hevner et al. (2004), in a way that some limits of the empirical research could be overcome as suggested by Le Masson et al. (2013).

The typical outputs from a design research project are constructs, models, methods and instantiations (March & Smith, 1995). In our case models are one particular concern since they impose constraints on the nature of the solutions one might expect from the applied methods and subsequent instantiations, as they are designed representations of the problem and its possible solutions (Gregor & Hevner, 2013).

Hevner et al. (2004) propose eight guidelines for design science projects which we have adopted as general guidelines for our research execution. As explained here, to produce a 'viable artefact' (guideline #1), specifically a simulation model, became instrumental to accomplish our strategic goal (studying VoI in the mobile network management setting), which is justified by the complexity of the task and the absence of available instruments fitted to the purpose. The relevance of the problem (guideline #2) is discussed throughout this document in several perspectives, including the importance of telecommunications for modern society, the importance of information and information value within this industry (and in general human activities), along with the paradox of research void related to VoI used to manage the telecommunication network activities despite the magnitude of information management investments required within this industry and, specifically, within this business function. Other guidelines such as design evaluation (guideline #3), research contributions (guideline #4), research rigour (guideline #5) and communication of research (guideline #7) were followed as much as possible, and we expect this thesis provide adequate evidence of our effort.

Regarding design as a search process (guideline #6) and the goal of creating an effective artifact, since our artifact is a discrete event simulator, we followed a process aligned with the suggestion by Law (2019), which is perfectly compatible with our general methodological guideline (design science research). The problem formulation (1) was followed by a sequence of meetings with network management practitioners, not only to collect information and data (2) used as input to the simulation (e.g., service profile usage along the week, service duration profile) but to formulate a set of model assumptions, clearly documented and validated (3) that would ensure that simplifications inherent to modelling would not compromise general validity of the model. The core technical elements of discrete event simulation were designed following the recommendations by Guizani et al. (2010) and after the programming of the model (4) the preliminary results and testing procedures were also presented and discussed with practitioners, thus allowing implementation flaws to be detected and corrected, towards attainment of a general validation (5) of the model. Finally, a structured procedure to conduct experiments to measure VoI was developed and applied to reach the research results. In Chapter 4 we explain the essential steps and deliverables from problem formulation towards model instantiation we have just described.

4 NIESIM - a Model to Simulate a Mobile Communications Setting

Our ultimate research challenge is to estimate and study the VoI used in mobile network management. In Chapter 2 we reported our efforts to find relevant contributions in the literature to this challenge ending up with the conclusion of a literature void and, thus, the absence of methods and tools to achieve this goal. In Chapter 3, we introduced the research strategy and the use of computational simulation as a means to estimate the VoI. The goal of this Chapter is to provide the context and technical background of our modelling efforts in the telecommunications domain, thus introducing the NIESIM (Network Information Economics SIMulation) as a model and, subsequently, as an instantiated artifact. Architecture and features of NIESIM are presented along with the procedures to develop experiments to estimate the VoI used in mobile network management.

The mobile communications setting, in its simplest terms, is presented as a dynamic interaction between a service provider and a population of users with certain geographical dynamics and service usage profiles. Thus, users and the network are key entities included in the modelling approach. The network infrastructure used by the service provider should be considered instrumental and not the focus of our modelling effort. Thus, the engineering aspects of the network itself are kept as simple as possible, although representative of the essence of a mobile communications setting: the ability to provide service in different geographic locations for the same user over time; infrastructure following a cellular architecture with a limited number of channels for end users at each cell (but with unlimited core capacity); and each channel modelled individually, thus allowing fault injection and fault correction at high granularity.

The users are modelled at the individual level in the sense that each one requests and uses the service independently, consuming his/her share of the service provider's physical resources during that time. In simple terms, the individual users are considered to have 'random' behaviour (within certain constraints), although the aggregate behaviour of the population does follow observed patterns both in terms of the number of calls during the daily periods and also in terms of the profile of the duration of calls (which are inputs for the modelling process).

The decision-making process is also modelled as a part of the system, considering that periodic reviews of the network's performance take place (if information is available) and that corrective actions will happen when service levels are below certain thresholds.

Although users are modelled as independent entities with many potential characteristics and behaviours, the most important aspect for our goal is the status regarding service usage (to be or not to be engaged in a call at a certain instant in time). The network resources required to establish a call and provide the service have limited states (available for service engagement, unavailable due to ongoing service, unavailable due to failure) and the same holds true for the management efforts to correct failures (maintenance team is active at site X or not). This corresponds to a discrete-state modelling approach.

To ensure that similar scenarios only differ regarding the availability of information, we define that the exact same set of basic events takes place in all scenarios (in this case, the same calls, by each user, as well as the same failure events affecting the network). This requires the adoption of a centralized events queue that ensures scenario comparability and ultimately defines our approach as discrete-event simulation as discussed in Chapter 3.

We include simulation results resembling the validation process of the NIESIM instantiation (the software developed to materialize the conceptual model described in the following sections), showing the model and simulation inputs along with exemplificative results obtained through the simulation. The validation process was iterative and included the participation of practitioners (telecommunications engineers participating in the network monitoring and network management activities of the main mobile service provider in Portugal) who reviewed simulation results similar to those presented in section 4.5 and shared important feedback towards model and instantiation improvements.

The content of this chapter has been used to prepare a conference communication entitled "NIESIM: A software for estimating the value of information in mobile networks" which has been accepted and published as conference paper (Mendes & Godinho, 2019).

4.1 Mobile Telecommunications

4.1.1 Mobile Telecommunications – Introduction to Technological Aspects

Mobile communication is essentially a service that allows users to communicate with others in different locations, using wireless personal devices. The underlying technology has evolved dramatically over the years, but some key architectural aspects have been around for some time (with adjustments and improvements). Users' wireless devices communicate through radio technology with cells within base stations, which are connected with a core backbone using optical fibre networks and other high-speed and broadband-wired infrastructures managed by the service provider (Figure 11). Management teams orchestrate all technologies and processes by means of highly sophisticated Operations Support Systems (OSS) and Business Support Systems (BSS), collecting and processing data and metrics on performance and service delivery, and searching for the best solutions for both the business and the customer.

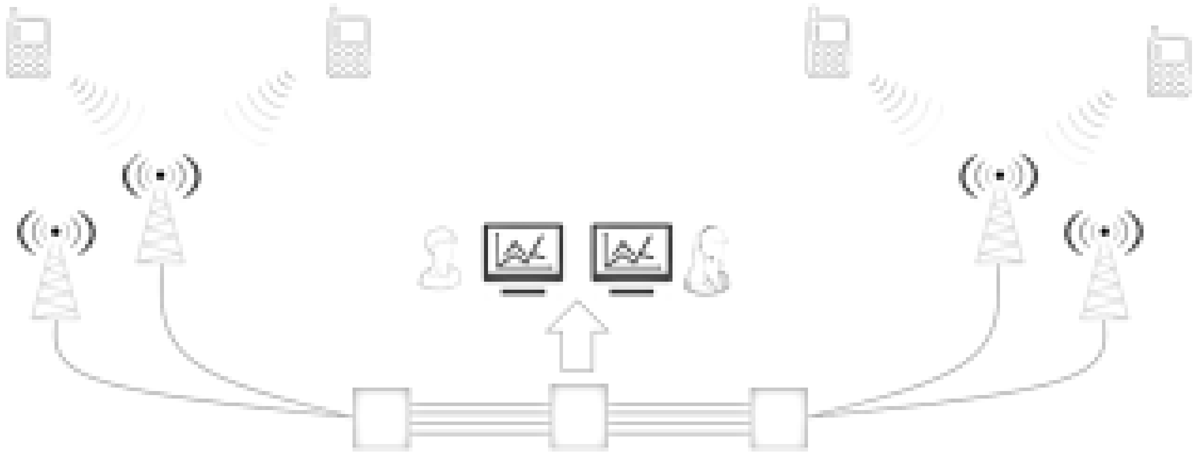

Figure 11. High level representation of the mobile communications setting: the users devices establish radio connection with the service provider infrastructure, which is connected to a backbone network infrastructure linking all the services and users. All the process is managed using information collected from the network resources (potentially including the end user device).

Mobile communication networks are also termed 'cellular networks', since the cellular concept is used in the planning and operation of the radio network infrastructure. In the cellular concept, a base station transmits and receives a radio signal and provides service for a particular coverage area called a cell[1]. Geographical areas are mapped into hexagonal cells, each one served by targeted and dedicated radio resources usually described as base station cells. Several

[1] In the United States a cell is called a sector.

cells are needed to cover a wide geographical area because transmit power is typically limited due to technical challenges (Lempiäinen, 2004). One base station may be designed and equipped to cover adjacent areas (represented by hexagon shapes), leading to 360^o coverage using three complementary radio cells, as depicted in Figure 12. In this figure, we can observe the common way this paradigm is represented within planning and management activities.

Our goal is to propose a framework for estimating value, particularly the VoI used by the management team responsible for service delivery. The value is thus related to the ability to provide the service under certain quality requirements and the VoI used in the management activities can be estimated by comparing the financial performance resulting from the service delivery under distinct contexts of information availability and information usage.

Figure 12. Cellular concept used within mobile telecommunications industry. Each cell corresponds to a geographical region where the radio network of the service provider is able to establish connection with user's devices and provide the service.

Estimating VoI is a management goal rather than an engineering one, so for the purpose of this endeavour we adopt a simplified vision of the service, focused on the major steps that are necessary for successful delivery of that service from the user's perspective. A typical mobile call between two users will require: both users to be connected to a service provider; both users being available and willing to establish the call; and resources available to establish a communication channel between those users, ensuring proper routing of the messages they will interchange. Thus, from a service perspective, the complex technological structure necessary to physically establish the call is reduced to a simple sequence of steps resulting in successful service delivery.

This simplified vision of the service matches the customer perspective, since a typical user cares about the successful service being provided but he/she does not necessarily care about the technical hurdles that make the service possible. This is also aligned with customer-centric visions, which actually propelled a shift in the telecommunications industry from being interconnection-driven towards being service-driven.

4.1.2 Measuring the Performance of the Telecommunications Service Provider

The financial performance of the system is measured in terms of value captured by the service provider, which corresponds to the total amount that is due from users, which results from charging for the communications that each user has been able to successfully establish. The cost for the user of those communications depends on the billing plan that has been agreed between the user and the service provider. In this work we will assume that the cost of each call is proportional to its duration (in seconds), with a cost per second that may change according to the user and the moment the call is started. Defining n to be the number of users, and $k(i)$ the number of calls established by user i, we can write:

$$ValueCaptured = \sum_{i}^{n} \sum_{j}^{k(i)} CD_{ij}.T_{ij}$$

CD_{ij}: Call Duration of call j from user i

T_{ij}: cost per time unit of the call j made by user i, according to the applicable service rate

To compute the value captured we have to consider:

- User initiating the successful call
- Initial moment of a successful call (which is key to identify the service rate applicable to each call)
- Call duration (in seconds)
- The service rate (per second) applicable to the specific call by that user (each user has a billing plan assigned to him)

The technical performance of the system is not as simple to define or calculate as the financial one. We wish to keep our analysis as simple as possible, although aligned with the best practices of telecommunications engineering, so we have chosen the key metrics from a service perspective (Call Setup Success Rate (CSSR), Call Drop Rate (CDR), Service Availability (SA)) along with the essential metrics of any telecommunications system, i.e., traffic metrics, such as carried traffic (Ec), offered traffic (Eo), blocked traffic (Eb) and probability of blocked traffic (Pb). These measures are explained in the subsequent paragraphs.

The Call Setup Success Rate (CSSR) metric is computed as the ratio between successful call attempts (SCA), meaning successfully initiated calls, and total call attempts (CA), within a certain time period from t_0 to t_1:

$$CSSR = \frac{\sum_{t=t0}^{t1} SCA_t}{\sum_{t=t0}^{t1} CA_t}$$

SCA_t: successful call attempts at instant *t*;

CA_t: total call attempts at instant *t*.

The Call Drop Rate (CDR) metric is defined as the ratio between the number of interrupted calls and the number of successful calls (calls that were uninterrupted until they were terminated by either the user that started the call or the one that received it), within a certain time period from t_0 to t_1:

$$CDR = \frac{\sum_{t=t0}^{t1} CD_t}{\sum_{t=t0}^{t1} SCA_t}$$

SCA_t: successful call attempts at instant *t*;

CD_t: unexpectedly interrupted calls at instant *t*.

Service Availability (SA), from a system perspective, is usually computed at Cell level and is given by

$$SA = \frac{\sum_{t=t0}^{t1} AvCell_t}{\sum_{t=t0}^{t1} TCell_t}$$

$AvCell_t$: number of cells available to provide service at instant *t*;

$TCell_t$: total number of cells (installed capacity) at instant *t*.

Now let us cover the traffic metrics, starting by introducing the Erlang, which is a unit of traffic intensity: one Erlang represents one hour of line (circuit) occupancy. From a telecommunications engineering perspective, the traffic that is instantaneously processed by a system or network (carried traffic – Ec) is as important as the traffic that does not get processed (blocked traffic – Eb) and together correspond to the offered traffic (Eo). Thus, Eo is the total traffic that ideally would be processed by the system, since it is the demand generated by the users.

Blocked traffic is a denial of service which should be very unlikely to happen if one claims high quality of service (QoS), and that is why this indicator (Pb) is a good candidate to be used in decision criteria by the network management team. Actually, in the telecommunications industry, the blocking probability (Pb) is a key input for network design and planning (note that Pb is synonymous of Grade of Service – GoS – which should not be confused with QoS). Blocking probability goals, at the planning stage, are usually stated as Pb = x% which means that during the busy hour (uninterrupted period of 60 minutes during the day when the offered traffic is maximum), x in 100 calls can be expected to meet blockage (Freeman, 2005).

To measure traffic flowing in a certain network at a certain time (expressed as a certain number of Erlangs), we have to count the exact number of calls taking place at a given point in time. If we take measures at each second, then the traffic in one hour starting at time t_0 is given by:

$$Onehourtraffic = \frac{\sum_{t=t0}^{t0+3600} AC_t}{3600}$$

AC_t: Number of Active Calls at instant *t*.

Thus, to compute the traffic flowing in a certain network, we have to gather the active calls for each of the instants of the time period, aggregated at the desired granularity, of the network (e.g., core network, base station, cell).

The offered traffic (Eo) is the incoming traffic, thus it is the sum of instantaneous traffic with blocked traffic (Eo=Ec+Eb), whereas blocked traffic (Eb) is the incoming traffic that could not get processed by the system (Eb=Eo-Ec). The probability of blocked traffic (Pb) can be computed using the following expression:

$$Pb = 1 - \frac{Ec}{Eo}$$

To compute the Pb at 'base station' level we need to consider:

- Carried traffic (Ec) at the base station
- Blocked traffic (Eb) at the base station or the ideal alternative of directly observing the offered traffic (Eo)

We are able to compute Ec easily, from successful calls that are registered by the system, but to compute Eo may not be so straightforward because a service provider does not necessarily get to know all the call attempts by users. Nevertheless, within the NIESIM model, we will assume that all unsuccessful calls are observable, so we will be able to compute Eo.

The mobile telecommunications setting is heavily contingent on the time dimension (service demand is highly correlated with human activity along the day), so performance indicators will vary accordingly throughout the day. The worst-case situation is when the system experiences service peaks and thus the 'busy hour' concept was adopted by the telecommunications industry. It is usually in the 'busy hour' that it is more relevant to measure the performance of the system. Considering the ITS[2] definition, the busy hour, in a communications system, is the sliding 60-minute period with the maximum total traffic load in a given 24-hour period[3]. Table 8 describes some concepts and examples of common usage metrics that can be computed considering the busy hour period to characterize the system.

Table 8

Examples of relevant concepts and performance indicators used by the telecommunications industry.

Concept	**Description**
Busy hour	One hour period of the day when processed traffic is the highest observed within that day
Busy hour traffic	Busy hour traffic (in Erlangs) is the traffic 'handled' within the busy hour period. It can refer to the blocked traffic (Eb), the carried traffic (Ec) or the offered traffic (Eo).
Busy hour Pb	Busy hour probability of blocked traffic (Pb) computed considering busy hour offered traffic and busy hour carried traffic.
Busy hour CSSR (Call Setup Success Rate)	Busy hour Call Setup Success Rate is the rate of calls that users have been able to setup successfully during the busy hour period.
Busy hour CDR (Call Drop Rate)	Busy hour Call Drop Rate is the rate of calls that users did not complete explicitly (service unexpectedly interrupted) during the busy hour period.
Busy hour Service Availability	Busy hour Service Availability is the percentage of available infrastructure (compared to installed infrastructure) during the busy hour period.

The telecommunications industry, adopts the busy hour paradigm to produce general performance metrics, thus obtaining insights on how the system performs in a highly demanding context where the risk of poor performance is higher. Nevertheless, in some situations we may wish to evaluate and analyse performance over a certain period of time,

[2] ITS - Institute for Telecommunication Sciences (https://www.its.bldrdoc.gov)

[3] Consulted online at https://www.its.bldrdoc.gov/fs-1037/dir-006/_0757.htm in November 20, 2021.

either to obtain cumulative values or to obtain periodic values, thus gaining insights on the dynamics of performance over time. In our research, all these options are used to maintain as much alignment to industry practices as possible.

4.2 Modelling the Mobile Communications Setting

In this section we introduce the modelling principles adopted to study the VoI in the mobile network management setting, which we have named NIESIM (Network Information Economics SIMulation).

4.2.1 General Assumptions

Modelling is all about capturing the core elements that define a system (regardless of its nature) and thus simplification is both a matter of necessity (to reduce complexity and be able to solve the problem) and convenience (focus on the topics that really matter). In our case, to grasp the value of the information used within the monitoring and operation of a mobile network system (our ultimate goal), we have to establish a common ground for modelling the service and the contexts where information can contribute to improve the service, which in our case means improving the management ability to operate the system in the most favourable conditions and, thereby, improving the system's value.

At a macro level, we could describe the mobile communications setting as one dynamic interaction between the service provider and a population of users. The customer acquisition process is out of our scope. Thus, we will skip that process and consider the following reference setting: customers trying to use the mobile communications service (requesting or accepting service from the network) and getting the corresponding bill charging for the services.

On the provider's side, network infrastructure will be modelled considering that any base station is composed by three cells, each one assembled with several radio units with a certain number of communication channels, and each cell is targeted to a certain region of the geographic area where the population is modelled (distributed along a time period). Moreover, the network management team receives information on the status and performance of the network (including service failures) through network monitoring systems and might change network configurations and settings or decide to take field actions to correct faults or improve performance. Note that OSS are computer systems used by telecommunications service providers to manage their networks, whereas BSS are the components used to manage processes aimed to run the business and the interactions with customers, for example dealing with product management, order management, revenue management and customer management. In Figure 13 we present a simplified mobile communications setting that includes activities supported by OSS type of systems (network monitoring) and also by BSS type of systems (billing, customer service).

User device monitoring is technically viable following several approaches (Boz & Manner, 2020; Jalil Piran et al., 2020). It is also suggested as part of service architectures with Quality of Experience (QoE) at the focal point in next generation technologies (5G) (Wang et al., 2017). Actually, there are even companies offering economic compensation to the users that participate in crowdsourcing data collection related to QoE/QoS performance (Hirth et al., 2015). Thus, we include the possibility of incorporating user device monitoring information in our model, providing a user perspective of the service performance and allowing for comparative evaluations of the value of different sources of information (traditional network-centred versus novel user-sourced information). This component allows the measurement of value contribution from user device-sourced information as complement to the traditional network-sourced information.

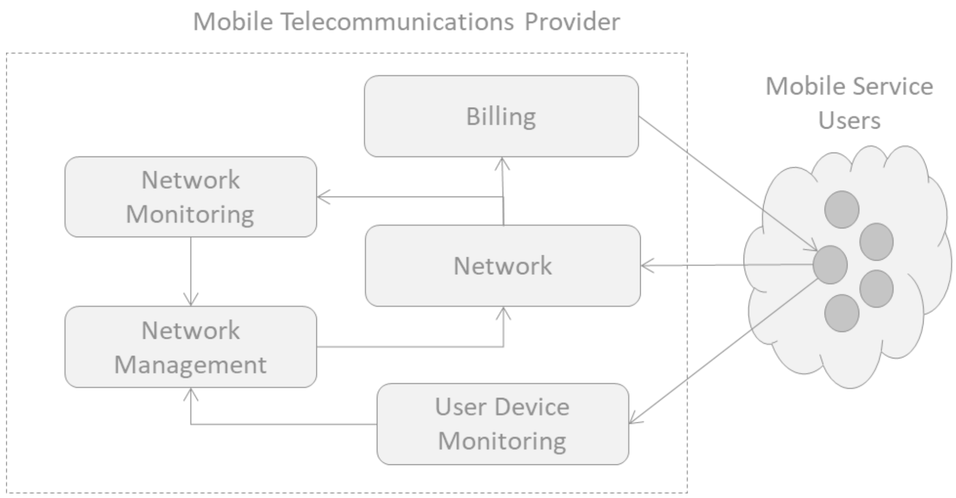

Figure 13. Simplified mobile communications setting

In order to model improvements in network management resulting from information availability and information usage, we have to understand why the service might fail, since some prerequisites are not under the control of the service provider and do not depend on information availability and information usage. Several conditions have to come together to successfully establish the service including: (a) agent availability; (b) service availability; (c) network resources availability

Agent availability refers to the users involved since a user A could be unable to establish a call with user B because the latter is already in a call with another user C, for example. Service availability is related to geographical coverage that a service provider is able to achieve - even if user A takes the initiative to set up a call with user B, he could find himself unable to even initiate the process if his geographic location is out of reach of the radio coverage of the mobile network infrastructure of the service provider (of course, the same applies to user B). Although service availability is the basic prerequisite to initiate the process, other factors related to the physical and technical requirements to deliver the service might block the processing of a certain call, namely the absence of network resources able to process that call which might result from ‘active failures’ on the network. We use the term network resources availability as an umbrella to refer to these factors.

Even if the agents (users A and B) are able to establish the call, this might not be enough to communicate since mobile communication uses complex signal transformations that could be affected by technical problems resulting in poor quality communication channels and thus unfeasible communication between people. Nevertheless, our effort to model the mobile communication service will not include quality problems of the communication channel itself. This simplification conveys significant limitations in the ability to model QoS-related parameters within our model, thus only some aspects of network performance that contribute towards QoS will be considered, such as service availability (the ability to establish the service).

We also assume some simplifications on the way failures take place and impact performance, and on the process of correcting failures. Failures are modelled as events that happen at a certain daily rate (the rate is calculated over the complete resources of the communication channels within the system) and at random timing. Network performance indicators are computed at global level and also at base station level but decisions using network performance indicators are based only on the base station level information. Thus, when it comes to fault correction actions, we assume that (i) any action will take place at base station level and that (ii) all active failures in a given base station will be corrected by one field action. Other aspects that are modelled in a simplified way are the moment of decision, the instant when field action takes place and the elapsed time period until resources are back in action. On the ‘moment of decision’ we assume this is taking place at an hourly basis, along with management KPI’s computation (although treated as separate and independent events). The scheduling of the field action is assumed to take place a certain fixed period after the decision if field teams are available (otherwise a rescheduling event is activated). Finally, we assume that a field team will always correct the failure within a certain fixed time period.

In conclusion, at a macro level the NIESIM model is a mobile communications setting described as one dynamic interaction between the service provider and a population of users, as depicted in Figure 13. Users use the mobile communications service (requesting or accepting service from the network) and get the corresponding bill which then charges for the services. On the provider's side, the network management team receives information on the status and performance of the network either from user's device monitoring agents or through network monitoring systems. The management team performs periodic reviews of performance metrics and applies decision rules that might translate into actions on the network, including changes in the network's characteristics and actions towards fault correction, thus improving the performance of the system The billing step, although important for financial performance metrics, does not play any role in the dynamics of the simulation. Therefore, it is handled as a post processing analysis.

The more relevant design principles of the NIESIM model are the following:

a) The goal is to model the service usage and the role of information flows that significantly influence service usage. Thus, technical complexities of the telecommunications systems are parsimoniously modelled and only to the extent that such modelling improves the understanding of service usage (and service failure) and the information flows used to manage the service delivery.

b) The usage of the mobile communications service is modelled at individual level, meaning that users have individual and independent characteristics and behaviours.

c) Mobile communication service failures are modelled at an infrastructure level, based on the representation of minimal relevant component (the radio unit, assembled to form a cell included in a base station). Other components of the network are assumed to have infinite capacity and work flawlessly at all instants.

d) Information flows are modelled to reproduce organizational and technical contexts along with constraints and business rules.

e) Discrete time is adopted as a valid approximation to the mobile communications setting, thus using a predefined and fixed minimum period of time of one second between events.

f) The duration of each call is defined by a random process aligned with a statistical distribution or with a distribution provided as input (e.g., one provided by a real service provider).

g) The frequency of service usage by the population is reproduced by the random distribution of call events among users, and thus a pattern of service usage should be provided as input covering one week on hourly basis.

h) The budget of the user will be ignored.

i) In order to assign the geographical position of a user at each period of the day, we assume that people will mostly be at their area of work or at their residence during the remaining periods of the day. Location changes are expected, taking into account the existence of those two reference locations for each user, and also assuming some variability of location of each user.

j) The population has N groups of people and each member of each group has a certain probability to be in the area of work during the working period, and in the area of residence during the period of rest. If a person is not in that preferential location, the model assumes they will be at an adjoining region, with an identical probability of being in each neighbouring region.

k) Network infrastructure will be modelled considering that any base station is composed of three cells, each cell assembled containing several radio units with a certain number of communication channels. Thus, each base station will have a limited capacity (i.e., communication channels) to fulfil service requests.

l) At each period of the day, each user is assumed to stay within the same area. In practical terms this means the base station serving the user is the same during a certain time period.

m) Failure events are modelled as following a predefined daily rate (expressed as a percentage that refers to the total number of network channels). The time instant when those events take place is established within each day using a random variable.

n) A failure will impact one individual radio element only (which means that all channels within this radio element are affected).

o) Network performance indicators used as input to the decision process, such as CSSR and Pb, are computed at base station level and decision by management is based on that information.

p) The material impact of the decisions is to act on the system at base station level, correcting all the active faults at that base station and leading to an increase on the available communication channels. These actions are executed by teams dedicated to maintenance on site (at a specific and well-known base station).

q) A field team will always correct the failure within a certain fixed time period.

4.2.2 Model of User Behaviour

Here we will establish the formal grounds for the approach to model user behaviour within the mobile communication setting, which have been translated into a computational implementation.

First, we discuss the mobility and geographical behaviour of users and afterwards we present the consumer behaviour and expected usage of the telecommunications service. From a formal standpoint, the population of users is formed by groups of users with common characteristics which might be interpreted as distinct segments of that global population.

$\varphi \in \{1, 2, 3, \ldots, G\}$: distinct groups forming the global population.

Customer segmentation is a major concern within the telecommunications industry, thus many characteristics might be considered in any population model. However, to keep focus and simplicity, we will incorporate only a few dimensions of user profile and characterisation:

- Mobility and geographical behaviour;
- Consumer behaviour regarding mobile communications service.

Either of the previous dimensions is highly time dependent since people usually have regular routines and habits such as going to work, having some free time, going home and staying with family or friends and so on, which leads us to define relevant time periods when characteristics of the behaviour might be assumed as being stable.

$\tau \in \{1, 2, 3, ..., T\}$: relevant time periods for modelling purposes.

We assume that people mobility is restricted to a certain region. For modelling purposes, this region is mapped as a matrix of regular areas (a hexagon shape is assumed) with a total of L distinct zones.

$\lambda \in \{1, 2, 3, ..., L\}$: distinct zones that form the region where users move.

Users belonging to the same group are assumed to share characteristics and, in our case, we assume they share mobility patterns. This means that, for all the users of the same group, the probability of being in a given area λ at period τ is the same.

$$\begin{cases} \beta_{\varphi\tau\lambda} \in [0,1]\text{: Probability of a user from group } \varphi \text{ being located in zone } \lambda \text{ at time period } \tau\text{, with:} \\ \forall\, \varphi, \tau : \sum_{\lambda=1}^{L} \beta_{\varphi\tau\lambda} = 1 \end{cases}$$

From a mobile telecommunications service perspective, mobility and geographical behaviour of the users is a fundamental input for any modelling effort and we have just introduced the elements needed to establish the location of any user at any instant of time: user location at instant t (which belongs to a certain time period τ) is stochastic, with a probability distribution determined by the time period and by the group the user belongs to (these probability distributions are inputs to the modelling process).

Thus, as an input to the simulation process, we must provide a population description in terms of groups and the corresponding properties, such as $\beta_{\varphi\tau\lambda}$, which will ultimately determine the location of users over time.

Now let us discuss the consumer behaviour and the expected usage of the telecommunications service. Besides the location of the users, the other key aspect of any mobile telecommunications service operation is the expected usage of the service, which is a matter of consumer behaviour. We recognize that individual behaviour might translate into significant variability of service usage among users, thus additional group characterization is needed to segment population according to usage patterns. The very straightforward metric we use to capture this is the number of calls that a regular user from group φ is expected to set up in the period of one day or, in more general and formal terms, the corresponding average value per each group of users.

Regardless of individual behaviour and of how that behaviour is translated into different group characterizations, there are collective patterns of service usage observed in real life that must be considered for a good modelling of a telecommunications setting. These patterns were obtained from a real-life service provider and used as inputs, and they consist of the number of calls per period τ that are expected from the global population of users we are modelling. Such patterns are particularly relevant for network planning and operation, since peaks of service usage may compromise user experience if the network is not properly designed to process all offered traffic.

Thus, at each instant t, a user from group φ either starts a call (1) or does not start a call (0) and, at an aggregated level, we know the average number of calls per day of a generic user from group φ as well as the total number of expected calls of the global population in period τ. Thus, we assign calls to users using a stochastic procedure, considering some constraints. Letting *i* represent a user and *t* a time moment:

$$\begin{cases} UserCallSetup_{\,i}(t) \in \{0,1\}; \\ \sum_{t\in\tau,i} UserCallSetup_i(t) = \alpha_\tau, \\ \frac{\sum_{i\in\varphi} UserCallSetup_{\,i}(t)}{N_\varphi} = \mu_\varphi \end{cases}$$

with:

μ_φ: the average number of calls per day from a generic user from group φ;

N_φ : number of users in group φ;

α_τ: the average number of calls from all the population of users in period τ.

By combining both inputs related to consumer behaviour with respect to telecommunications service usage (population level and group level), we are able to assign each user a specific behaviour that is consistent with the usage pattern of both the global population and the group to which the user belongs, thus attaining the goal of modelling the population of mobile telecommunications users at an individual level.

We acknowledge some limitations of this modelling approach since it artificially reduces the service usage daily variability. We believe that this is a minor limitation and there are ways to introduce variability in future improvements of the model. More important, the number of calls is not the only factor impacting the system performance (and its variability) and factors like call duration are also very important. Finally, daily variability of service usage is expected to have a regular statistical behaviour, thus the individual impact (positive and negative) is expected to be averaged out in the long term and should have a reduced impact on the VoI measured.

4.2.3 Information Flow Modelling and Decision-Making

Although common sense frequently narrows decision-making to alternative selection, the decision process actually comprises of more steps. Marakas (2003) suggests that the decision process includes five components: ‘Stimulus’, ‘Decision Maker’, ‘Problem Definition’, ‘Alternative Selection’ and ‘Implementation’. The ‘Stimulus’ is by nature an externality or force that causes the decision maker to acknowledge that a problem exists and a decision is required. A problem is the perception that a difference exists between the current state of affairs and the desired state, which is fairly simple to understand, but the ‘Problem Definition’, is actually a complex step since the way you frame the problem will impact the solution in the similar way that the way a question if framed might influence the answer (to give a glimpse of what is at stake). Marakas presents ‘Problem Definition’ with a broader perspective, including not only the problem statement but also the scope and the structure (described in terms of choices, uncertainties and objectives) as key elements of this step. The ‘Alternative Selection’ is the step where an effective solution is chosen, usually requiring high cognitive effort by humans involved in the process and thus is where decision support systems are most useful. Finally the ‘Implementation’ step is when action takes place, transformation and change is required to solve the problem (which can be challenging for the decision makers and leaders involved). The ‘Decision Maker’ component, as characterized by Marakas, actually refers to the organization and methodology adopted to address the decision challenge associated with each acknowledged problem. Depending on the nature of the problem, organizations might use individual decision-making processes (human or machine based) or one form of multiple decision makers with certain negotiation consensus involved (team level, group decision structure, organizational level).

The framework suggested by Marakas is a fairly comprehensive one but needs some adjustments and adaptation to be helpful in our own decision setting. First, it is our understanding that any decision process is a combination of a flow of activities that take place in an organizational context. Therefore, the decision maker and the decision structure will inevitably influence every step of the decision process. Hence, we propose a clear distinction between the process and the context where it takes place, at least in operational decision settings - which is a fair description of the network management activities we have in mind - specifically those activities aimed at operating the network, which means monitoring performance and making decisions based on the information gathered.

This setting is highly structured both in terms of the ‘Problem Definition’ step (as discussed by Marakas) but also in terms of processes and workflows in place, decision participants and even in terms of the information available as ‘Stimulus’. In this setting, beyond a narrow understand of ‘Stimulus’ (essentially network performance KPIs that are symptoms of problems, not necessarily with obvious root causes attached) we believe it is useful to reframe the following step as problem acknowledgement or 'Problem Identification' (our choice given that the each possible problem is well framed specially the nature, the scope and the structure but you still have to identify specific problems with specific challenges requiring actions to re-establish the desired operational state). Indeed certainly the following steps 'Alternative Selection' and 'Implementation' are also highly bounded by technical and organizational constrains and yet the essence of each step is applicable to the setting (meaning multiple alternatives exist to address each problem – with exceptions of course – and implementation is not just a matter of blind execution but entails significant margin for improvement, change and innovation). In conclusion, in Figure 14 we present our vision of the operational decision-making process, adapted from Marakas both in simplified and narrow terms. The steps of the decision process we consider in our analysis are: 'Stimulus', 'Problem Identification', 'Alternative Selection' and, finally, 'Implementation'.

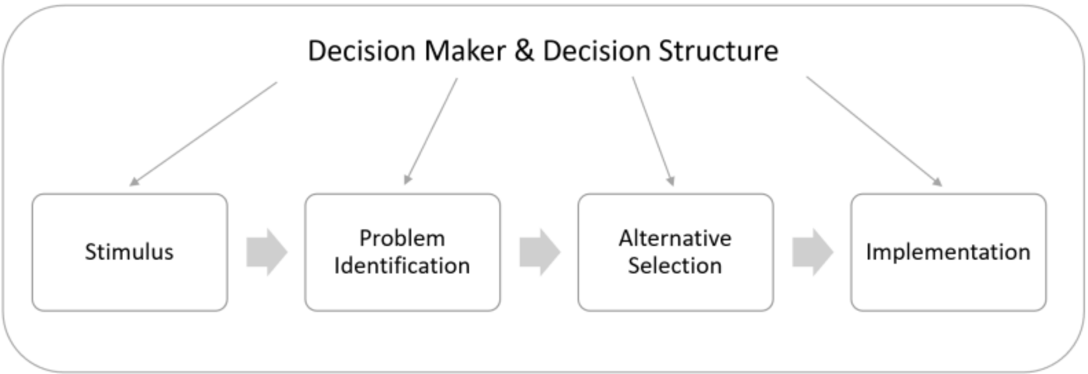

Figure 14. Operational Decision-Making Process (adapted from Marakas (2003)).

In the context of network management activities, assuming an operational setting, problems often manifest themselves through network performance downgrade symptoms and decision makers (usually a team) have to identify the problem before they look into the alternative courses of action. If the true nature of the problem is not uncovered during this step, the outcome of the decision process is doomed to failure. The 'Alternative Selection' step is presumed to consider only feasible solutions to the problem at hand and its aim is to identify and choose the one that best suits the goal of achieving an optimal outcome (considering one or multiple criteria including technical, economic and organizational perspectives). Finally, the 'Implementation' step will ensure that action is taken to solve the problem (regardless of any hurdles, obstacles and negotiations that might be required).

Our analytic efforts to understand and break down the decision-making process, in the network management setting, lead us to consider two assumptions based both on practitioners' inputs and on the decision process modelling adopted in NIESIM. The assumptions are as follows: (i) problem definition and problem identification criteria are clearly established with no uncertainty regarding either the performance indicators that are used as inputs, (ii) nor the business rules applicable in the interpretation of those inputs as signalling a problem. Under those assumptions, the 'Problem Identification' step becomes the pivotal moment in the process. Since this step is quite clear in the context of network monitoring (as it is in the case of information from user device monitoring), it does not offer significant challenges in terms of information quality (we assume this step to be neutral in terms of information integrity) and is actually a turning point in terms of the nature and complexity of the information required and managed in the decision-making process.

The network management setting is complex and some simplifications are useful to model and simulate the impact of information used in decision-making. Regarding the information gathered internally by network monitoring, we adopt the simplest decision model possible: internal information, collected from network infrastructure, is processed to compute the network performance KPIs at base station level and, if a threshold is surpassed, it is considered that the base station is malfunctioning and an action is taken to correct the failure, thus recovering full service again (Figure 15).

Note that corrective measures are taken at base station level and the model does assume that a successful corrective action in a certain base station corresponds to the correction of all active failures, thus restoring full operational performance in terms of communication channels. In the experiments conducted to generate the results presented in this document, we used the call blocking probability (Pb) as the key indicator of network performance, which in our case represents the stimulus to the decision-making process.

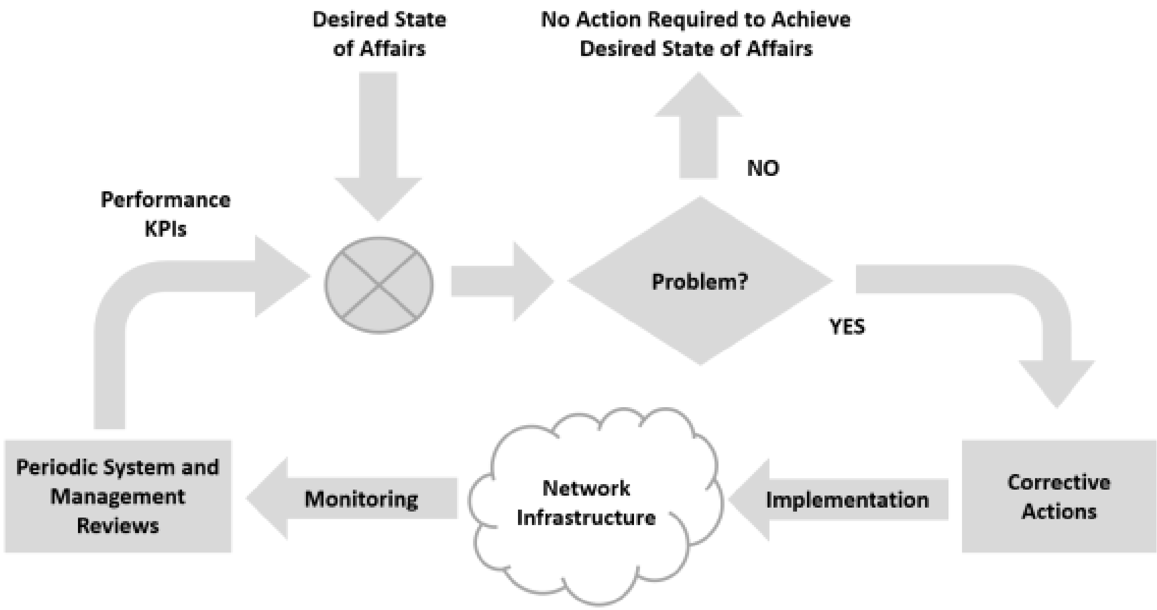

Figure 15. Simplified decision model for mobile communications network management activities using monitoring information from the network infrastructure.

Under a perfect information context, the key performance indicators (KPIs) used as stimulus to the decision process show all attributes of quality that ensure that the decision process outcome is absolutely correct and the material effects of the actions are also effective. The source of information used in the decision process is presumed reliable (and accurate) and this simple model also takes for granted that there is perfect information within the alternative selection of corrective actions and in the decision implementation process, which means ability to perform flawless corrective actions at the base station by the field teams. In this description some major simplifications are adopted, namely that the nature of the problem is evident, considering the input information, but also that the action is straightforward, as if only one unique and effective action would solve the problem. From an engineering perspective, this is hardly the case in the mobile telecommunications network management setting, but from a service perspective this simplification is perfectly acceptable and useful for our modelling and information value estimation.

Now let us take a look at the information flow coming from the user's device monitoring branch which provides a user perspective of the service delivery to the management team (and a different stimulus to the decision process), presented in Figure 16. So, from a modelling perspective, user experience is captured and kept as historic data (according to management options) and subsequently used to produce KPIs that will be the stimulus in a decision process.

Performance is evaluated against a desired state of affairs and eventually corrective actions are implemented in the network if a problem is detected.

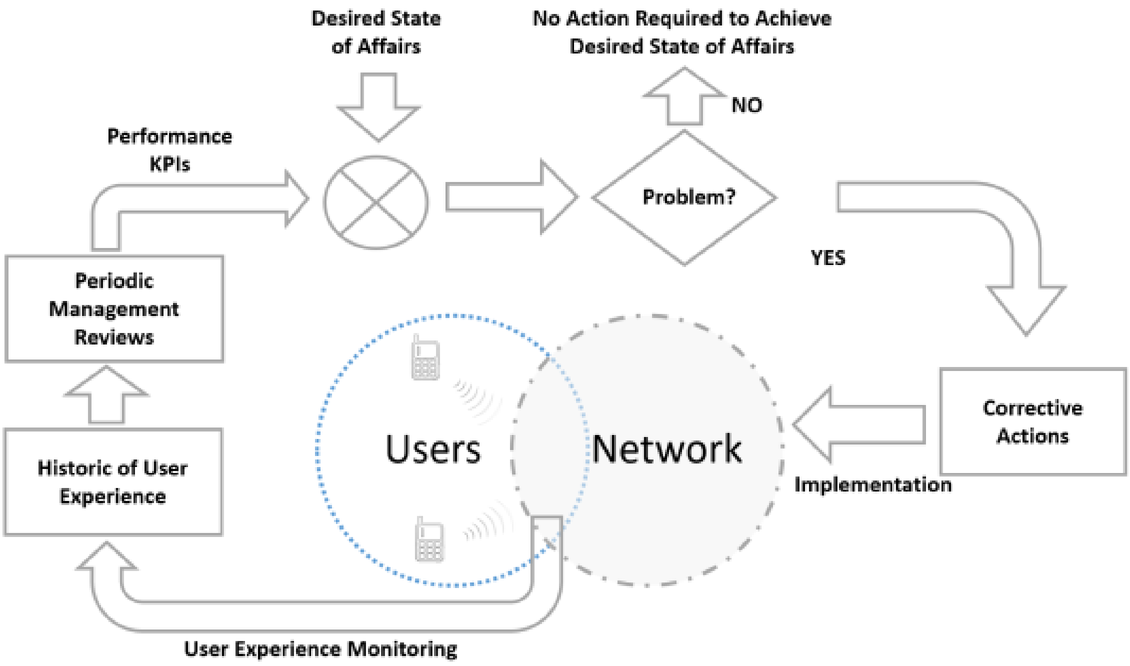

Figure 16. Simplified decision model for mobile communications network management activities using information coming from the users' device monitoring branch.

Notice that a simplified model as ours provides simple user-centric metrics. For the purpose of our experiments, we adopted the call setup success rate computed from a user perspective as KPI. To compute this individual user's CSSR we have to consider a certain time span of at least a few days (historic data) to resemble a human historical perspective on service events and to augment the robustness of the KPI. This time period is completely different from the one used to compute network KPIs (which in our model is assumed to be on hourly basis) and may be adjusted for each experiment.

This user perspective of the service delivery is a challenging stimulus for the management team because you have to balance problem relevance at the individual user level with the problem relevance at the system level (the network), thus requiring a problem identification and decision criteria different from the ones used with the network monitoring information. Isolated episodes of failure can be misleading in terms of nature of network problems and individual experience provides limited perspective on the magnitude of network problems. Therefore, a group of users must be sampled from the population of users and used to draw conclusions from aggregated experiences to provide evidence supporting problem identification and decision making by the management team. Since the cost of collecting and manage individual data is also significant, the method of sampling and the quantity of users to include in the sample are relevant options to be made by the management team, along with KPIs at user level and the threshold associated with identifying that a problem exists at individual level. In other words, management must decide how many users experiencing problem X should be enough to signal it as a service problem requiring management action as opposed to unfortunate and isolated bad user experiences. In the event of this service problem, there is also the challenge of identifying network resources that have high probability of being the root cause of the problem and thus require corrective action.

In terms of our model, the previous discussion of the operational decision-making process (Figure 14) and the differences between the workflow based on network monitoring information (Figure 15) versus information coming from user's device monitoring (Figure 16) are the following:

a) The 'Stimulus' step, corresponds to the effort of information gathering (which in our case is essentially KPI computing) to be provided as input to the 'Problem Identification' step. As explained before, this requires different approaches depending on the source and nature of the information (network monitoring information versus information coming from user's device monitoring). Thus, the 'Stimulus' step is modelled using two distinct types of events;

b) The 'Problem Identification' step, corresponds in our model to the management team periodically reviewing the available information (KPIs) and deciding if action is required or not given the business rules and business guidelines in place. These are modelled as periodic events taking place during the work period of the week;

c) As explained before we assume many simplifications in our modelling effort, particularly in the communications engineering layer which imposes limitations in terms of hypothetical simulation of multiple alternatives to solve problems and consequently 'Alternative Selection' step is not part of our model;

d) The 'Implementation' step, is explicitly modelled and corresponds to field interventions with the goal of execute corrective actions at the network infrastructure, following the decisions from the management reviews events.

4.2.4 Imperfect Information both in Ex ante and Ex post ‘Problem Identification’

In an ideal world, information would be perfect, but we all know that in real operational settings, multiple aspects of information *ex post* and *ex ante* the identification of the problem might be compromised for several reasons. For example, the incoming information from network monitoring (*ex ante* the detection of a failure), which is processed and combined to produce KPIs used as decision inputs, might suffer from accuracy problems due to inaccurate measurements, computing errors or difficulties in merging and matching raw data from different technology providers, just to mention a few possibilities.

In our model, the *ex ante* imperfect information is introduced through measurement error rate, assigned to each base station (stable during the simulation period) and with impact on the corresponding KPIs. Imperfect information, when present in this step (‘Stimulus’), will produce false negative and false positives in terms of ‘Problem Identification’ outcomes and, ultimately, leads to useless actions (because they intend to correct one illusional failure) and absent actions (because there is a real failure that requires action). Figure 17 integrates the *ex ante* imperfect information within the operational decision-making process you have presented in previous section.

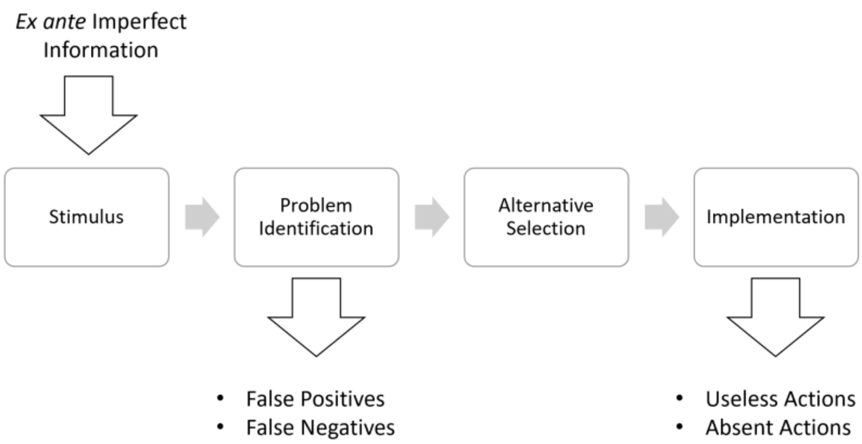

Figure 17. Ex ante ‘Problem Identification’ imperfect information in the Operational Decision-Making Process.

On the other hand, the *ex post* ‘Problem Identification’ information might be compromised for completely different reasons, since the same symptom (KPI value) usually results from completely different root causes (thus needs completely different actions to solve the problem), not to mention that several alternatives may be frequently considered or combined to address the problem. One of the real challenges that the network management team faces every day is to grasp the nature of the problem, given the signals they receive from the network through monitoring activities, and thus identify alternative actions that presumably will solve the root cause of the problem and finally select the best alternative. In other words, *ex post* information includes answers to questions, such as "What alternative actions are available to solve the problem?" or "Where and how to implement such actions?", which might require complex efforts in terms of 'information acquisition'. This is an engineering goal that we do not model. Actually, as far as our modelling efforts are concerned, *ex post* information corresponds to the information used in the 'Alternative Selection' and the 'Implementation' steps (Figure 18) and it is considered perfect if the problem is always solved. However, it is considered imperfect if the problem still prevails after the action is taken.

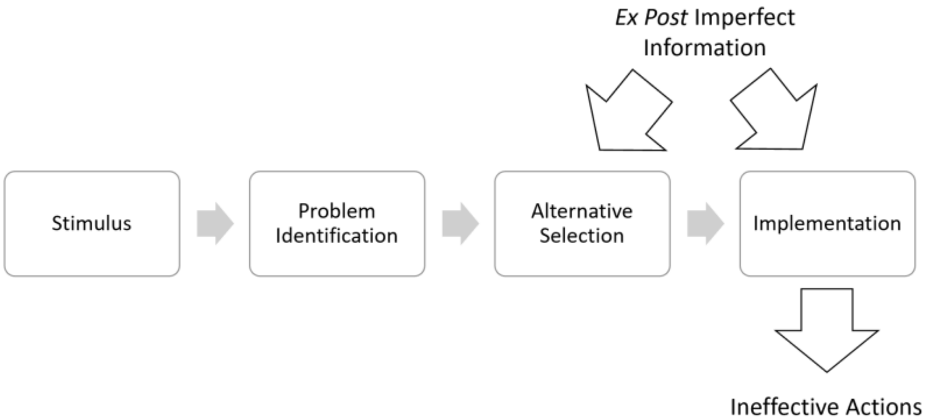

Figure 18. Ex post 'Problem Identification' imperfect information in the Operational Decision-Making Process.

The importance of perfect implementation is recognized among VoI practitioners through the definition and practical usage of concepts like expected value of perfect implementation, which is the difference between the expected value of a decision that is implemented perfectly and the expected value of a decision with suboptimal implementation (Tuffaha et al., 2014). The concept itself is not used in our experiments, but has been instrumental and useful to uncover the importance of the *ex post* information imperfection in the network management setting.

Our research is directed at estimating VoI and for this purpose it is enough and convenient to consider just the outcomes of information usage and not the nature of the information itself. Consequently, knowing the outcomes of *ex post* information usage allows us to infer the uncertainty attached to it (information will translate into the problem solution with a certain probability) and we thus have a practical way to grasp its value.

At simulation level, *ex post* imperfect information was implemented as an implementation error rate, leading to unsuccessful failure solving. This rate is stable during the simulation period and applied, in general, to all corrective actions, part of which became ineffective actions.

Thus, the imperfect information, when present in the stimulus, will produce false negatives and false positives in terms of outcomes of the 'Problem Identification' step (with corresponding useless and absent actions). Imperfect information, when present in the 'Alternative Selection' and/or in the 'Implementation' step, will decrease the effectiveness of the corrective actions.

4.2.5 The VoI Used to Manage the Service

As we have stated before, as far as this work is concerned, the source of value is a possible action that an agent might undertake and we follow the valuation principle suggested by Birchler and Butler (2007:32), applicable to the context of information as a guide to action: "VoI is the increase in utility an individual expects from receiving the information and from optimally reacting to it". In the case of this work, we consider financial value instead of utility. The pay-offs from alternative courses of action, measured by the financial value, are the underlying criteria for establishing the VoI (computed comparing the system's performance with and without a certain piece of information).

The simplified mobile communications setting (see Figure 13) might be interpreted as a control situation in which the system under control is the network infrastructure, the controller is the network management team and the system output is the communications service. The management team's goal is to operate the network assuring that a certain grade of service is provided, which demands constant information gathering and information processing (computation of performance indicators) to evaluate performance and decide if actions to 'adjust' the system (correct active failures at the network) are needed. The effectiveness of those actions relies on qualified information that ultimately will guide field teams on where (specific hardware location) and what should be done.

Following a service perspective, a typical mobile call between two users will require: both users to be connected to a service provider; both users being available and willing to establish the call; and that there are available resources to establish a communication channel between those users, ensuring proper routing of the messages they will interchange (Figure 19). In other words, from a service perspective, the complex technological infrastructure necessary to physically establish the call is reduced to simple sequence of steps resulting in a successful (or not) service delivery.

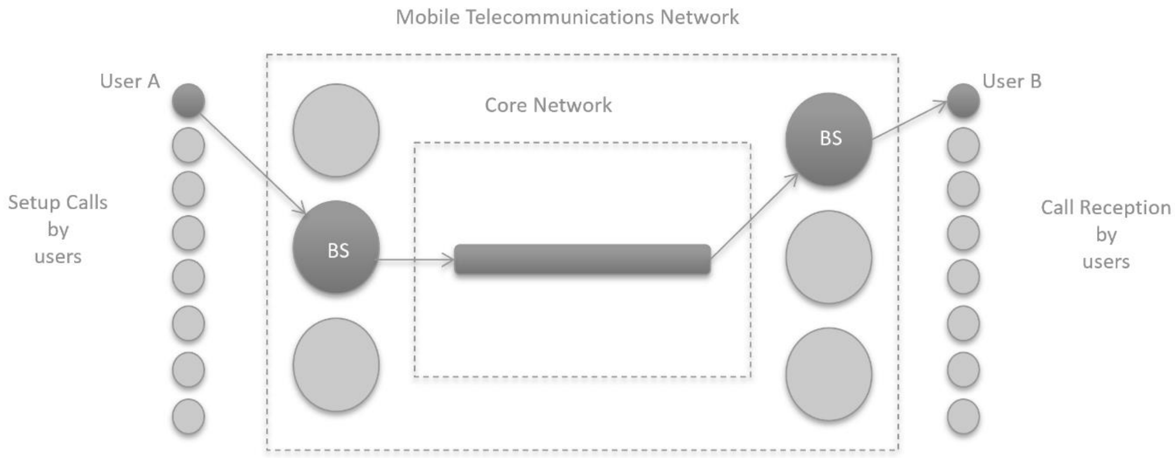

Figure 19. Mobile call routing through the simplified mobile network architecture.

We are able to estimate the value of this system (regardless of our simplified description) just by measuring the ability to successfully deliver the service, assuming that each successfully established call grants a monetary compensation for the service delivery, charged to the user initiating the call, according to certain billing rules. The value of the network is thus related to the ability to provide the service under certain quality requirements and the VoI used in the management activities can be estimated by comparing the financial performance of the system under distinct contexts of information availability and information usage. If the service provider aims to maximize profit, the network management team must achieve a certain level of QoS (enough to retain users), at the minimum cost. Since network monitoring and supervision activities are information intensive, an information value driver to decision making is the natural path towards information selection, gathering and processing to achieve those optimization goals (along with other efforts to minimize costs and ensure QoS).

We narrow our analysis to the VoI used in the mobile network management process, which is necessary to monitor the network performance and identify network failures resulting in service denial or service interruption. This allows actions to be taken towards the correction of those failures, thus restoring service availability. We assume that generic failures take place in stochastic random terms and impact the network by diminishing the operating communication channels available to end users. The management team's ability to take action and correct those failures depends on the information available both on the performance and on the location and nature of the failure. If this information is perfect and complete, the corrective actions take place flawlessly. Since information itself is not always perfect and complete in real scenarios we discuss the Imperfect Information within our context in the previous subsection.

When information is available to the management team, at each decision moment and depending on the observed network performance, corrective maintenance should take place at those areas with low performance, letting the system operate 'as is' in other areas (no action takes place). The financial performance is then measured against one equivalent context where the management team operates under 'No Information', to estimate the value of that information. Thus, the VoI used to monitor the network is the net financial improvement obtained by the service provider when information is available to the management team.

In order to isolate and measure the contribution of information (either perfect or imperfect), we must establish a 'No information' context, so that we can obtain the VoI by comparing the financial performance with and without information. Thus, each scenario is processed considering two alternative contexts regarding information availability: (i) information on the network status and performance is available and used by the management team; and (ii) no information is available to the management team.

From a modelling perspective, we assume that (i) generic network failures take place in stochastic random terms that impact the network by reducing the communication channels available to end users and (ii) the service provider is able to restore full operational performance at base station level, once the problem is detected (when information is available).

So, one strict interpretation of a 'No Information' context would be to consider absolute absence of information about the network, which would lead us to a dead-end in the sense that after a brief period of time, the network would become unable to deliver any service (we have actually tested this option during the validation steps of NIESIM and we included these results in section 4.5). This is completely unrealistic and does not qualify as a sustainable operational setting for a real service provider and thus nor does it qualify as a 'No Information' context to the purpose of reaching realistic estimates to VoI.

The challenge is then to choose a reasonable context representing one hypothetical business setting and management team operating under 'No Information'. Since any system under stochastic failures will eventually collapse, such a system must be provided with some sort of maintenance and corrective actions as to assure minimal operability even in the absence of information about its performance and operational status. On the other hand, there is no point in considering absence of information as equivalent to absence of maintenance and corrective actions.

Actually, the availability of information should translate into qualitative difference between two otherwise equivalent courses of action, regarding maintenance and corrective actions at the network level. Thus the ‘No Information’ context should include a plan for maintenance and corrective actions, assuring an average number of actions identical to the context with available information, for a certain period of time. This way the cost of each maintenance action is irrelevant (because it is identical for both contexts) and the value of the information is therefore estimated by comparing the financial performance of these contexts, which differ only in the information available to each one.

The simplest and most coherent maintenance plan we considered and which proved sustainable through simulation results (able to assure long-term operability under the incoming failures), is the one which assumes a sequential and periodic maintenance plan. In such a plan, each base station is sequentially inspected and subject to maintenance procedures at the same pace (number of weekly actions) and with the same idealized outcomes (solving any existing failure within the base station) as the corresponding ‘information context’.

We recognize that this is a very high-level and simplified description for this industry, yet it entails the essence of the problem we propose to tackle: estimating the value of information used to correct failures resulting in service denial. Moreover, the assumption of ability to inspect and solve problems by field teams performing both the corrective action and the maintenance activities is, of course, challenged by the complexity of the communication network systems and might be considered unrealistic (meaning impracticable) for the majority of situations. We argue that it is applicable in some situations (e.g., power supply, hardware and infrastructure related to radio stations), thus being valid for the purpose of our information value estimation endeavour. Moreover, if we accept the criticism that the maintenance plan is impracticable, we would come to the conclusion that the performance of the system under ‘No Information’ is positively overestimated by us, which means that the estimates of the VoI are conservative (underestimated).

Finally, one might argue that under *ex post* imperfect information, specifically in the implementation step, the assumptions of the ‘No Information’ context leads to inconsistency in the estimate of VoI, because in one case imperfect information is used leading to unsuccessful corrective actions while, in the ‘No Information’ case, maintenance teams would correct existing failures, demonstrating full availability to solve issues. This objection is understandable, but refutable. Let us assume a ‘No Information’ context and thus a certain field team, performing the maintenance plan, does visit site A and identifies a certain problem and eventually corrects the issue. Now let us consider the operation under imperfect information and the same team is sent to solve a problem that was identified. Assuming the problem exists at site A, if the correct location is provided to this team the problem will be equally identified and eventually solved. Now, if the incorrect location is provided (thus imperfect information), the team ends up going to site B and the original problem will not be solved.

In conclusion, we consider this 'No Information' context definition perfectly adequate for our goal, since it enables us to provide conservative estimate of the VoI even if imperfect information is used. All the experiments presented in Chapter 5 adopt this 'No Information' definition we have just described.

4.3 NIESIM Software Instantiation

4.3.1 Software Architecture as DES

In Chapter 3 we have explained our adoption of the DES paradigm and in the previous section we presented the modelling principles adopted to describe the mobile communications setting. In this section, we present the software architecture of NIESIM instantiation. The entities that we need to consider in the simulation model are:

a) Users (representing a population);

b) Telecommunications Network (detailed at the level of the communications channel);

c) Management (responsible for deciding and taking action towards the telecommunications network).

The status of these entities evolves over time, through interactions with each other, by means of events such as call setup, network registration, feedback messages and fault correction, to name a few. These interactions are represented in Figure 20. Some entities are influenced by external events that may be part of a scenario definition, like random call attempts by users, random network failures that happen by chance (in Figure 20 attributed to 'Nature') or the business rules that govern management activity (periodicity of the business review and decision making).

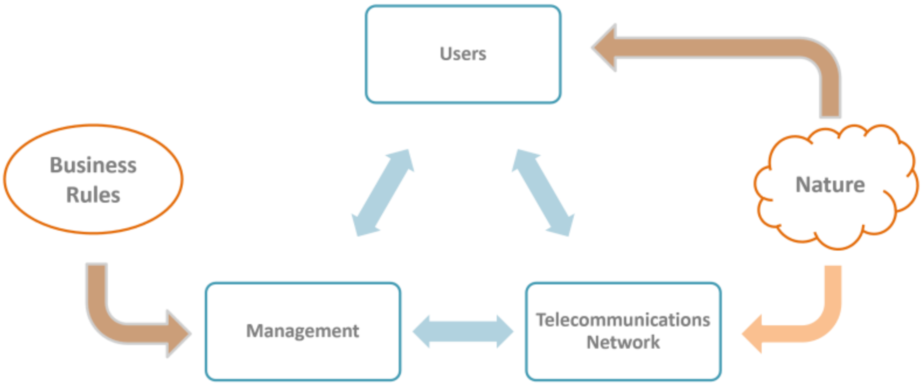

Figure 20. Entities modelled by NIESIM and their macro interactions.

The main event types used in NIESIM that represent explicit agent interactions during the simulation period are represented in Figure 21. One example of event that is missing in the diagram is the fault injection event because it is an external input, not an interaction between the agents that are explicitly modelled. There are additional events used at the implementation level either to distinguish events of the same type (e.g., fault correction driven from network information versus fault correction driven from user device monitoring) or to better represent a process (e.g., corrective action following the decision-making process is modelled distinguishing the trigger and initialization of the fault correction process from the end of that process with a certain network resource put back to service). Note that events are instrumental to model not only the mobile communications service but also the operational decision-making process taking place at the network management setting. In our case, events of type 'KPI Computation' model the 'Stimulus' step of the operational decision-making process (with independent implementations for user experience KPIs computation and for network performance KPIs computation) while events of type 'Management Review' model the 'Problem Identification' step (corresponding to the management team periodically reviewing the available information (KPIs) and deciding if action is required or not given the business rules and business guidelines in place). Events of type 'Maintenance Action' and 'Fault Correction' both model field interventions with the goal of execute corrective actions at the network infrastructure, but only 'Fault Correction' is modelling a step of the decision cycle ('Implementation') while 'Maintenance Action' type of events are basically routine pre-planned field actions that do not depend on information collected from the system nor the internal operational decision-making process (and actually are used to model 'No Information' contexts as we will explain later).

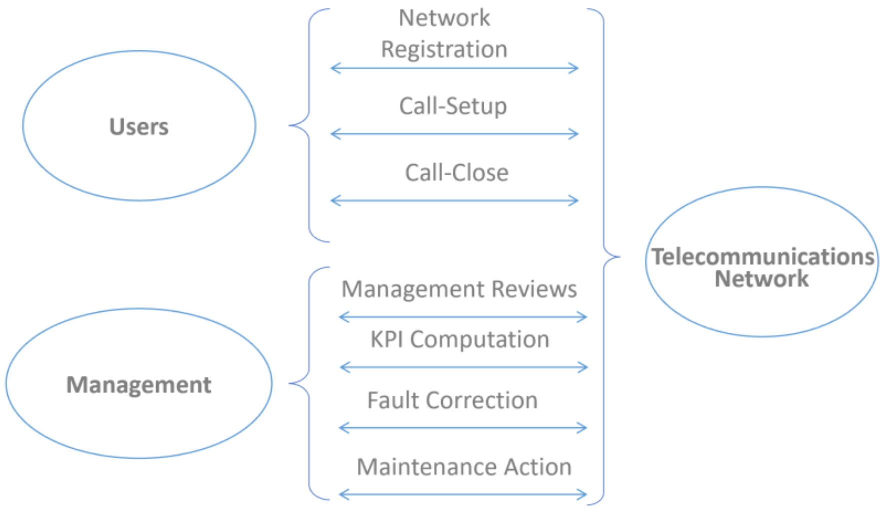

Figure 21. List of event types used to model explicit agent interaction during the simulation period in NIESIM

There are two classes of events: fixed events and dynamic events. Fixed events are those defined before the simulation processing begins and include user behaviour, service-related events (including call setup and network registration), management rules (e.g., management reviews) and fault events. On the other hand, dynamic events are those events that will be created as part of the simulation processing and could not be defined a priori, namely the fault correction events (that correspond to implementation stage of the decision cycle).

NIESIM software instantiation is a tool to execute experiments, thus the running of a simulation should be one step within a carefully designed experiment comprising a general and stable setting along with specific elements that will change in each step of the experiment.

As we have stated before, the goal is to measure the isolated contribution of a piece of information to the financial performance of the modelled system. To do this, we will repeat a simulation with the exact same characteristics except for the information element. This repeatable setting (with certain characteristics that will show the same behaviour each time it is processed) is called the baseline and our DES architecture allows us to establish a baseline setting through the creation of a fixed set of events defining all the interactions of the agents of the system modelled (Figure 22).

These events are randomly generated ('Nature' type) or generated according to predefined rules ('Business Rules' type) at the beginning of the experiment (setup process) so, when the actual simulation begins, they are already defined and, therefore, they may be seen as 'pre-determined' at this stage.

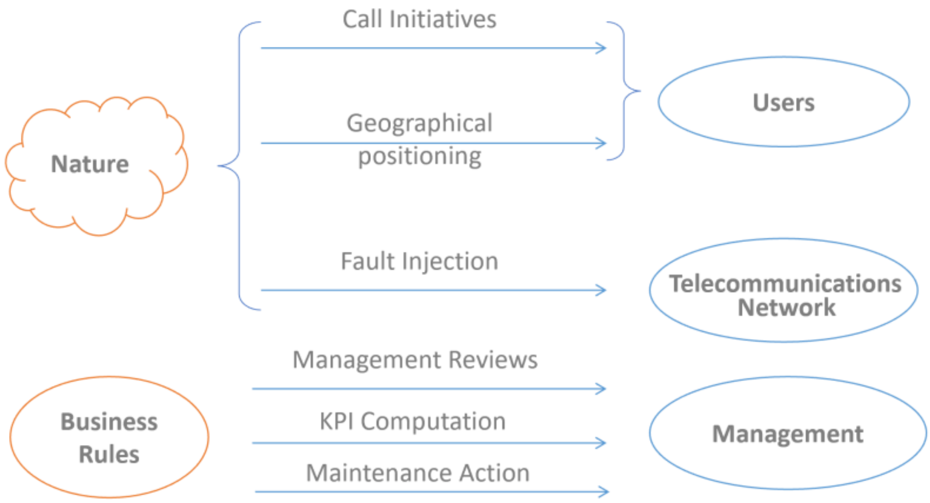

Figure 22. List of predetermined event types that influence agent's behaviour during simulation period.

Note that, by changing specific conditions (for example, information flow and decision-making rules) and keeping exactly the same set of 'pre-determined' events, we are able to simulate the influence and impact of our experiment's variables (experiment and variables discussed with more detail in section 4.4). Thus, an experiment developed using NIESIM should follow a process with three independent steps:

- Setup – context is provided for initialization of the experiment (in the form of a set of parameters) and the complete set of random events that defines a baseline (Figure 23) are created and saved for iterative processing in subsequent steps of the experiment;
- Processing – each experiment context is submitted to the actual simulation processing, thus producing specific raw results;
- Analysis – The performance indicators are extracted from the raw data gathered in the processing phase, computations and aggregations are produced and translated into experiment's observations (following procedures described in section 4.4 and subsection 5.1.3 to obtain the VoI).

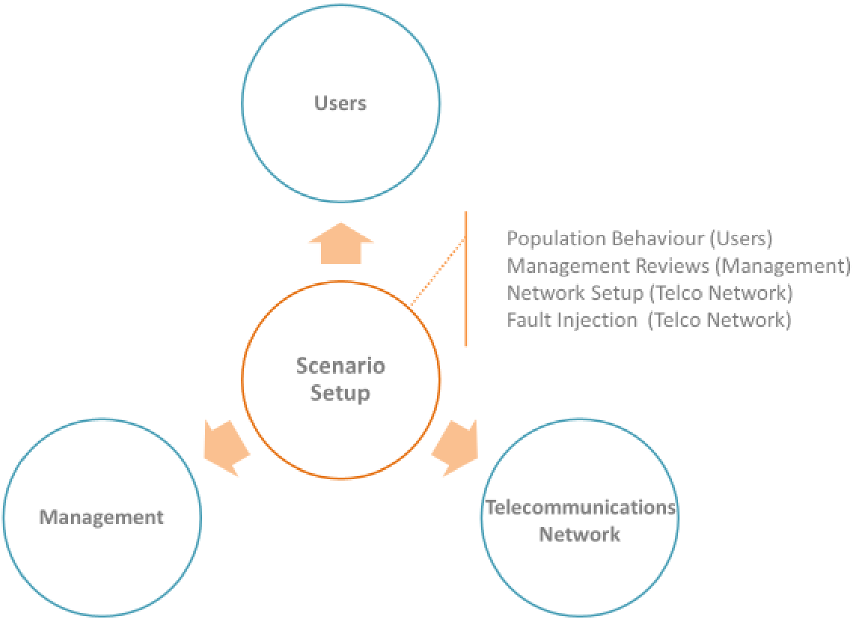

Figure 23. The main elements that contribute to a baseline definition during setup phase of NIESIM.

4.3.2 Implementation Options, Assumptions and Guidelines

For NIESIM software implementation purposes, a set of assumptions and options has been considered. Some of them were already mentioned, but we repeat them here to help the reader to understand the essence of the implementation. Part of these options are about flexibility of the software implementation from a user perspective, thus choosing which concepts should be open to adjustment by the software user when developing an experiment using NIESIM.

In the following list of assumptions and options we refer to parameters. In computer science, a parameter is a special kind of variable used in a function to refer to one of the pieces of data provided as input to the software. These pieces of data are the values of the arguments with which the internal function is going to be called/invoked, thus allowing the software to model as many variants of a system as possible combinations of all the input parameters the software is able to accept.

We present a list of assumptions and options as complete and relevant as possible:

a) The minimum period of time modelled by the system will be 1 second.

b) The duration of each call is randomly assigned to each event, reproducing the input profile provided in the setup stage.

c) We assume that each day of the week is split into distinct periods (the default is 1 hour), with specific patterns of usage frequency and activity of the users.

d) In order to assign the geographical position of a user at each period of the day, we assume that people will mostly be at their work area in day periods from 8 a.m. until 6 p.m. and will mostly be at a residential area in the remaining periods of the day.

e) Location changes are expected, taking into account the existence of two periods with different characteristics: a resting period and a working period. The working period goes from 8 a.m. to 6 p.m. and the resting period takes place before 8 a.m. and after 6 p.m. (these are input parameters).

f) The simulated population is built assuming N groups of people and each group has a certain probability to be in a preferential location during the working period and at another preferential location during the resting period. If a person is not in that preferential location, the model assumes he/she will be at a nearby region, with an identical probability of being in each neighbouring region. Two parameters (mobility rate during 'leisure period' and mobility rate during 'working period') are used to randomly locate people outside the reference zone and a third parameter is used to decide the maximum distance from the reference location that is considered in this process.

g) A global service usage pattern is defined for the global population.

h) A global service duration pattern is defined for the global population.

i) Network infrastructure is modelled considering that any base station is composed by three cells, each one assembled with several radio units with a certain number of communication channels (seven in our current implementation of NIESIM). Thus, each base station has a limited capacity (i.e., limited number of communication channels) for inbound and outbound requests for service.

j) The timeline is segmented in hourly periods and, at each period, each user is assumed to stay within the same area. In practical terms this means the base station serving the user is the same in each of those time periods.

k) Failure events are modelled as following a predefined daily rate (this percentage refers to the total number of network channels), which is a parameter of the simulation setup process.

l) A failure impacts only one individual radio element, but all channels within this radio element are affected.

m) Network performance indicators such as CSSR and Pb are computed at base station level and decision by management is based on that information. Pb is used as the decision threshold for taking corrective actions.

n) The material impact of the decisions is to act on the system at base station level, correcting all the active faults at that base station and leading to an increase on the available communication channels. These actions are executed by teams dedicated to maintenance on site (at a specific and well-known base station).

o) A field team always corrects the failure within a certain fixed time period comprised of planning and actual field intervention. So the software user is able to define the planning period (delay between problem identification and the start field action) and the implementation period (elapsed time for a field action team to solve a problem). The default time is 1h for the plan and 1h for the field action.

p) The number of field action teams is unlimited by default, but it can be parameterized to consider a certain number of teams.

q) Time granularity of computation of performance indicators is 1h.

r) Management reviews dedicated to KPIs evaluation and decision-making are also made at 1h intervals. In the current implementation no restrictions are applied based on work periods or weekends, thus these events take place on a regular and continuous mode (24x7 basis).

s) The user device is assumed to be always on (power shut down or user turning device off are not considered as possible status of the user's device).

t) User device information might be used as input to the decision process in two alternative modes: exclusive (only this information is used) or combined mode (this information is used on top of the traditional network information).

u) When user device information is used as input to the decision process, there is a process of screening the population of users and collecting their user experience towards problem identification. This process is implemented defining the 'sampling group dimension' (the actual selection might by random or based on the population groups), the 'user expected service level' (in our case measured in terms call success rate experienced by the user considering an historical time window – user CSSR), the historical ‘time window’ (expressed as a number of days) used to compute user KPIs (user CSSR is the implemented KPI) and finally the ‘service relevance threshold’ (the dimension of the group, within the population sampling, which in the limit of people experiencing low performance – beyond this limit, a problem is considered identified). In case of positive problem identification, the base stations frequently used (by the users experiencing low performance) are the target of corrective actions in the implementation phase of the decision.

v) Decisions based on user device information are daily decisions (planned for 8:00 a.m of each day) using the KPIs computed for the historical time window defined by the software user.

w) The *ex post* imperfect information is implemented using an unsuccessful implementation rate (stable during the simulation period), applied randomly to all corrective actions, part of which became ineffective actions.

x) The *ex ante* imperfect information is introduced through an error assigned to each base station, resembling a measurement error (although in real situations this error might result from other situations), complemented by random noise signal to resemble real world variability. Thus, the (imperfect) information provided as stimulus to the decision process is the ‘Measured Pb’, which results from aggregation of the real state of the world (Real Pb), plus the error characteristic of each base station (BS Error) and the random noise, as detailed in following equation:

$$\textit{Measured Pb} = \textit{Real Pb} + \textit{BS Error} + \textit{Noise}$$

Measured Pb: Is the (imperfect) information provided as stimulus for the decision-making process

Real Pb: True Pb

BS Error: Error (bias) characteristic of a certain base station (stable during the simulation period)

Noise: Random noise signal to resemble real world variability (random value generated, considering zero mean)

The magnitude of imperfection is a characteristic of each base station, thus it is not equal in every base station of a certain experiment scenario, because the engineering experience shows that equipment has intrinsic performance variability and the common way to deal with it is through quality controls ensuring error is kept within certain limits (precision of a measurement, for example).

4.3.3 Implementation platform – R Project

NIESIM was initially implemented using R[4] version 3.4.4. and is currently based on version 4.0.5. R is a free, open source and platform-independent programming language, very popular in academia and in the world of Data Science. R is very powerful in the statistical and advanced analytics arena but also powerful for data wrangling, cleaning, analysis, and visualization. It is widely used by researchers from diverse disciplines to perform all analytic tasks and display results. It is continuously evolving with collaborative contributions from academia and opensource community.

Although we have confirmed many of positive expectations regarding R, we have experienced some issues mainly related to performance and scalability when we tried to increase the magnitude of the simulations.

4.4 Experiment and Simulation Procedure using NIESIM Software

The NIESIM discrete-event simulation model allows absolute control over the baseline events that take place. The model is designed to ensure that the exact same set of events defining the service delivery can be repeatedly reproduced with the same outcomes except the availability of the information.

Our goal is to estimate VoI used to monitor and correct network failures resulting in service denial. Thus, from an experiment perspective, our dependent variable is the economic outcome and the availability of information is our independent variable, whereas the control variables come from the general circumstances of the mobile communications service delivery to the population of users.

The experiment procedure comprises four major steps: baseline setup, scenario definition, processing (Figure 24) and analysis (which is a post processing activity). These steps should be executed to produce a coherent and repeatable experiment where the cause-effect

[4] https://www.r-project.org/

relationship between variables is clear and thus observations (as outcomes of the processing and post-processing) become reliable inputs for the experiment's analysis process and lead to meaningful conclusions.

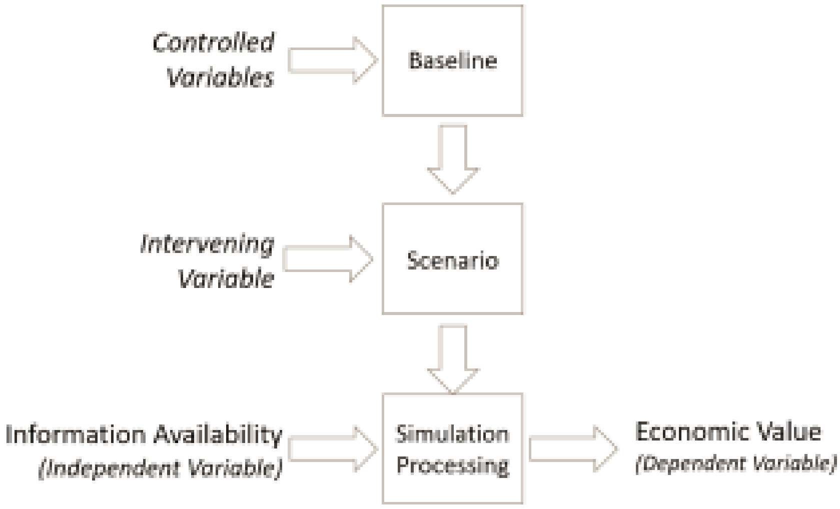

Figure 24. Overview of experiment plan when using NIESIM to capture VoI.

Note that VoI computation requires a post processing computation since VoI is computed as the difference between two simulation runs (one with information available and the other without information available), as we will discuss in detail later on. So, it is critical to have a repeatable context (with certain characteristics that will show the same behaviour each time it is processed, if nothing is changed such as a user input parameter value) to use as baseline to the experiments devoted to estimate VoI.

The baseline setup is a preliminary step, aimed to create a set of events defining the service delivery to a population of users and includes definitions about the service events (calls), geographic scope of the population, how that population is spread within that geographic area over time and the mobile network adopted to serve that population accordingly. Thus, baseline setup is designed considering which aspects of our experiment we wish to have tight control (controlled variables) and thus will remain constant throughout the experiment. Thus, baseline setup is designed considering which aspects of our experiment we wish to have tight control (controlled variables) and it will remain constant throughout the experiment. The baseline is created considering one hypothetical service delivery setting, in the form of a set of parameters, providing boundaries and general guidelines towards the generation of a set of random events. These will define the mobile communication service delivery to a population of users which is created once and saved for iterative processing in subsequent steps of the experiment.

In order to capture the behaviour of the VoI from a more general perspective, we repeat the experiment introducing slight changes in one chosen aspect (one mediating or intervening variable), which we refer to as a scenario within the broad experiment. As an example, in section 5.2 we present experimental results that explore two distinct perspectives: (i) how VoI evolves when the fault rate affecting the network infrastructure changes and (ii) how VoI evolves when the decision thresholds change. In that case, we present two experiments using the same baseline. In the first case, the fault rate is our intervening variable, so we add a different fault rate for each scenario. In the second, the decision thresholds (used by management team to take action and correct network failures) constitute our intervening variable so we consider a different decision threshold for each scenario.

At each step, one scenario (baseline plus intervening variable) is submitted to the actual simulation processing twice: one for the ‘No Information’ context and the other for the ‘Information Available’ context. For each simulation processing, the financial performance of the system is calculated (dependent variable) as part of the analysis step.

In the analysis step, the performance indicators are extracted from the raw data gathered in the processing phase, one context at a time (‘No Information’ context and ‘Information Available’ context), and the VoI, computed in financial terms, is obtained by comparing the results from those two contexts (with and without information) for the scenario under evaluation.

4.5 NIESIM Validation Results

We will now present introductory NIESIM simulation results which reproduce the steps necessary to run simulations and also aim to share examples of simulations developed within the validation process of the model and the NIESIM software. We introduce the inputs necessary to create a business setting and we comment on the basic results from a model validation perspective.

We will compare the performance of the system under different circumstances of information availability and different information usage by the management team. We will consider three distinct contexts (related with the same scenario):

a) ‘No Fault’ context – the system is simulated assuming that no failure event interferes with its performance;

b) ‘No Information’ context – the system is simulated assuming that it is subject to failures, but it has no ability to detect and correct those failures (no information).

c) ‘Information Available’ context – the system is simulated assuming that it is subject to failures, but with ability to detect and correct those failures (information available)

In subsection 4.2.5 we discussed the ‘No Information’ context and two alternatives have been presented: (i) a strict approach (no information used and no corrective action) and (ii) a sustainable approach (no information used but corrective actions take place according to maintenance plan). When we began the NIESIM software validation process we used the strict approach for the ‘No Information’ context and those results are shared in this section, while in the experiments presented in Chapter 5 we adopt the ‘sustainable approach’.

The validation process unfolded into a sequence of experiments part of which we reproduce here (in the following sections, up to the end of this chapter), starting with the situation where the system runs without failures affecting its activity (‘No Fault’), then proceeding towards the context where the system is simulated under failure stress (which resembles real world infrastructure that is error prone), considering two opposite situations in terms of information usage: (i) information is not available, thus management is not able to take action and correct failures (resulting in continuous decay of service, observable in indicators like CSSR and Pb of the network); (ii) information is available and management is able to make decisions and take action accordingly, thus correcting the failures (resulting in service recovery).

We will combine the outcomes of these simulations to understand the differences between those contexts both in terms of service performance and financial performance. In these examples we will only use network monitoring information as the source of information.

4.5.1 Description of the Business Setting

Now let us present the business setting itself. We chose a simplified setting in which the population (service users) is uniformly distributed across a certain region served by a radio telecommunications infrastructure. We considered a population of 7000 users distributed evenly along all the operating region with smooth variations in terms of population location between adjacent areas (implemented using the concept of ‘mobility rate’, in this case with assigned value of 50%). The service usage profile of the population is variable throughout the day and we used a profile from a real situation as input for the simulation process, thus making sure that the appropriate volume of calls was generated at each time period (on an hourly basis) by this population.

The population and the region where that population evolves along time are very important for planning the infrastructure topology that a service provider has to deploy to ensure a certain grade of service. However, it is not our intention to discuss geographical optimization of the infrastructure and other complex technical details related to the telecommunications engineering perspective. We chose to follow a general standard in the industry for expected grade of service (1%) and combine that with the simplest topology possible: we assume that each cell is served by one base station with only one operational cell, thus no redundancy (in terms of radio coverage of each geographical area) is considered for this basic business setting. As we applied this simplified topology model into practice, we considered the region itself to be evenly segmented in cells in such a way that a matrix with five lines and five columns of cells is used to assign the radio network infrastructure that will ensure mobile communications coverage for the whole region. Finally, we assigned 4 radio units (28 communication channels) to each cell (and consequently to each base station, in this particular case). We have verified through simulation results that this infrastructure is adequate to ensure that grade of service and, while not perfect (thus we did not reach an over-dimensioned infrastructure), it is nevertheless always within the industry limit ($Pb<=1\%$). Finally, we assigned a daily rate of 6% of faults in the infrastructure. The experiment baseline definition is summarized in Table 9. Both the ‘communication channels by base station’ and the ‘daily rate for steady inflow of faults’ were chosen after a trial and error process given practitioners recommendations (regarding the network planning part) and the convenience of a fast impact on the performance (failure rate). The ‘failure rate’ is obviously a purely hypothetical and convenient value, otherwise we would have to produce simulations for long periods (many weeks or months), thus being impractical to implement.

Table 9

Technical summary of our experiment baseline

Modelling concept or input	**Units/Values**
Total geographical zones	25
Longitudinal range	5
Latitudinal range	5
Total users	7000
Average number of users per zone	280
Mobility rate	50%
Total base stations	25
Average communication channels by base station	28
Total communication channels	700
Daily rate for steady inflow of faults	6%

As stated previously, users do not stand still in a certain location, but they are expected to move within the geographic area in which the simulation evolves. In Table 10 we present a summary of the values of the simulation parameters related to the process of decision making and subsequent actions (those parameters only apply to 'Information Available' context). The simulation parameters have been chosen by considering an idealized situation with no limitations on the teams available for field actions (unlimited number of teams, hypothetically working at any moment in a day), a smooth decision-to-action procedure is in place (small delay between decision and execution) and that a team field will always correct the failure within a certain fixed time period.

Table 10

Simulation parameters related to the process of decision making and subsequent actions

Modelling concept or input	**Units/Values**
Pb used as decision threshold	6%
Decision to field action delay	1h
Elapsed time for a field action team solve a problem	1h
Number of field action teams	Unlimited
Limitation on field teams work periods	NO
Time granularity of computation of performance indicators	1h
Management evaluation of KPIs and decision-making period	1h

We are aware that those options are fairly optimistic and we expect to explore how those options might impact the economic performance in subsequent studies. Finally, in Figure 25 we present the call duration profile used as input in our experiments, based in data shared by a mobile telecommunications provider. Note that the curve is similar to a power law.

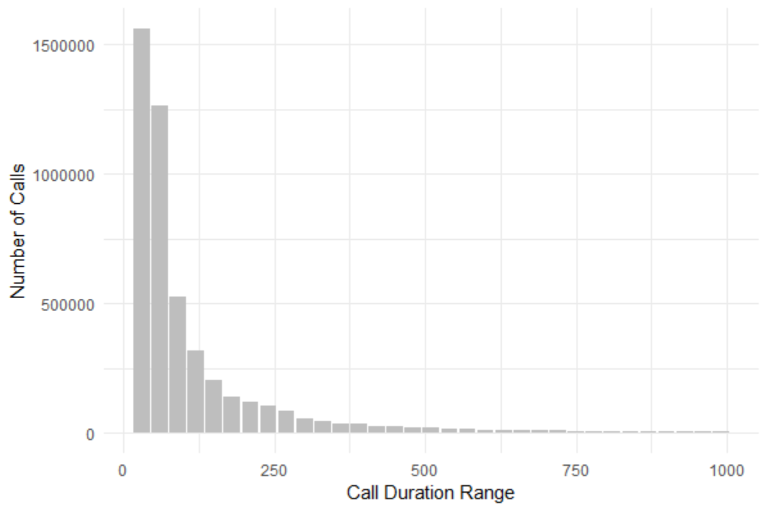

Figure 25. Call duration profile expressed as number of calls for successive ranges of duration (30 s).

4.5.2 Experiment Validation through Basic Outcomes from the Simulation Process

Before we analyse the simulation results, we will to provide some generic information on how the business setting inputs presented in the last subsection actually translate into the 'No Fault' context of the experiment.

Beginning with the population of users, Figure 26 presents the user distribution per zones during the working period (considering the average number of users in each area), which illustrate the geographic distribution trends of this experiment.

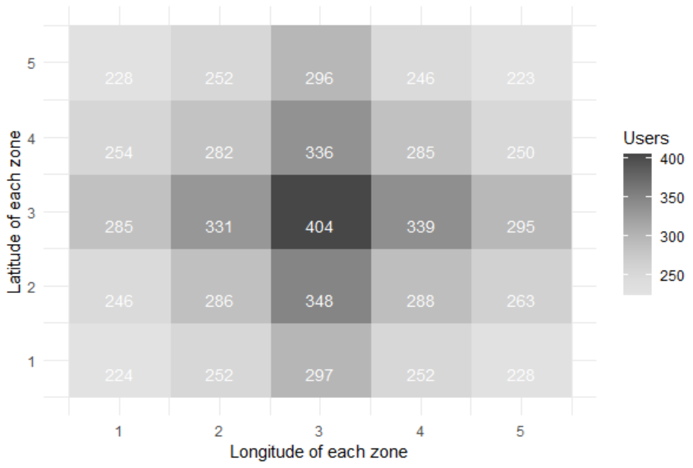

Figure 26. Average number of users in each region, during the working period.

Next, we present the behaviour of users in terms of service usage along time. In real life, the mobile telecommunications service demand is time-dependent, with periods of the day with high demand and other periods with low demand, as shown by field data obtained from a Portuguese service provider used as input to our experiments. In Figure 27 we compare the input profile of the real telecommunications provider with the usage profile that resulted from the NIESIM's setup phase. The simulation provided by NIESIM, generated using the 'No Fault' context, clearly resembles the reference profile used as input at the setup phase and shows the ability of NIESIM to reproduce a realistic profile of service user by the population despite all the randomness described in the user behaviour model (subsection 4.2.2) implemented in the software.

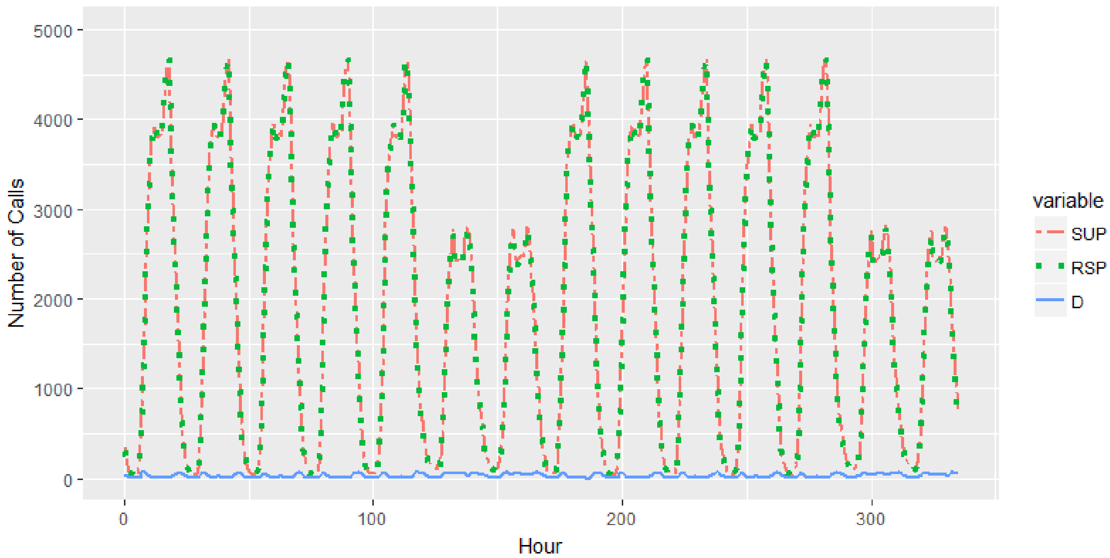

Figure 27. Comparison of service usage pattern from a 'real' service provider (RSP), which is one input to the setup process, and the service usage pattern (SUP) of the population created for the 'No Fault' context. The difference (D) between those curves is also plotted.

Finally, let us review the network infrastructure, particularly the ability to process traffic resulting from the 'No Fault' context just described. We considered that the traffic capacity of the infrastructure should be dimensioned at a minimum configuration assuring that, in the absence of faults (REF curve in Figure 28, corresponding to 'No Fault' context), the grade of service would be aligned with industry reference recommendations (Pb<=1%) as suggested by Freeman (2005), which means a *quasi*-perfect service level is provided to users but avoiding over-provisioning of resources (thus a limited traffic blocking is observable).

In Figure 28, we also plot the performance in terms of Pb when a steady inflow of faults (rate 6% of installed capacity) is injected into the system (with no information available, thus no ability to correct faults which we call ‘No Information’ context and tagged with AFNCINT[5]). This plot shows that the infrastructure is fitted to our goal (in the ‘No Fault’ context, in which the system is under no stress by failure events, we observe small perturbations in the service, thus we are sure to avoid over-provisioning) and also gives some insight on the impact of faults over time if no action is taken to correct those faults.

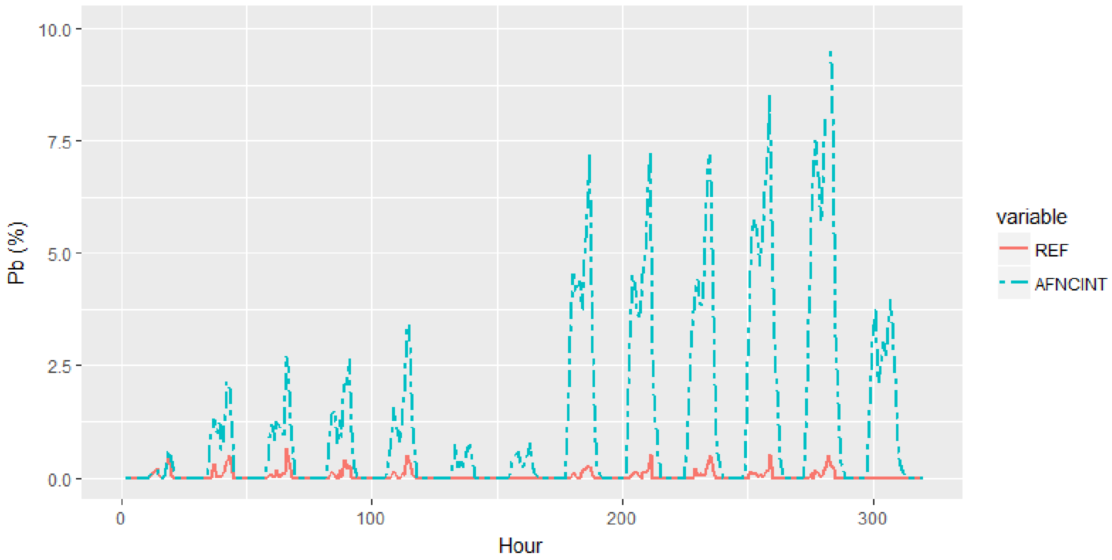

Figure 28. Impact on the performance of the system of a steady inflow of faults (rate 6% of installed capacity) measured in terms of Pb. REF is the ‘No Fault’ context without faults and AFNCINT is the ‘No information’ context with active faults.

4.5.3 Simulation Results

We chose to present results from the simulation process combining the ‘No Fault’ context, the ‘No Information’ and the ‘Information Available’ contexts, showing the main differences between them as we present and explain the performance of the system considering several analytical perspectives. Recall that the ‘No Fault’ context (tagged REF) is the one assuming no failure event interferes with the systems performance, whereas the ‘No Information’ context (tagged AFNCINT) assumes the system is under failure pressure but not able to detect and correct failures (no information).

As explained before, we assume that generic failures take place in stochastic random terms and impact the network by reducing the operational communication channels available to end users. In this section, we consider one strict interpretation of a ‘No Information’ context which is to

[5] Acronym for “Active Failure, No Control using INTernal information” context.

consider absolute absence of information about the network. By the end of this section, we will comment on the implications of this option used at the validation stage of NIESIM and introduce the need for an alternative 'No Information' context definition.

Finally, we also introduce one example of an 'Information Available' context, which assumes that information is available for the management team to take action, thus allowing the detection and correction of those failures. In this example we chose a threshold of 6% of probability of call failure (Pb) as the trigger to act upon correcting faults. The 'Information Available' context (tagged AFACINTPB6[6]) assumes the system is under failure pressure but now with ability to detect and correct those failures (information available)

The simulation ran for two weeks and the pattern of attempts to use the service is presented in Figure 29. Along with the attempts to use the service, we also show the attempts that were successful and the attempts that could not be successfully completed, regardless of the reason.

There are three major causes for the failure of a call attempt: the receiving user is already on a call, thus unavailable (A); unreachable users that are not registered on the network (either for service availability limitations or for user option to be disconnected, for example) (B) and finally call attempts that fail because of network resources limitations (C). Our focus shall be the call attempts that fail due to technical problems, which correspond to the latter ones.

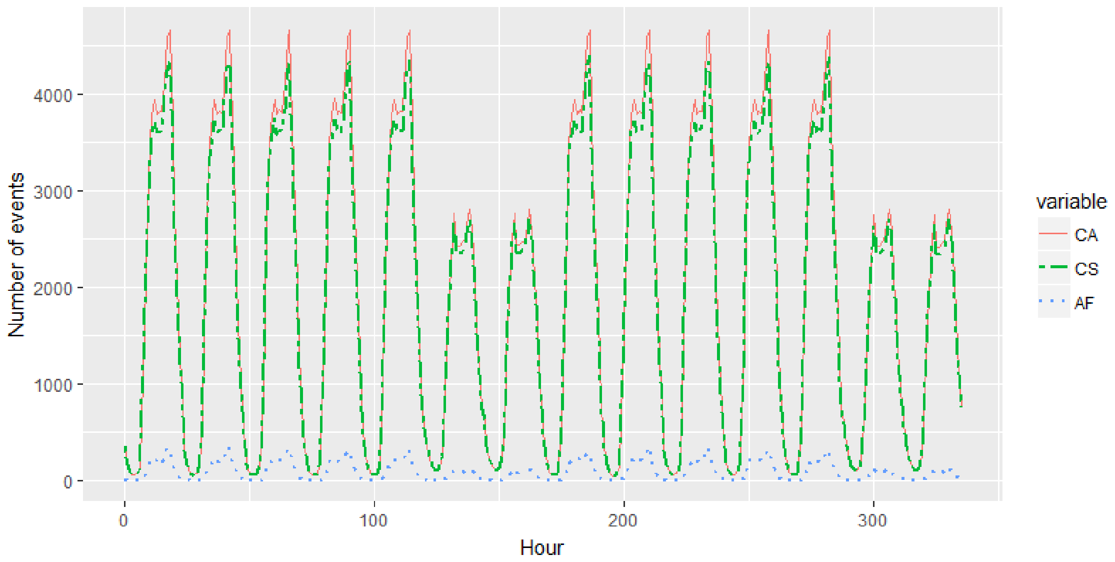

Figure 29. Performance of the 'No Fault' context: Pattern of attempts to use the service (CA - Call Attempts) along with their successful (Call Success – CS) and unsuccessful (Active Failure - AF) counterparts.

[6] Acronym for "Active Failure, Active Control using INTernal information with Pb of 6% as decision threshold" context.

A significant number of call attempts do fail due to simple fact that those were unviable (example: the destination user is already on a call). The unviable calls are identified as A in Figure 30 while unsuccessful calls due to resource limitations are identified as C. We observe that only a small portion of those failures result from network limitations (C), actually capacity limits, since in the 'No Fault' context we assume no faults are active in the system. On the other hand, there are no unreachable users (B) which is a consequence of our option to provide full coverage within all geographic zones included in this experiment. Note that unreachable users are users not registered in the network, either because their phone is off (not included in our modelling efforts since we assume the user device is always on) or because the user is positioned in an area out of radio signal coverage.

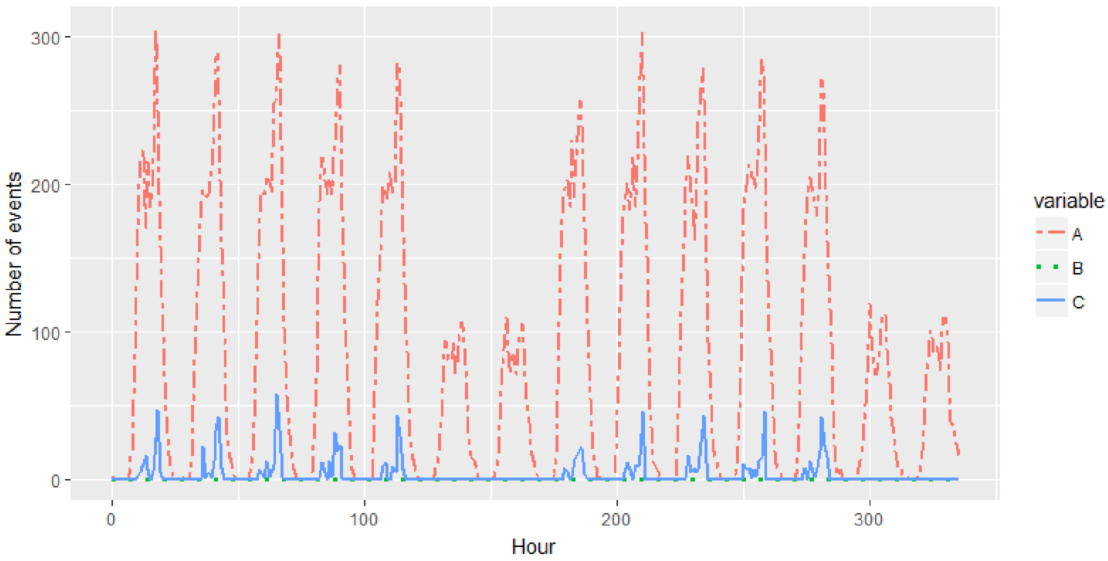

Figure 30. Patterns of distinct reasons for call failure obtained for the 'No Fault' context namely unavailable user (A), unreachable users (B) (due to the setting of the simulation, this number is always zero), network resources limitations (C).

Since the ability to provide the service is contingent to the availability of resources of the telecommunications infrastructure, the full understanding of service usage must consider not only the number of attempts to use the service (successful and not successful) but also the duration of the service (duration of calls), since the service could be denied because of unavailability of resources (either because they are in use in that moment or because they are under a failure status, thus not available).

Next, we show how some indicators concerning traffic evolve during the simulation period, in the 'No Fault' context. Figure 31 presents the offered traffic (Eo) hand in hand with carried traffic (Ec) along with the difference between those metrics, and Figure 32 depicts the probability of blocked traffic (Pb).

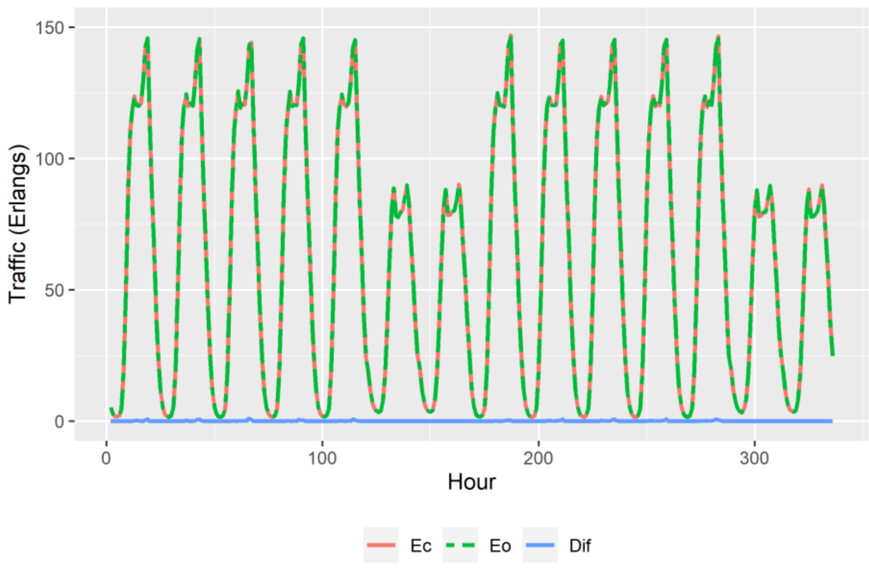

Figure 31. Pattern of Offered traffic (Eo), Carried traffic (Ec) obtained and the difference (Dif) between these metrics for the 'No Fault' context

As expected, the value of Pb in the 'No Fault' context is always low (ensuring that a high service is provided to the users), but it is not always zero, thus taking into account the requirement of avoiding over-provisioning of resources.

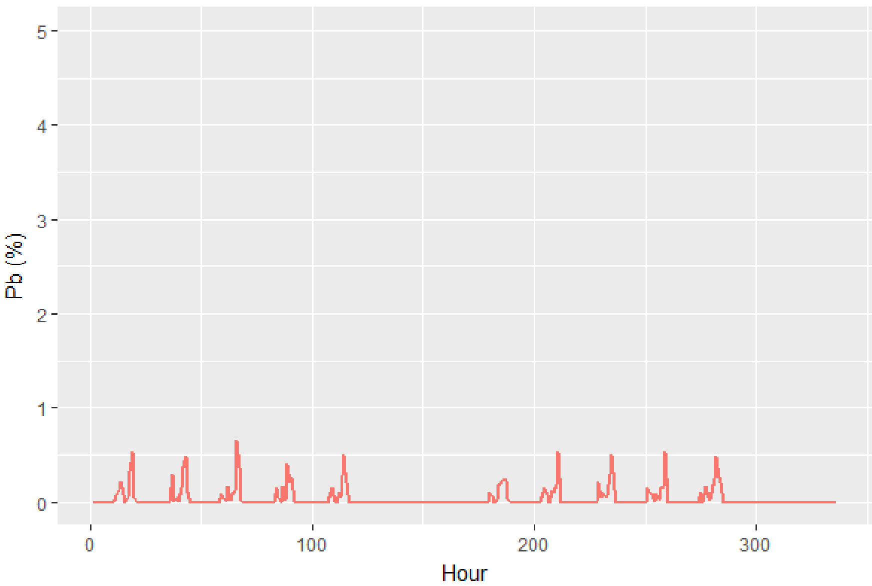

Figure 32. Pattern of Probability of blocked traffic (Pb) obtained for the 'No Fault' context.

Now let us introduce the nuances from failures and actions to correct those failures in terms of call failures originated by network resources limitations. Note that, to ensure comparable results, the 'No Information' and the 'Information Available' contexts assume the system is under failure pressure (in this case, we considered a 6% rate of equipment failures on a daily basis) and that the exact same failure events take place in both simulations. The 6% rate is higher than observed in real systems, but it is instrumental for the purpose of getting a visible impact on performance in a small period of time (we chose to only consider two weeks as the simulation period).

Since the failure events are the trigger element for the differences between the 'No Fault' context and the other ones, we start by observing the failure events (Figure 33) and the corresponding impact on the infrastructure in terms of available channels to provide the service.

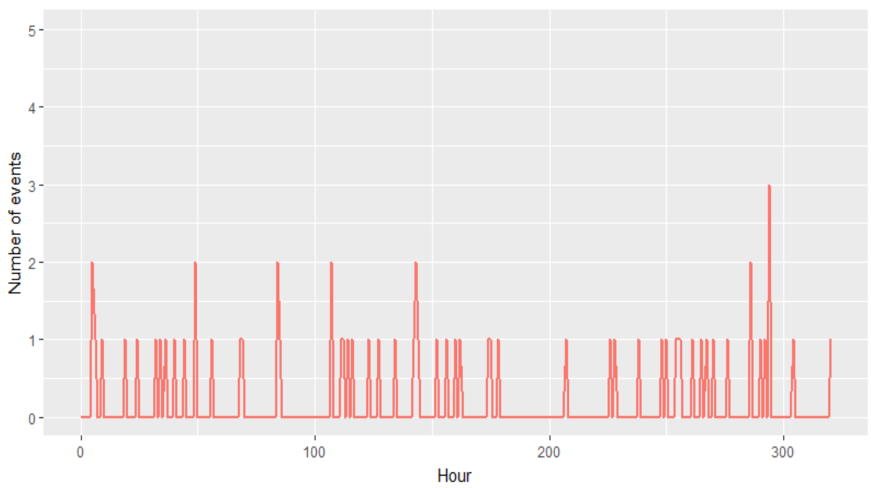

Figure 33. Number of failure events by hour, common to the 'No Information' and the 'Information Available' contexts.

Figure 34 presents the contrast of those three complementary contexts in terms of channel availability: 'No Fault' context (subsequently referenced using REF in the plots); 'No Information' (subsequently referenced using AFNCINT in the plots) and the 'Information Available' (subsequently referenced using AFACINTPB6 in the plots) following the decision threshold of 6% of probability of call failure (Pb). It is clear that information availability and the actions based on that information result in a responsive system regarding failures and a completely different performance in the long term.

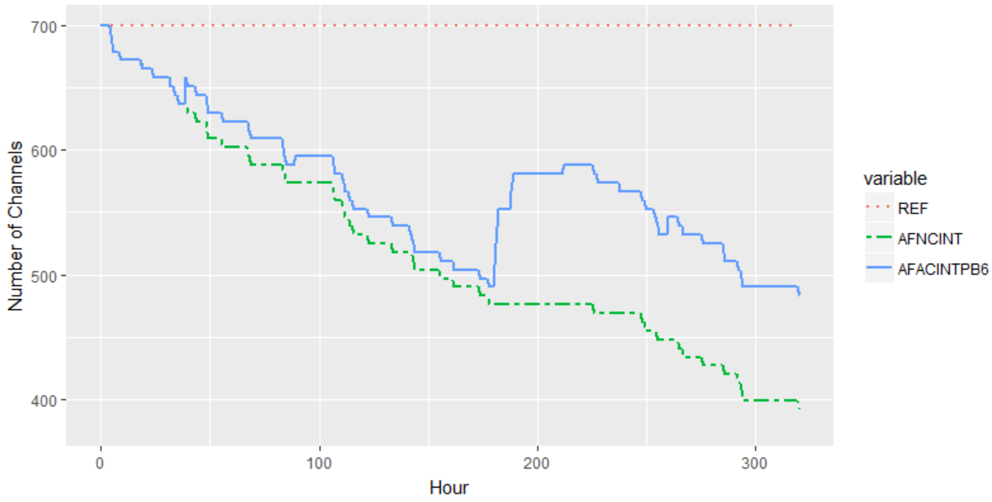

Figure 34. Comparison of different contexts regarding communication's channels availability (minimum within each hour period). REF: 'No Fault' context; AFNCINT: 'No Information' context with active faults; AFACINTPB6: 'Information Available' context with a grade of service of 6% at the base station level.

If we compare the Pb performance indicator across these contexts (Figure 35), the obvious conclusion is that the 'Information Available' context does ensure that the service level is kept under control, while in the 'No Information' context the service level is in continuous decay. Such decay is also observable when we consider other performance indicators, such as CSSR (Figure 36).

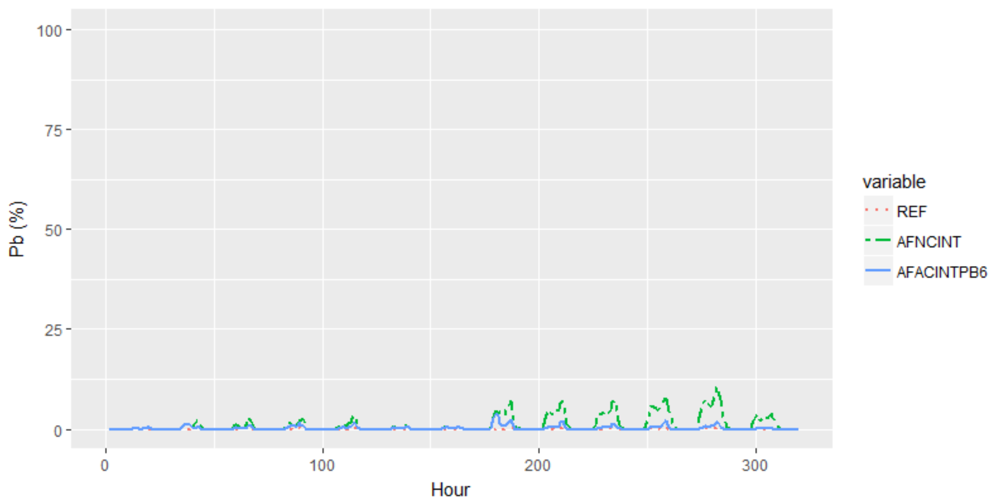

Figure 35. Comparison of the different contexts regarding the probability of blocked traffic (Pb). REF: 'No Fault' context; AFNCINT: 'No Information' context with active faults; AFACINTPB6: 'Information Available' context with a grade of service of 6% at the base station level.

The Call Setup Success Rate (CSSR) is related to successful call attempts and it measures the ability of the provider to set up a call attempt by the user. The performance we got in our simulation for the three contexts is presented in the Figure 36, showing that the system under the 'Information Available' context is able to provide a much better service level to users when compared to the 'No Information' context.

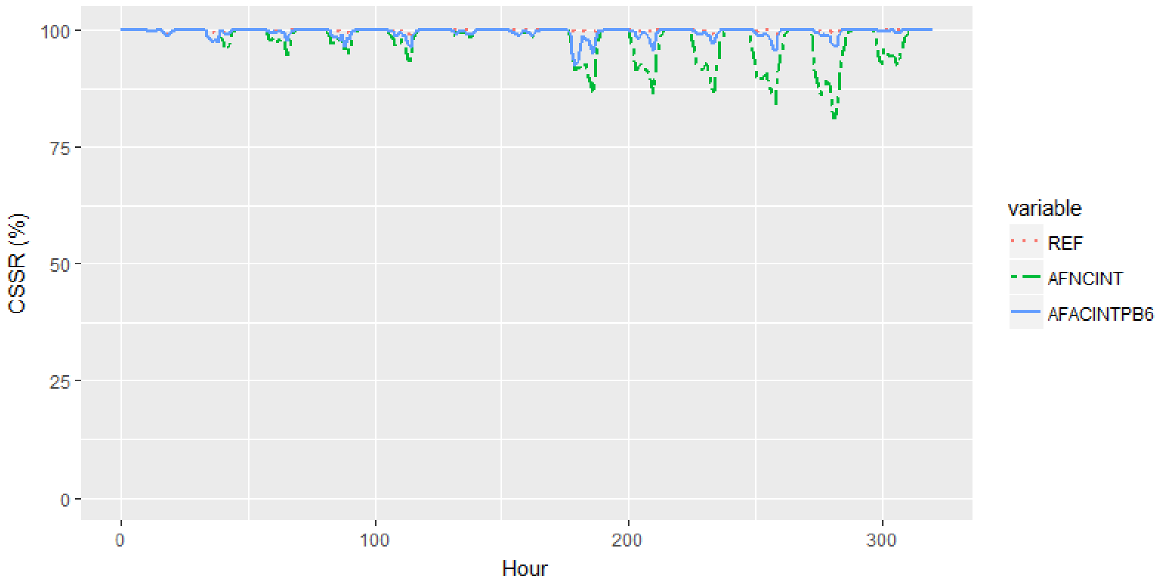

Figure 36. Comparison of the different contexts regarding Call Setup Success Rate (CSSR). REF: 'No Fault' context; AFNCINT: 'No Information' context with active faults; AFACINTPB6: 'Information Available' context with a grade of service of 6% at the base station level.

A macro analysis of the main performance indicators, considering busy hour observations for the entire network (or system), is commonly adopted by the telecommunications industry. Comparing the three contexts using busy hour performance indicators gives a clear picture of the performance trends of each one and thus a simpler way to reach insights.

In terms of processed traffic (Figure 37), it is clear that, in absence of information (and control), there is a continuous decline in traffic (weekend days should be ignored within this exercise since the expected traffic is far below that of a regular working day). However, when information is available (and action taken based on that information), the traffic loss is staunched and an equilibrium is achieved (in this business setting, after the first week), and traffic shape is aligned with the 'No Fault' context, confirming that the system is performing under a stable condition although at a lower level of service.

If we compare those contexts considering Pb performance indicator (Figure 38), which is a proxy for QoS provided to users within this experimental setting, the description would be similar: when information is available, the service level is kept stable (after a stabilization period - in this setting, after the first week) although at low performance when compared to the 'No Fault' context.

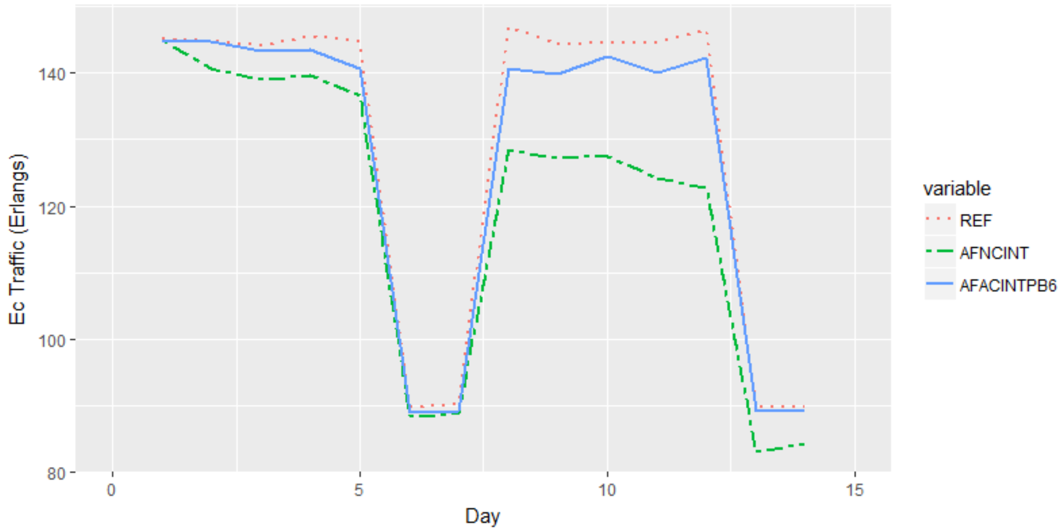

Figure 37. Comparison of the different contexts regarding the observations for Carried Traffic (Ec) in the busy hour. REF: 'No Fault' context; AFNCINT: 'No Information' context with active faults; AFACINTPB6: 'Information Available' context with a grade of service of 6% at the base station level.

Reviewing those plots is very insightful in terms of sensing the difference that one should expect in terms of performance of a telecommunications network if information on system faults is available and action based on that information can be taken.

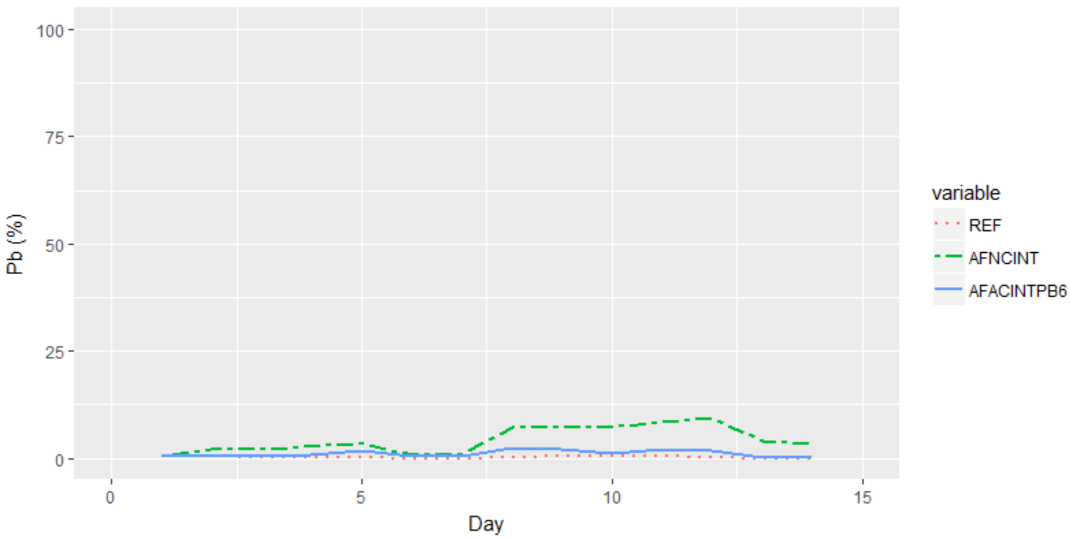

Figure 38. Comparison of the different contexts regarding the observations for Carried Traffic (Ec) in the busy hour. REF: 'No Fault' context; AFNCINT: 'No information' context with active faults; AFACINTPB6: 'Information Available' context with a Pb of 6% at the base station level.

4.5.4 Lessons Learned from Experiments Developed within the Validation of NIESIM

The NIESIM validation process included a sequence of experiments with the goal of (i) ensuring the model was correctly implemented, (ii) detecting and correcting bugs, and (iii) identifying limitations of the model or the implementation that required improvements. This process included periodic meetings with practitioners not only to discuss the model design aspects but also to share results and obtain critical reviews, feedback and suggestions for improvements (and sometimes additional inputs to use as reference for more realistic simulations). Some of the lessons learned are the following:

a) Defining the 'No Information' context was not trivial: The adoption of one strict interpretation of a 'No Information' context, as we initially did and report in the previous sections, would lead us to a dead end in the sense that after a brief period of time, the network would become unable to deliver any service (as Figures 34 and 37 show). Eventually we reached the conclusion that this 'No Information' definition is unrealistic and does not qualify as a sustainable operational setting. Therefore, as previously explained, we adopted a different definition in which base stations are sequentially inspected and subject to maintenance procedures.

b) Simulation of the mobile communications setting is very demanding in terms of computational resources and time. The simulation of a small population of 10000 users of the mobile communications service for a couple of months, requires several weeks (at least using regular hardware – 4CPU/8Gb RAM – otherwise the computing cost is prohibitive for a non-funded project as was our case). We developed and executed dozens of tests and experiments and eventually had to adopt a balance between desire and reality, thus the period of time under simulation was limited to 6 weeks (as a general rule).

c) Our intuitive interpretation of a modern mobile communication setting surely includes high rates of population mobility. However, high mobility of the population has important implications in terms of network infrastructure (and capacity/provisioning dilemmas). As we have stated before, our motivation does not include communications engineering aspects, but if we adopted oversized infrastructure (even partially), we would undermine VoI estimation (information value is highly correlated with scarce resources management). Note that, in our initial experiments, we adopted high mobility rates in small geographical settings which generate asymmetric distribution of the population with high concentration at the centre (as shown in Figure 26), thus requiring costly iterative simulations just to reach adequate network resources deployment, and also the implication of introducing another complex variable, since there would be numerous viable alternatives of network deployments to address each population scenario (considering that technically the same zone could be covered by multiple base stations). We then decided to adopt low mobility and a very simplified network infrastructure for our experiments, since otherwise the complexity would be overwhelming and extracting conclusions would become almost impossible (without significant computational cost, both in terms of time and money).

5 Using NIESIM to Estimate the Value of Information

In this chapter we report our main experiments developed using NIESIM. We have developed experiments considering perfect information and imperfect information using information sourced in the network infrastructure, but we also developed experiments combining user sourced information with network sourced information (in this case only perfect information is considered).

The first two experiments are designed to estimate the Value of Perfect Information (VoPI) and to study the relation between VoPI and other variables. Experiment A explores the relationship between VoPI and the fault rate affecting the network infrastructure while experiment B addresses the relationship between VoPI and decision thresholds used by the management team. The other two experiments explore the Value of Imperfect Information (VoII) used in decision making: one (experiment C) considers imperfect information *ex ante* 'Problem Definition' and the other one (experiment D) addresses imperfect information *ex post* 'Problem Definition'. All experiments described before use information provided by the network monitoring activities but we will end this chapter presenting experiment E based on two types of information: user sourced information and network sourced information (in this case only perfect information is considered).

The experiments based on information provided by the network monitoring activities share the same baseline so we decided to start this chapter by presenting the experiment setting along with some practical aspects of the computation procedure of the value of information followed in all experiments (including an extrapolation exercise). Afterwards the experimental results for the experiments using perfect information are presented and then imperfect information is considered. Finally, we end this chapter with experiment E based on a different baseline and with a distinct approach in terms of results presentation.

5.1 Experiments Settings

5.1.1 Baseline

In this subsection, we introduce the general characteristics of the business setting used as a reference for the experiments A, B, C and D. The performance of a mobile telecommunications provider is subject to multiple contingencies such as customer base fluctuations, user mobility and infrastructure reliability. To reduce those contingencies, we consider a simple business setting: we assume a constant customer base (8750 active users), regularly distributed within a region (segmented in 25 cells), with low mobility ratios (we considered 5% mobility rate, meaning that there is 95% probability of finding the user within the residential area, during the leisure period, or in the work area, during the working period). Our baseline considers that the population is segmented into 25 groups, each one having one residential area and one work area, regularly distributed, which results in a stable and balanced distribution of users regardless of the leisure or working period of the day.

Keeping the network infrastructure as simple as possible leads us to consider that each area is served by one independent base station with one cell and no radio coverage overlapping. The number of communication channels per cell is 28 (thus 700 in total) and this was chosen to follow a general standard in the industry for the expected Grade of Service (GoS); this was verified through simulation results, acknowledging that GoS is not perfect (thus we do not reach an over-dimensioned infrastructure), but it is always within the industry guidelines (GoS <= 1%). In the telecommunications industry, GoS is synonymous of call blocking probability (Pb), which will be the key indicator of network performance used throughout the experiments.

Financial performance is obviously related to the way service plans are charged to customers. In the experiments A, B, C and D we do not distinguish groups of users with respect to service plans, nor do we consider different expectations that those groups might have, for example with respect to quality of service. We assume that a single and generic flat rate service plan applies to all users, in the exact same terms to every simulation included in the experiments described in this document. The service plan considered in our experiments is based on assumption that all calls are limited to the same service provider and charged on a 'per second' basis and no other services than calls (like SMS, Internet) are available. The price of one minute of communications is 0.01 monetary units (m.u.), the service is charged to the user initiating the call, and the same price applies for any call at any instant of the day.

The experiment baseline definition is summarized in Table 11. The number of 'communication channels by base station' was chosen after a trial-and-error process given practitioners recommendations (regarding the network planning part).

Table 11

Technical summary of our experiment baseline

Modelling concept or input	**Units/Values**
Total geographical zones	25
Longitudinal range	5
Latitudinal range	5
Total users	8750
Average number of users per zone	350
Mobility rate during 'leisure period'	5%
Mobility rate during 'working period'	5%
Total base stations	25
Average communication channels by base station	28
Total communication channels	700
The price of one minute of communications	0.01

The service usage profile and the call duration profile are important inputs to the baseline setup. In this experiment, we used identical profiles to those presented in Figure 27 (subsection 4.5.2) and Figure 25 (subsection 4.5.1), respectively. Those profiles are based on data from a real service provider, to get as close as possible to a real-life scenario.

In our experiments, we also model management activities and their decisions (when we consider that information is available). In Table 12 we present a summary of the values of the simulation parameters related to the process of decision making and subsequent actions (those parameters only apply to 'Information Available' context).

Table 12

Simulation parameters related to the process of decision making and subsequent actions

Modelling concept or input	**Units/Values**
Decision to field action delay	1h
Elapsed time for a field action team solve a problem	1h
Number of field action teams	Unlimited
Limitation on field teams work periods	NO
Time granularity of computation of performance indicators	1h
Management evaluation of KPIs and decision-making period	1h

Once again, we keep it as simple as possible: performance indicators are computed at regular periods (1 hour) and reviewed by the management team, which will take action according to the business rules. The decision criterion is that if probability of blocking calls – Pb – within a certain area is over a threshold value, corrective actions on the field should take place. The simulation parameters have been chosen considering an idealized situation in which there are no limitations on the teams available for field actions (unlimited number of teams, hypothetically working at any moment in a day), a smooth decision-to-action procedure is in place (small delay of one hour between decision and execution) and a field team will always correct the failure within a certain fixed time period without restrictions in terms of working periods of those teams. We are aware that those options are fairly optimistic and we expect to explore how those options might impact the economic performance in subsequent studies.

5.1.2 Scenario Definition

Given the existing baseline, introduced in previous section, we have to complete the steps for proper experiment implementation defining the intervening variables characteristic of each scenario with each experiment but we also have to complement the common baseline with complementary adjustments (additional controlled variables) specific of each experiment (see subsection 4.4 for detailed discussion and Figure 24 for visual description). First let us recall the goal and assumptions of each experiment:

a) In experiment A, the goal is to understand how VoPI evolves when the fault rate affecting the network infrastructure changes; thus, we assign a constant decision threshold (Pb of 2% is the additional controlled variable) and we change the failure rate affecting the network (fault rates of 2%, 4% 6% and 8% are used to define each scenario).

b) In experiment B, the goal is to understand how VoPI evolves when the decision thresholds change, so we always assume the same failure rate affecting the network in each scenario (failure rate of 6% is our controlled variable), while we change the decision threshold used by the management team to take action and re-establish service delivery within an expected GoS.

c) In experiment C we explore how the VoII evolves when the *ex ante* imperfection magnitude changes thus the *ex ante* imperfection magnitude is our intervening variable (magnitudes of 15%, 30%, 45% and 60% are used for each scenario).

d) In experiment D we analyse how VoII evolves when the *ex post* imperfection magnitude changes, thus the *ex post* imperfection magnitude constitutes our intervening variable (magnitudes of 15%, 30%, 45% and 60% are used for each scenario).

In experiments C and D two controlled variables are used to complement the baseline: failure rate (6%) and Pb (using threshold of 2% as decision criteria). In table 13 we present this information in a more schematic form.

Table 13

Scenario definition for each experiment using only network sourced information.

Experiment	**Goal**	**Controlled Variables**	**Intervening Variables**	**Values for Each Scenario**
A	Understand how VoPI evolves when the fault rate affecting the network infrastructure changes	Decision threshold (Pb of 2%	Failure Rate	2%, 4%, 6%, 8%
B	Understand how VoPI evolves when the decision thresholds change	Failure rate of 6%	Decision Threshold	2%, 4%, 6%, 8%
C	Understand how VoII evolves when the *ex ante* imperfection magnitude changes	Failure rate (6%) and Pb (using threshold of 2% as decision criterion)	*Ex ante* Imperfection Magnitude	15%, 30%, 45%, 60%
D	Understand how VoII evolves when the *ex post* imperfection magnitude changes	Failure rate (6%) and Pb (using threshold of 2% as decision criterion)	*Ex post* Imperfection Magnitude	15%, 30%, 45%, 60%

We have some final remarks applicable to all experiments:

i) We do not focus on any particular source of failure affecting the network, although we assume that failures do translate into limited capacity of the infrastructure to process communications (simulated as a reduction in communication channels). For simplicity, we assume that failures take place at a constant rate (considering the total number of communication channels as the reference).

ii) The ‘daily rate for steady inflow of faults’ (failure rate) was chosen for convenience of a fast impact on the performance. The ‘failure rate’ is obviously a purely hypothetical and convenient value, otherwise we would have to produce simulations for long periods (many weeks or months), thus being impractical to implement.

5.1.3 VoI Estimation (Procedure and Options)

The estimate for the value of the information (VoI) for each scenario compares the 'No Information' outcomes with the 'Information Available' outcomes, assuming that the exact same failure events take place in both contexts. The difference between the outcomes is the VoI for the corresponding scenario. Below we will go through the process of VoI estimation in detail, using the baseline we have introduced, considering a scenario with a fault rate of 6% and a decision threshold of 6% Pb.

Three different contexts were simulated for each experiment:

a) 'No Fault' context – the system is simulated assuming that no failure event interferes with its performance;

b) 'Information Available' context (subsequently referenced using 'INF' in the plots) – the system is simulated assuming that it is subject to failures, but the management team has access to performance information, and thus it has the ability to take action and correct those failures (information available);

c) 'No Information' context (subsequently referenced using 'NoINF' in the plots) – the system is simulated assuming that it is subject to failures and the management team has not access to performance information (no information) so it has no ability to take action according to that information. Yet corrective actions take place assuming a static maintenance plan, following the rule that the number of corrective actions per week is the same as the number of corrective actions per week emerging from the 'Information Available' context. This way, both approaches have the same cost and VoI is difference of revenues between these alternatives (VoI = INF – NoINF).

We start by observing the failure events and the corresponding impact in terms of available channels to provide the service. Figure 39 presents the results of the three described settings in terms of availability of communication channels.

It is clear that information availability and the actions based on that information result in a more responsive system regarding failures and a completely different performance in the long term. We observe this performance improvement arising from information availability (when compared to the 'No Information' alternative) translated into a higher number of communications channels available (Figure 40), but also in terms of lower level of blocking probability (Pb) throughout the simulation and the higher level of processed traffic.

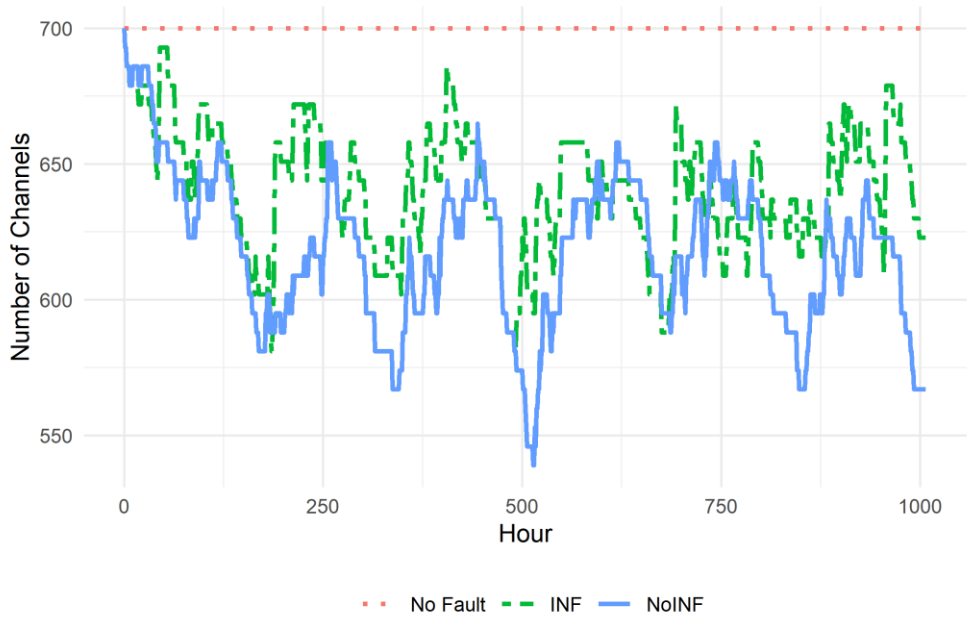

Figure 39. Comparison of different simulations regarding availability of communication channels (maximum within each hour period), considering the complete simulation period (6 weeks): ‘No Fault’; NoINF: ‘No Information’; INF: ‘Information Available’.

Now let us compute the financial performance of each simulation, get the economic perspective of the differences we have presented from the service delivery perspective and obtain VoI estimates we are looking for. We assume that a single and generic flat rate service plan applies to all users, defined under the guidelines presented in baseline definition (subsection 5.1.1). Under these circumstances, the financial performance of each simulation is a mirror of the traffic processed (Ec). Thus, after applying the charge plan, the aggregated data for the financial performance of the system (per day) leads to Figure 40, where the value of information is plotted side by side with the global performance of each simulation. The improvement on the service delivery is therefore also meaningful from the financial perspective.

Since the revenue follows service delivery ups and downs (affected by demand and network ability to deliver), we benefit from a daily estimate for VoPI covering a significant range of days, but we have to consider at least two observations. First, weekend mobile traffic is substantially lower when compared to the average working days (see Figure 40 for a financial perspective over the whole simulation period), which means that information benefits often get eclipsed within the weekend because the network is actually working as if overprovisioned (thus, able to deliver service even when there are some faults). Second, the simulation starts with a fully operational network subject to a subsequent adaptation period due to random faults injected into the system at a regular pace. Corrective actions take place (either resulting from planned maintenance or information flow and decision procedures) and eventually lead the system to a stable operation that is our proxy for a continuous operation of the telecommunications service. In other words, it is wise to exclude an initial period of simulation since the system is (highly) dependent on the initial conditions ('initialization bias').

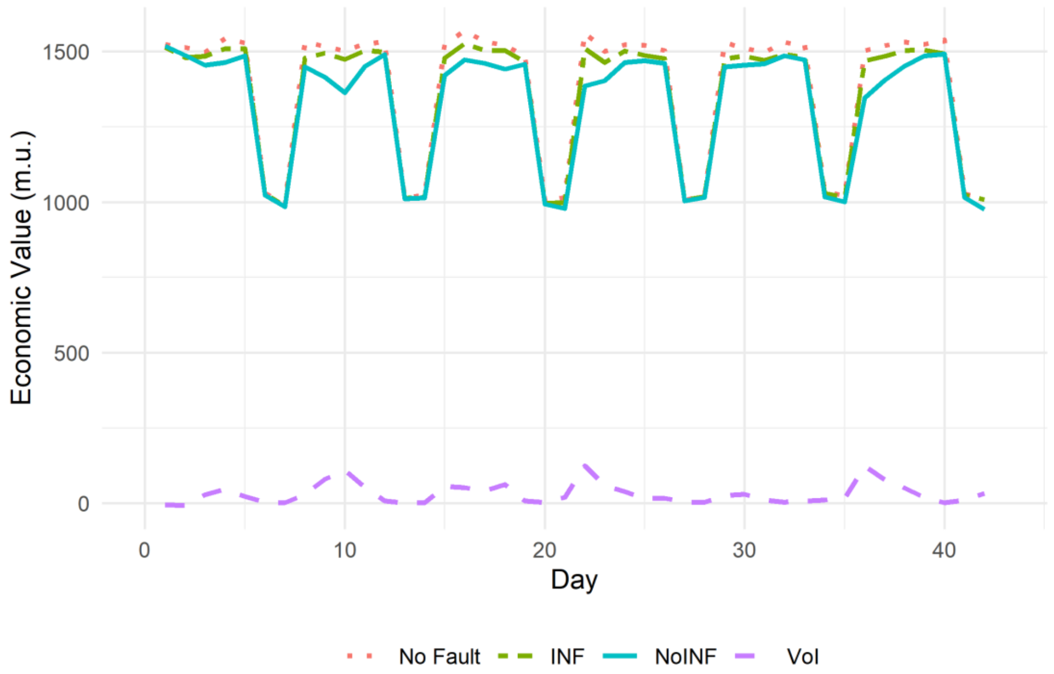

Figure 40. Daily revenue generated by the system (contexts of 'No Fault'; NoINF: 'No Information'; INF: 'Information Available'), based on services billed to users using a rate of 0.01 monetary units (m.u.) per minute, and the value of information computed on a daily basis during the simulation period (VoI: 'Value of Information').

The 'initialization bias' is inherent to any simulation model (in our case, it is essentially due to the assumption that the whole network infrastructure is in perfect operational conditions at the beginning of the simulation) and the usual method to minimize its impact is to define a 'truncation point' after which data is retained for analysis (Schruben, 1982). There are trade-offs involved in selecting the truncation point but Schruben recommends that bias control efforts should be kept in line with the magnitude of the problem.

Combining former observations, we chose to build our financial estimation for daily VoI of each scenario assuming (i) only business days are included (excluding weekends, since traffic is substantially lower when compared to business days and information benefits are blurred by the network's overcapacity); and (ii) an initial period of the simulation is excluded to minimize the 'initialization bias'.

In our case, the goal is to estimate the VoI, and this value always starts at zero and evolves smoothly, as shown in Figure 40. This means that we do not risk of getting inflated estimates for VoI resulting from the initialization bias, but still we may encounter biased estimates due to initial conditions of the simulation. Taking into account the behaviour of the revenues, including its weekly seasonality, we selected the end of the first week as the truncation point, meaning that VoI and related variables will be computed using data collected from the second week onwards (thus five weeks of simulation data will be used in experiments A, B, C and D).

In Table 14 we gather a summary of the basic descriptive statistics of the daily revenues for our example of scenario simulation. VoI was computed for each day (VoPI = INF - NoINF) leading to 25 values retrieved from the scenario and used in the analysis (since the simulation ran for 6 weeks but the first week is ignored and we excluded weekends).

Table 14

Descriptive statistics of daily revenues (expressed in m.u.) along with the value of information (VoI).

Context*	**Min**	**1Q****	**Median**	**Mean**	**3Q****	**Max**
'No Fault'	1488	1488	1511	1523	1532	1568
INF	1464	1477	1487	1489	1503	1526
NoINF	1346	1421	1455	1444	1470	1492
VoI	1.38	16.42	38.68	44.47	59.94	123.98

* VoI computed as INF-NoINF, given the contexts of 'No information' (NoINF) and 'Information Available' (INF). The 'No Fault' context is the the system simulated assuming that no failure event interferes with its performance.

** 1Q is the first quartile (25th percentile); 3Q is the third quartile (75th percentile)

To minimize the impact of extreme values we adopt the median (instead of mean) as the reference value for the estimates of daily revenue in the subsequent discussion and analysis. While the absence of information (NoINF) results in a financial loss of 56 monetary units (m.u.) when compared with the 'No Fault' context, when information is available that loss is reduced to 24 m.u. which means that VoI actually represents a huge reduction in the expected loss (57%).

The VoI is actually very sensitive to the 'No Information' operational conditions (we have discussed two alternative views of what a 'No Information' context could look like and adopted a static maintenance plan, but this is not the only possible alternative) and thus VoI value could be different both in nominal and relative terms depending on those operational conditions (in our experiment the 'No Information' performance is just 5.0% lower than the 'No Fault' context).

Beyond doubt is the fact that 'information availability' is comparable to an insurance policy against huge losses. As illustrated in this simulation, when the network is operating under failure pressure but management is able to take corrective actions based on perfect information, the reduction in revenue is kept at a low level (1.6% below performance under perfect operational conditions).

Finally, this general discussion on the VoI daily estimate (specifically the methods and general procedure followed) is valid regardless of the information being perfect or imperfect and thus will be applied in all experiments.

5.1.4 VoI Estimate Considering Real Life Charging Plans

In order to put these results into the practitioner's perspective, we will now extrapolate this simulation context to a more common-sense business situation. This exercise (and similar ones in this text) is developed using a certain billing rate of the service (which may have limited adoption in the marketplace) and with speculative assumptions (the fault rates adopted are not grounded in practitioners' inputs but in values adopted for simulation convenience). Nevertheless, we believe this is a valuable exercise because translates theoretical results (since simulation is always a theoretical endeavour) into more tangible and market related estimates. This is also a stimulus for practitioners to come forward, discuss these results, provide insights into the incomplete or limited information used and, in this way, set the stage for more accurate and valuable estimates.

We carry out this exercise by considering one publicly available charging plan for prepaid mobile communication mobile service by UZO,[7] a Portuguese service provider, offering the service for €0.099 per minute of communications. Table 15 summarizes this extrapolation exercise considering only working days (250 per fiscal year). This should be considered a conservative estimate, although very insightful, about the huge financial benefits that one should expect from information usage.

The extrapolation towards one million users challenges us to acknowledge that the magnitude of savings resulting from information usage and action taken to correct faulty network within the telecommunications context could easily reach millions of euros per year. Based on the previous example, the loss under a 'No Information' situation is €15.8M but keep in mind that this is a benign prospect from operating with no information. The improvement from the 'No

[7] https://www.uzo.pt/tarifarios/carregamento, accessed on 19th December 2021.

Information' to the 'Information Available' context is €10.9M and this rise in value resulting from information availability and action taken by the management team is actually the value of information (considering the presumed outcome from the 'No Information' context). The 'Information Available' context, although leading to a huge improvement compared to the 'No Information' context, still represents a loss of €6.8M when compared to the 'No Fault' context in which there are no faults.

Table 15

Extrapolation of revenue by a service provider with 1 million active customers adopting a flat rate charging plan of €0.099.

Description	**'No Fault' context**	**INF**	**NoINF**	**VoI***
Value captured on a daily basis considering 1 million users	€1 709 589	€1 682 434	€1 646 229	€43 764
Value captured in 250 working days considering 1 million users	€427 397 143	€420 608 571	€411 557 143	€10 940 914

* VoI computed as INF-NoINF, given the contexts of 'No information' (NoINF) and 'Information Available' (INF).

Recall that the results presented in this section resulted from considering (i) a failure rate affecting the network of 6% and (ii) a Pb of 6% used as the decision threshold by the management team to take action and re-establish service delivery within the expected GoS. Both the values assigned to the 'intervening variables' used to set the scenario were chosen for convenience, not based on practitioner inputs. In the following sections, we will present the results obtained from exploring each path (changing one variable while keeping the other constant) aiming to provide a broader understanding of the relationship of VoI with those relevant aspects of the telecommunications business (degree of network vulnerability to failures with impact on service delivery and decision threshold regarding network management).

5.2 Value of Perfect Information Sourced in the Network

In this section we present two experiments with the important assumption that the information available to the management team is perfect information (thus we will refer to it as Value of Perfect Information – VoPI) collected from the network monitoring in the sense that it allows for field action at the right site and assuring effective maintenance action with the net effect of recovering full operative capacity (in terms of communication channels) after a certain time period. For these experiments, the simulation ran throughout six weeks ensuring that enough output data is produced to obtain an accurate estimate of value and other performance indicators. An initial period of the simulation is excluded to minimize the initialization bias (one week).

5.2.1 VoPI Relationship with the Fault Rate

In this section we present the results obtained from exploring the impact on VoPI of changing network vulnerability to failures (expressed as fault rates) while keeping the same decision threshold regarding network management (experiment A). We consider a decision threshold at 2% Pb, which corresponds to choosing a high standard in terms of service grade delivered to the customer base.

The net effect of the failures is to diminish the ability of the network to process traffic, which in our case is captured by observing the available channels to provide the service. Figure 41 presents the contrast of four scenarios with increasing fault rates (2%, 4%, 6% and 8%) presented along with the 'No Fault' context (flat and stable line corresponding to the installed capacity and assuming perfect operational conditions of the network). Note that during the weekend, traffic is substantially lower when compared to business days and thus it is more unlikely to diverge from desired state of affairs in terms of grade of service (traffic blocking, which is the decision criterion to take action and correct failures) even with incoming fault events. This is why we observe the huge reduction of available channels during the weekend (we included some marks signalling the end of weeks 1, 2 and 3).

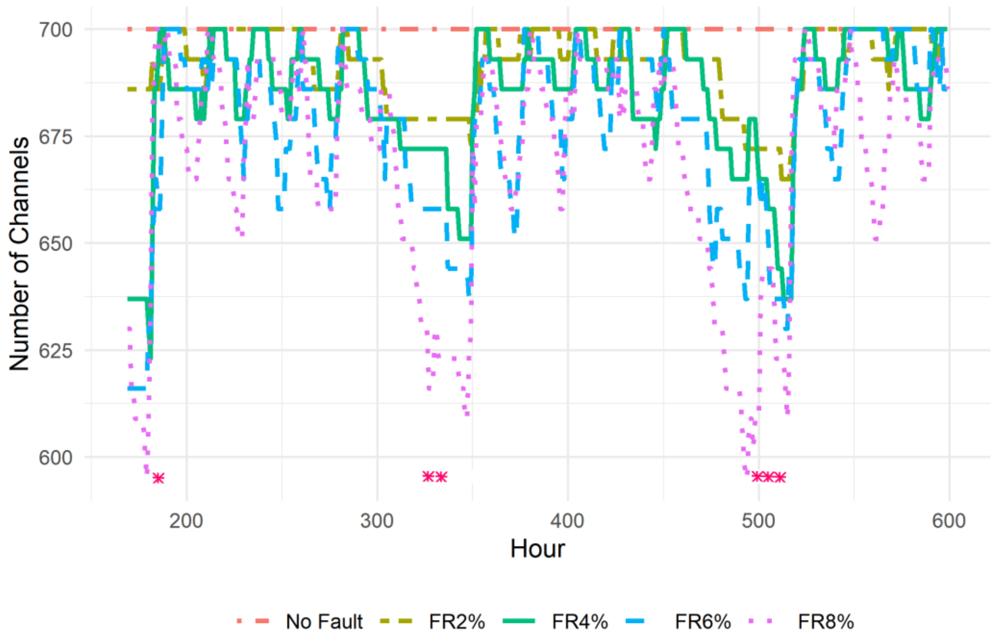

Figure 41. Comparison of different fault rate (FR) scenarios, namely 2%, 4%, 6% and 8% along with the 'No Fault' context that considers no faults. This plot corresponds approximately to two weeks (out of six) of the simulation under 'Information Available' supporting decisions towards corrective actions considering a threshold of 2% for Pb as the decision threshold (at the base station level). End of weeks 1 (*), 2(**) and 3 (***) signalled.

The availability of communications channels during the simulation period is the result of a balance between faults coming in, putting the network under operational stress, and efforts to correct those failures. In Figure 42 we show the average number of corrective actions generated by the simulation under 'Information Available' context (considering fault rates of 2%, 4%, 6% and 8%) and there seems to be a quasi-linear relationship between the fault rates and the number of corrective actions (which is the expected behaviour).

Recall that, for all these scenarios of experiment A, the decisions towards corrective actions use the same threshold of 2% of Pb at the base station level. Also, it is very important to keep in mindthat the simulations under the 'No Information' context get maintenance plans with the same number of actions (per week), thus ensuring that the economic improvements are directly linked to the use of information to take better actions (as opposed to the default maintenance plan).

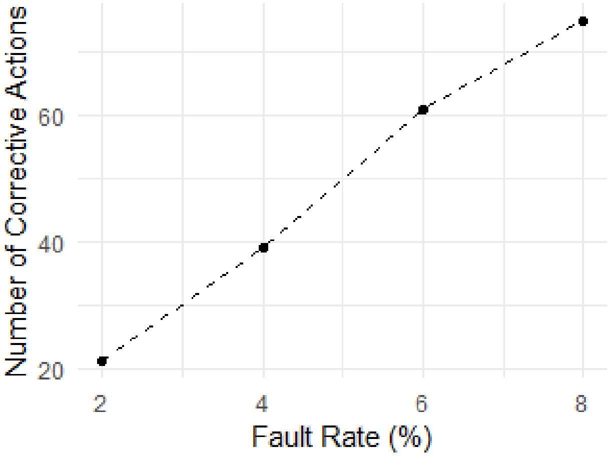

Figure 42. Average number of corrective actions (per week) generated by the simulation under 'Information Available' for different scenarios (fault rates of 2%, 4%, 6% and 8%), considering a decision threshold of 2% (Pb) at the base station level. The simulations under 'No Information' get maintenance plans with the same number of actions (per week).

We will now focus on the VoPI estimates. The daily values obtained in the simulations are presented in Figure 43, for the four scenarios associated with fault rates of 2% (FR2%), 4% (FR4%), 6% (FR6%) and 8% (FR8%). This spiky graph is explained by the fact that VoPI is computed as the difference between values captured for the global system; thus, relatively small differences in the total revenue become relatively high when compared with peer values.

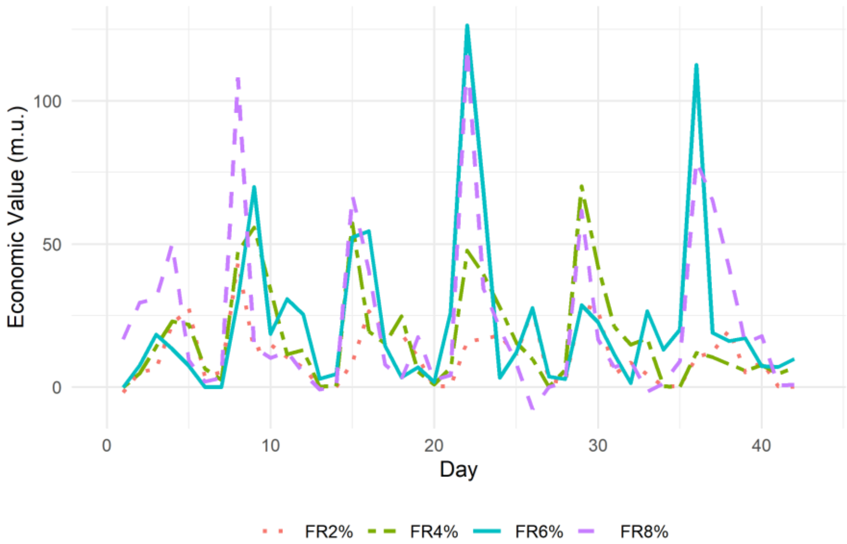

Figure 43. VoPI expressed in monetary units (m.u.) computed on a daily basis during the simulation period for the different scenarios (fault rates of 2%, 4%, 6% and 8%), considering a decision threshold of 2% (Pb) at the base station level.

We followed the VoI computation procedure explained in subsection 5.1.3 and in Figure 44 we explore the VoPI variability using the classic boxplot approach using VoPI data obtained in different scenarios (fault rates from 2% up to 8%), expressed in monetary units (m.u.), for experiment A.

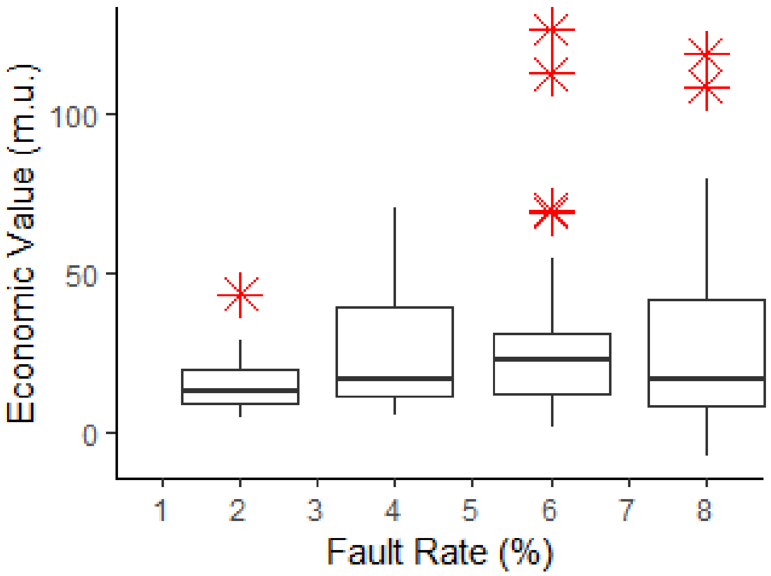

Figure 44. Boxplot of all the data points from VoPI for each considered fault rate, with data collected from the simulation period for the different scenarios (fault rates of 2%, 4%, 6% and 8%).

Results from simulations shows that the VoPI varies significantly on a daily basis, even within the same scenario. Although several simulated values qualify as outliers (in this case we used the IQR – interquartile range method because it does not depend on the mean and standard deviation of a dataset), it is fair to observe that, as fault rates get higher, the variability magnitude within the same scenario seems to increase. At the first glance adopting the mean value or the median value are both justifiable alternatives. Nevertheless, when we compare the results (Figure 45), a few questions emerge.

First and foremost, adopting a median value of VoPI from collected data as a daily VoPI estimate provides a conservative proxy for VoPI, since the mean alternative always provides much higher estimates. In both cases, VoPI seems to follow a monotonic relationship with the fault rate (which was our expected behaviour) until some sort of limit is reached, and afterwards it does fall down significantly. This rises an important interpretation question since this could point to a VoPI maximum related to the fault rate. Since VoPI is computed considering simulations with and without information availability, we proceed investigating how each of these curves behaves (Figure 46).

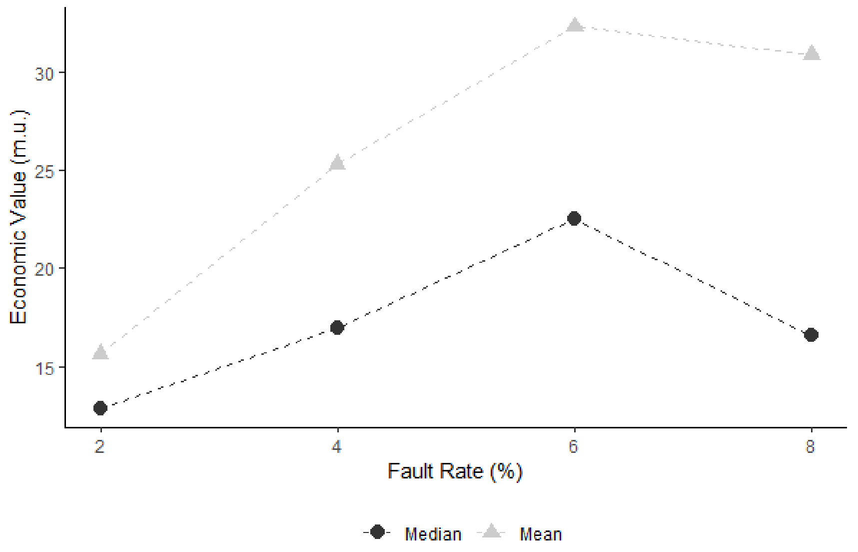

Figure 45. Graphical presentation of two approaches regarding VoPI estimation: (i) the one resulting from median values obtained from collected data and the other (ii) assuming VoPI is better estimated using the mean value.

In Figure 46 we represent the median values of revenue captured by the service provider, obtained from collected data for the 'No Fault' context, 'No Information' context and 'Information Available' contexts (using decision threshold of Pb=2% at the base station level and different fault rates per scenario).

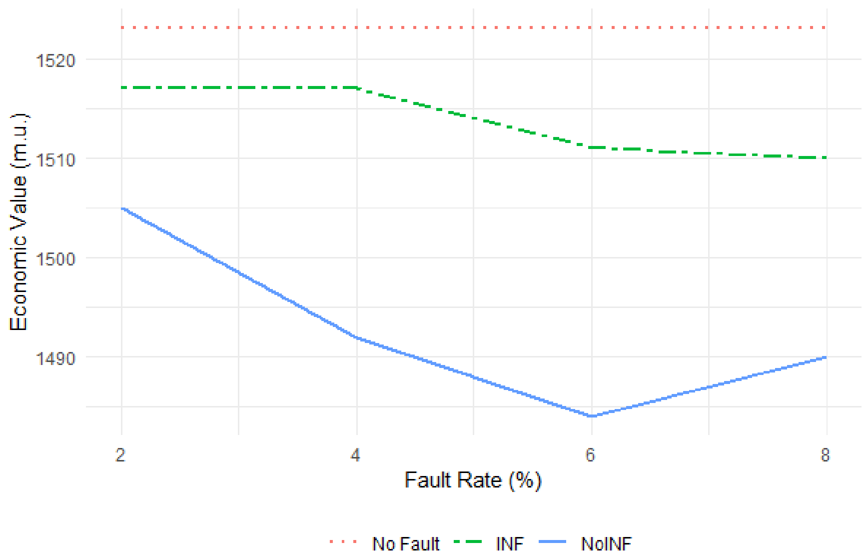

Figure 46. Graphical presentation of median of the daily revenue captured (billed) by the service provider from their users (expressed in m.u.). 'No Fault' context presented for reference; 'No information' (NoINF) and 'Information Available' (INF) both with active faults at different rates (FR).

We observe that the revenue captured when information is available is compatible with a simple negative relationship with the fault rate while the revenue captured when information is absent is not monotonic: it seems to decrease at higher rate until it reaches a limit after which it changes behaviour and even grows. This inflexion behaviour, although not expected, is perfectly understandable. In fact, we assumed a regular maintenance plan with an absolute efficiency in correcting the existing faults and with a number of corrective actions, in the 'No Information' context, which is identical to the number of necessary actions in the 'Information Available' context. Higher fault rates lead to a higher number of corrective actions in the 'Information Available' context and, therefore, they also lead to a higher number of actions in the 'No Information' context. In fact, the 8% fault rate scenario considers an average of 75 corrective actions per week, as shown in Figure 42, which is triple the number of base stations, meaning each base station is checked three times per week). In a sense, this is evidence of exhaustion of the small setting considered for this experiment and we have to take that issue into account at the moment of broader interpretation of the results.

The main conclusion at this point is that, before the exhaustion limit of the model, there is a positive relationship between the VoPI and the fault rate (higher the fault rate conveys higher VoIP) impacting the network and the service delivery.

Applying the same exact terms of the previous extrapolation (UZO service provider charging plan of €0.099 per minute of communication) we reach the results presented in Table 16 which summarizes this extrapolation exercise considering only working days (250 per fiscal year), excluding the 8% fault rate scenario for caution, as previously discussed.

Table 16

Extrapolation of revenue by a service provider with 1 million active customers adopting a flat rate charging plan of €0.099 for several contexts with active faults at different rates (FR) and a decision criterion at Pb of 2%..

Value captured on a daily basis considering 1 million users				
'No Fault' context	**INF**	**NoINF**	**VoPI***	**Fault Rate**
€1 723 166	€1 716 377	€1 702 800	€14 549	FR 2%
€1 723 166	€1 716 377	€1 688 091	€19 222	FR 4%
€1 723 166	€1 709 589	€1 679 040	€25 511	FR 6%
Value captured in 250 working days considering 1 million users				
'No Fault' context	**INF**	**NoINF**	**VoPI***	**Fault Rate**
€430 791 429	€429 094 286	€425 700 000	€3 637 260	FR 2%
€430 791 429	€429 094 286	€422 022 857	€4 805 460	FR 4%
€430 791 429	€427 397 143	€419 760 000	€6 377 863	FR 6%

* VoPI computed as INF-NoINF, given the contexts of 'No information' (NoINF) and 'Information Available' (INF).

A significant insight from this exercise is that, even with low fault rates affecting the network, the value of information easily reaches 7-digit values on an annual basis per million customers and even for a low fault rate of 2%, VoPI will surpass €3.6M.

The impact of any increase in the failure rate is an increase in the VoPI. This increase is as much as 16% for each 1% increase in the fault rate (with a nominal VoPI of €685 151 per additional 1% in the fault rate). In more general terms, network vulnerability (in this case measured in terms of failure rate) correlates positively with VoPI and is far from being an irrelevant aspect when evaluating the value of information.

5.2.2 VoPI Relationship with the Decision Thresholds

In the previous section we analysed the relationship between the VoPI and the network vulnerability to failures (expressed as fault rates), which is an important aspect, although not easily changeable by the management team. Now we turn our attention to the decision threshold used to take action and correct network failures (experiment B), an aspect that is purely a management choice and easily changeable as part of the company strategic options.

Recall that experiment B uses the baseline defined in subsection 5.1.1 and since this baseline was created assuming the GoS could reach a maximum of 1% (in line with industry standards used at the network planning stage), we considered it appropriate to start our study considering a decision threshold of 2% Pb and then explore successive scenarios of 4%, 6% and 8% (recall that these values of Pb used as input for decision making are computed at the base station level). Note that to adopt a decision threshold at 2% Pb is equivalent to choosing a high standard in terms of service grade delivered to the customer base. On the other hand, recall that in experiment B we use as additional controlled variable the fault rate of 6% (value chosen for convenience, i. e. fast impact of failures on network), thus used in every scenario presented in experiment B.

Again, the net effect of the failures is to reduce the ability of the network to process traffic, which in our case is captured by observing the available channels to provide the service. Figure 47 presents the contrast of four scenarios with the same fault rate (6%) but increasing values of Pb (2%, 4%, 6% and 8%), which corresponds to adopting increasingly relaxed grade of service for the end user.

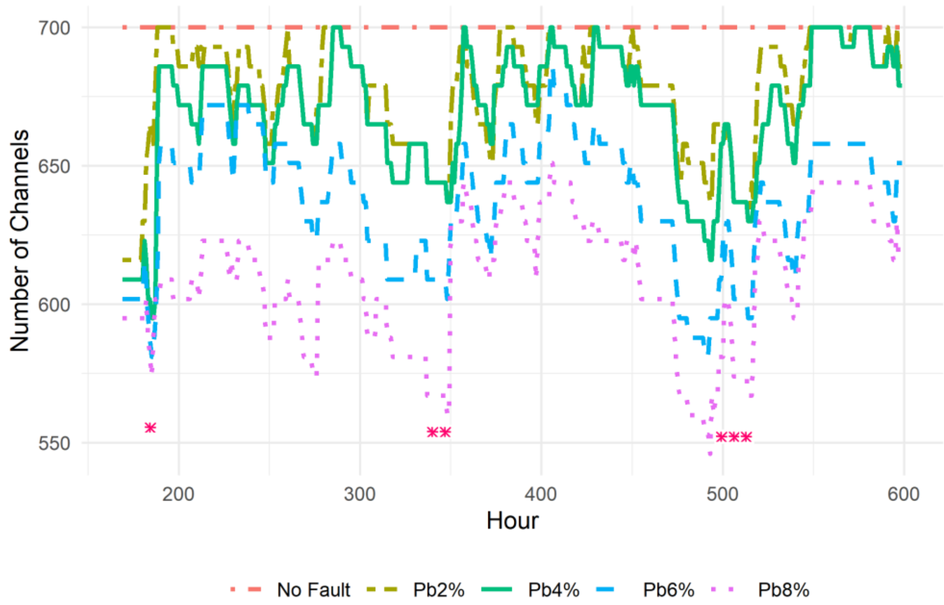

Figure 47. Comparison of different decision thresholds scenarios, namely considering Pb of 2%, 4%, 6% and 8% along with the 'No Fault' context (only two weeks). This plot corresponds the simulation under 'Information Available' supporting decisions towards corrective actions considering a fault rate of 6% affecting the system. End of weeks 1 (*), 2(**) and 3 (***) signalled.

As observed in the previous section, during the weekend, traffic is substantially lower, which has a side effect of changing the conditions to take action and correct failures, and that is why we observe the huge reduction of available channels during the weekend (we included some marks signalling the end the weeks 1, 2 and 3). In Figure 48 we show the average number of corrective actions (per week) generated by the simulation under 'Information Available' for different scenarios (Pb from 2% to 8%) and clearly there is a negative relationship between the decision thresholds and the number of corrective actions generated by the 'Information Available' context (which is the expected behaviour). As explained before, the simulations under 'No Information' available get maintenance plans with the same average number of actions as the same scenario simulation under the 'Information Available' context.

When compared with those of experiment A (presented in the previous section and adopting a fixed decision threshold and different fault rates per scenario), it is worth mentioning that the average number of actions (per week) decreases as we increase the Pb value used as decision threshold (in a fairly linear way although we have limited data to draw a definite conclusion). In other words, growing values of Pb do not generate high values of corrective actions (as high fault rates do) but the opposite is true, as shown in Figure 48.

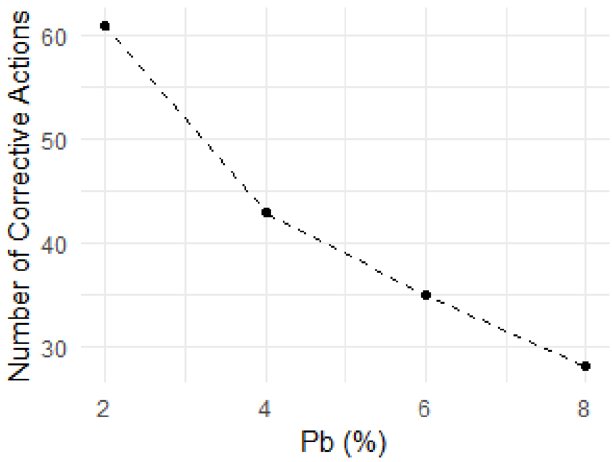

Figure 48. Average number of corrective actions (per week) generated by the simulation under 'Information Available' for different scenarios (Pb from 2% to 8%) supporting decisions towards corrective actions considering a fault rate of 6% affecting the system. The simulations under 'No Information' get maintenance plans with the same weekly average number of actions.

Now let us focus on the VoPI estimates, starting with the daily values presented in Figure 49 for the four scenarios associated with decision thresholds defined by values of Pb of 2%, 4%, 6% and 8%.

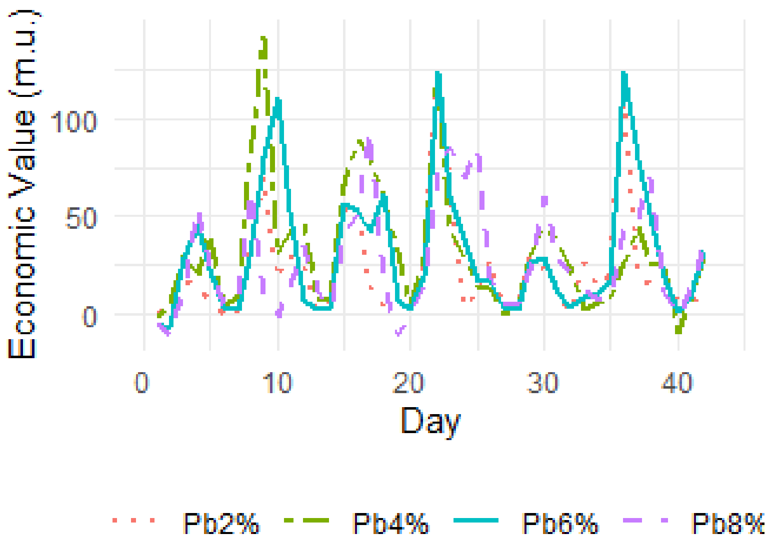

Figure 49. VoPI expressed in monetary units (m.u.) computed on a daily basis during the simulation period for the different scenarios (Pb of 2%, 4%, 6% and 8% at the base station level), considering a fault rate of 6% for all scenarios.

In Figure 50 we explore the VoPI variability using the classic boxplot approach using VoPI data obtained in different scenarios (Pb from 2% up to 8%), expressed in monetary units (m.u.), for experiment B. The data confirms the expected impact of decision threshold on the VoPI and actually shows that VoPI varies significantly on a daily basis, even within the same scenario (similar behaviour as in the experiment with changing fault rates) with outliers associated with low Pb (and corresponding high volume of corrective actions).

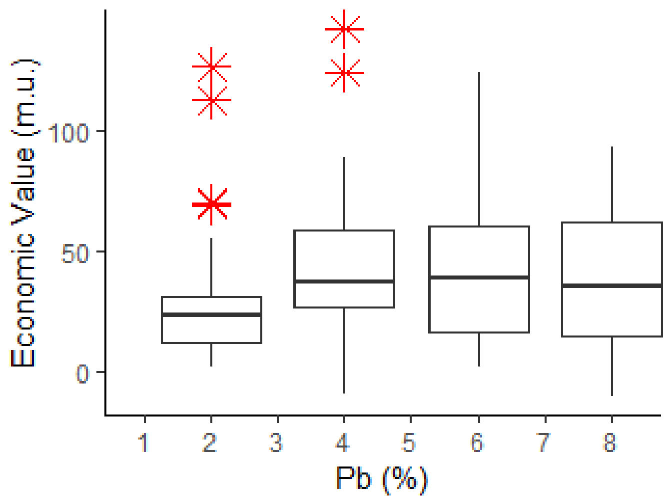

Figure 50. Boxplot of all the data points from VoPI, with data collected from the simulation period for the different scenarios (Pb of 2%, 4%, 6% and 8%).

In Figure 51 we compare the mean and median estimates for VoPI confirming that adopting a median value of VoPI from collected data as a daily VoPI estimate provides a conservative proxy for VoPI (although the distance between both curves decreases as the Pb goes up).

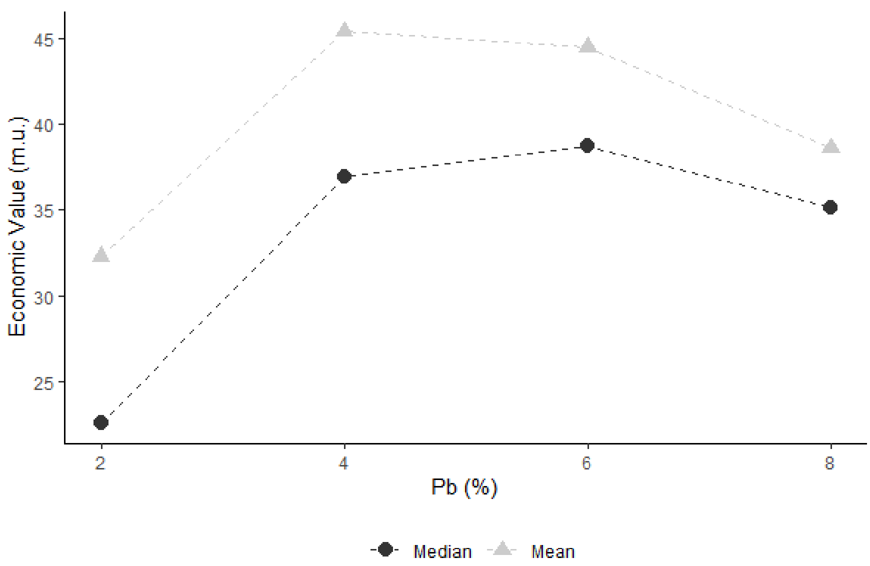

Figure 51. Graphical presentation of two approaches regarding VoPI estimation: (i) one resulting from median values obtained from collected data and (ii) the other assuming VoPI is better estimated using the mean.

The VoPI seems to follow a non-linear relationship with Pb with a convex type of curve, with an initial increase, a maximum value of VoPI and then decreasing values. Given the available data, VoPI might have a maximum related to Pb (we have gathered limited data to sustain that conclusion but the current evidence points in this direction). Since VoPI is computed considering simulations with and without information availability, we proceed to investigate how each of these curves behave (Figure 52).

In Figure 52 we represent the median values obtained from collected data for the 'No Fault' context, 'No information' context and 'Information Available' context with variable Pb per scenario (and constant fault rate of 6%). We observe that the revenue captured when information is available is compatible with a negative relationship with Pb and the value captured when information is absent also seems to decrease in a monotonic way. Those curves do not change proportionally to Pb, thus leading to the existence of a maximum in the VoPI curve.

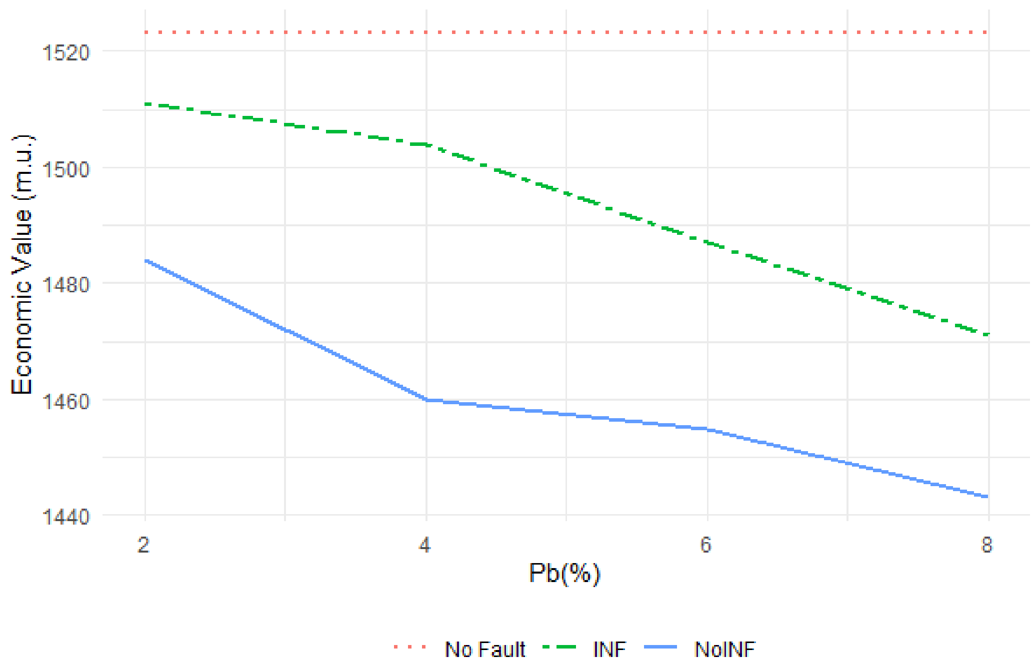

Figure 52. Graphical presentation of the median of the daily revenue by the service provider from their users (expressed in m.u) for the contexts of 'No Fault'; 'No information' (NoINF) and 'Information Available' (INF), both with active faults at constant rates (6%). Scenarios included are Pb of 2%, 4%, 6% and 8%.

Finally applying the same exact terms of the previous extrapolation (UZO service provider charging plan of €0.099 per minute of communication) we reach the results presented in Table 17 which summarizes this extrapolation exercise considering only working days (250 per fiscal year), as previously discussed.

This exercise is a variant of the extrapolation presented in the last section, so it is not surprising that we found similar magnitudes in VoPI. Apart from the magnitude, it is very important to underscore the conclusion that the matter of choosing the decision threshold is not innocuous in terms of VoPI and actually the impact of any increment in Pb might result in increasing the VoPI as much as 30% for each 1% increase in the Pb (valid for the fault rate of 6% used in this experiment and if Pb is in the range from 2% to 4%).

Table 17

Extrapolation of revenue by a service provider with 1 million active customers adopting a flat rate charging plan of €0.099 for several contexts at different Pb as decision criterion and with active faults at 6% rate.

Value captured on a daily basis considering 1 million users				
'No Fault' context	**INF**	**NoINF**	**VoPI***	**Pb**
€1 723 166	€1 709 589	€1 679 040	€25 511	Pb 2%
€1 723 166	€1 701 669	€1 651 886	€41 775	Pb 4%
€1 723 166	€1 682 434	€1 646 229	€43 761	Pb 6%
€1 723 166	€1 664 331	€1 632 651	€39 781	Pb 8%
Value captured in 250 working days considering 1 million users				
'No Fault' context	**INF**	**NoINF**	**VoPI***	**Pb**
€430 791 429	€427 397 143	419 760 00€0	€6 377 863	Pb 2%
€430 791 429	€425 417 143	€412 971 429	€10 443 651	Pb 4%
€430 791 429	€420 608 571	€411 557 143	€10 940 349	Pb 6%
€430 791 429	€416 082 857	€408 162 857	€9 945 257	Pb 8%

* VoPI computed as INF-NoINF, given the contexts of 'No information' (NoINF) and 'Information Available' (INF).

In more general terms, the decision threshold (in this case based on Pb used in terms of threshold value towards action) shows a non-linear relation with VoPI with a convex type of curve with a maximum value of €10.9M for VoPI (per million users, and fault rate of 6%) and is far from being an irrelevant aspect in the hands of the management team.

5.2.3 VoPI Relationship with the Volume of Corrective Actions

The data collected from the simulation experiments A and B, presented in previous sections, showed that the volume of corrective actions does vary significantly. In the initial experiment we varied the fault rate from 2% up to 8% and we observed that average number of corrective actions (per week) increased from 21 to 75 (Figure 43), and an implicit relation between number of corrective actions and the VoPI seemed plausible. In the second experiment, we varied the decision threshold from Pb 2% up to 8% and the corresponding number of actions went down from 61 to 28 (Figure 50) but the hypothetical relationship between number of actions and VoPI is not obvious. In both experiments, there is a strong impact from the intervening variables in the number of corrective actions and we also observed significant impact on the VoPI, so we decided to investigate a possible correlation between the number of corrective actions and VoPI as that correlation seems reasonable. In Figure 53 we plot VoPI as dependent from the observed number of corrective actions resulting from both experiments (which used the same baseline). The two experiments show a complete distinct profile in terms of VoPI relation to the number of corrective actions.

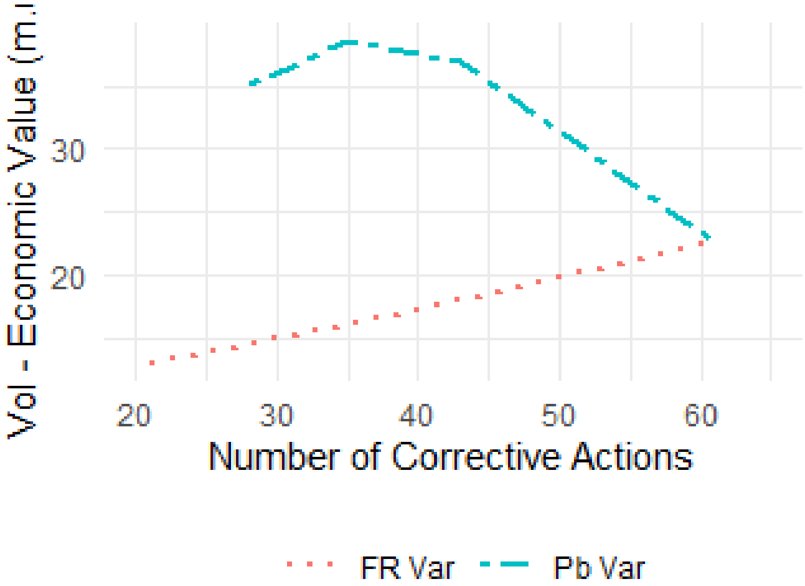

Figure 53. VoPI relationship with the volume of corrective actions.

In Figure 54 we combine the data in a scatter plot and we test the hypothesis that the correlation is significantly different from zero. This hypothesis is not confirmed (the p-value of the Pearson test is 0.9444, which is not less than the significance level alpha = 0.05).

The absence of general correlation between number of corrective actions and the VoPI is a significant insight since that conclusion was not obvious considering the data collected from experiment A presented before.

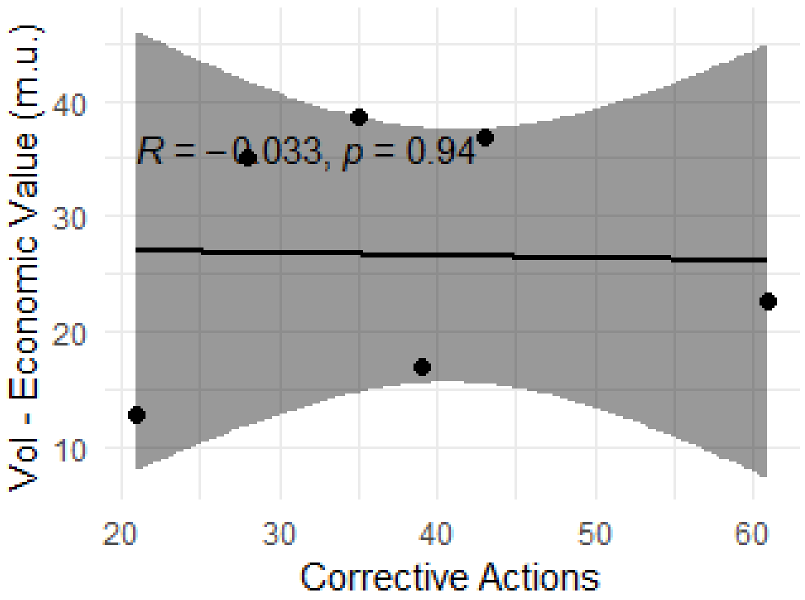

Figure 54. Correlation between VoPI and the volume of corrective actions.

5.3 Value of Imperfect Information Sourced in the Network

In this section we present two experiments (C and D) designed explore the impact of imperfect information used by the management team within the decision-making cycle (as discussed in subsection 4.2.4) thus we will refer to it as Value of Imperfect Information – VoII. The basic aspects of imperfect information modelling are explained in subsection 4.3.2. We used the 'call blocking probability' (Pb) as the key indicator of network performance, which represents the stimulus to the decision (thus only information from the network monitoring activities is used).

In experiments C and D we explore two distinct perspectives of VoII: (i) how VoII evolves when the *ex ante* imperfection magnitude changes and (ii) how VoII evolves when the *ex post* imperfection magnitude changes. Both two experiments use the same baseline (subsection 5.1.1). In experiment C, the *ex ante* imperfection magnitude is our intervening variable, so we add a different *ex ante* imperfection magnitude for each scenario. In experiment D, the *ex post* imperfection magnitude constitutes our intervening variable, so we consider different *ex post* imperfection magnitudes for each scenario. To ensure comparability, we use the same imperfection magnitudes (15%, 30%, 45% and 60%) in both experiments, thus creating four scenarios for each experiment.

For these experiments, the simulations also ran throughout six weeks, ensuring that enough output data is produced to apply the value of information computation procedure described in subsection 5.1.3 for each iteration of the scenario. In these experiments we introduce extra randomness in the simulation and we expect to augmented the robustness of the results by performing multiple iterations of the same scenario, producing VoII estimates that afterwards are combined to the final scenario estimated VoII adopting the mean value of those iterations (of the same scenario). As discussed in the previous section, we faced high computational cost (both in the time and in the financial perspectives of each iteration of the simulation), thus we assumed the limit of four iterations by scenario treating experiments C and D with similar criteria.

5.3.1 The Relationship between VoII and *Ex Ante* Imperfection Magnitude

Experiment C was designed to look into the impact on the value of information when the *ex ante* information becomes (increasingly) imperfect thus the *ex ante* imperfection magnitude is our intervening variable (magnitudes of 15%, 30%, 45% and 60% are used for each scenario).

The imperfect information was simulated through an error assigned to each base station, as described in subsection 4.3.2. We ran four iterations per scenario (as discussed in the following paragraphs) and final VoII estimate is assigned to each scenario as the average value of the corresponding iterations.

Before we present results, some additional contextualization to this experiment is required. In our model of the *ex ante* imperfect information, the magnitude of imperfection is a characteristic of each base station, thus it is not equal in every base station of a certain experiment scenario. The translation of this paradigm into our model leads us to assign random values of error to each base station comprised within maximum limits (positive and negative). From an experiment perspective, if we assign a 15% 'BS error' to the scenario, this value thus corresponds to the upper (+15%) and lower (-15%) limits of the error each base station will get in the setup step, assigned considering a uniform probability distribution between those limits. In our scenario we considered 25 cells, each one served by an independent base station, which means 25 random values (ranging from the minimum to the maximum) are generated and assigned to each base station during the scenario setup step. In Figure 55, we show the outcome of the 'BS error' sampling for the example of 15% limit in the *ex ante* imperfect information experiment (four iterations of the scenario are considered).

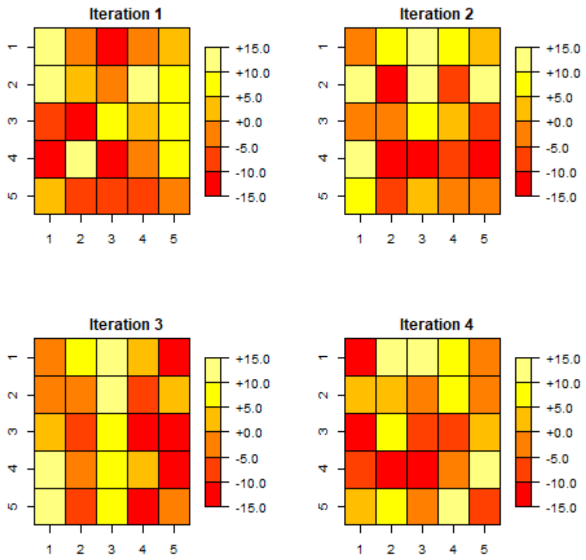

Figure 55 – Ex ante imperfect information – four samples of BS error values used for the scenario with 15% error limit. Each position in the matrix corresponds to different geographic areas served by individual BASE STATION s.

Finally, the random noise signal should have minor significance in the imperfection, and is thus generated dynamically in each measuring instant considering a Gauss distribution of zero mean (and, in this experiment, 10% of the imperfection magnitude value is used as standard deviation).

One big issue with this experiment was the computational cost (both in time and economic perspectives) of each iteration of the simulation. In our context, to obtain meaningful and valid results we had to generate multiple samples, thus creating repeated variations of the same scenario (iterations) and finally combining them to obtain more robust results (the scenario result is the average of the iteration's results associated with that scenario). However, each simulation can take some weeks to run. In our case, due to the computational cost, we assumed the limit of four scenarios and four iterations for each scenario.

A variety of techniques may be used to generate samples in a simulation (Douglas-Smith et al., 2020), including the Latin Hypercube Sampling (LHS), which is a technique particularly tailored for generating random samples of parameter values and drastically reducing the number of runs that are necessary for achieving reasonably accurate results. The LHS method improves upon simple random sampling and is recognized as a good method to use for selecting values of input variables (Mckay et al., 2000). Moreover, it is available in the R project and we implemented our experiment using the FME package (Soetaert & Petzoldt, 2010).

As we introduced before, imperfect information, when present in the stimulus, will produce false negatives and false positives in terms of problem identification. The purpose of the signal Pb is to detect faulty base station (in our experiment, the threshold is Pb > 2%). We can thus classify the outcome of the problem identification as:

- True positives (TP): base station is faulty and is detected as such (these are cases in which the 'Measured Pb' is greater than threshold, and 'Real Pb' is actually above the threshold).
- True negatives (TN): base station is not faulty and is detected as such (these are cases in which the 'Measured Pb' is lower than threshold, and 'Real Pb' is actually below the threshold).
- False positives (FP): base station is detected as faulty, while base station is operating within performance limits (these are cases in which the 'Measured Pb' is greater than the threshold, and 'Real Pb' is actually lower than the threshold).
- False negatives (FN): base station is detected as operating within performance limits, but actually base station is faulty (these are cases in which the 'Measured Pb' is lower than the threshold, and 'Real Pb' is actually above the threshold).

In Table 18, we present the aggregated values of problem identification outcome, considering the average of the four iterations in each scenario. Notice that we excluded the first week's results (thus only five weeks are considered) and we narrowed the decisions to the period between 11 am and 8 pm, since the demand is far below the installed capacity and thus the probability of call blocking is very low, i.e. close to zero. As a general rule, the following results assigned to each scenario are computed as the average values of the corresponding iterations.

Table 18

Ex ante imperfect information – summary of problem identification outcomes per scenario.

	Imperfection magnitude of the scenario			
Outcome Classification	**15%**	**30%**	**45%**	**60%**
FN	36	64	91	117
FP	30	58	92	139
TN	5763	5714	5669	5615
TP	422	414	398	379
Error Rate	1.04%	1.95%	2.92%	4.09%

Figure 56 highlights the evidence we got in the simulation results from our experiment on how the increasing degree of *ex ante* imperfect information translates into problem identification error rate. In this experiment we observe that the problem identification strategy based on threshold limits used in this context is able to limit the problem identification error to nearly 1% for every 15% increment in the imperfection magnitude of the stimulus.

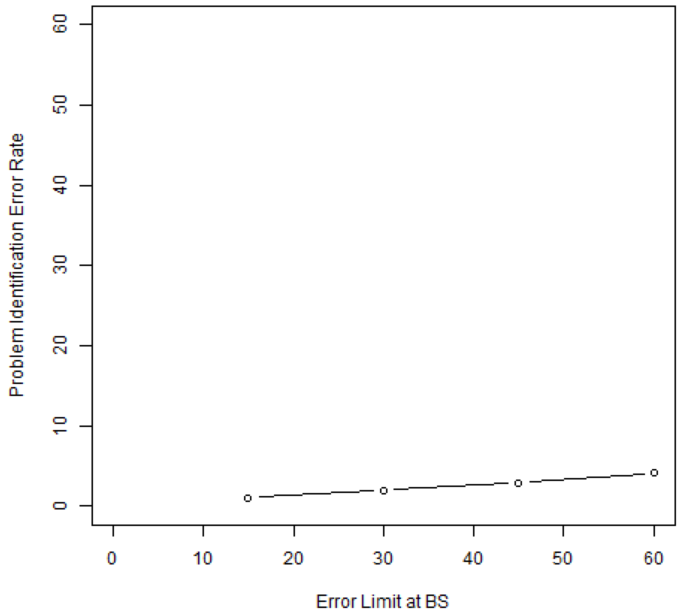

Figure 56 –Error rate, as it relates to the degree of ex ante imperfect information.

Combining all the observations from the experiment (the number of corrective actions of each scenario is computed as the average value for the corresponding iterations), a pattern of growing number of corrective actions following the increasing degree of *ex ante* imperfect information is evident, as shown in Figure 57. However, the range of values for the number of corrective actions overlaps between distinct scenarios, meaning that the variance observed (in number of corrective actions) is such that some iterations of a scenario with a lower imperfection magnitude may have higher number of corrective actions than other iterations of one scenario with higher imperfection magnitude.

The net effect of the *ex ante* information imperfection are useless corrective actions and absence of corrective actions, thus impacting the ability of the network to deliver the service and, in our model, this is shown by the availability of communication channels throughout the simulation period.

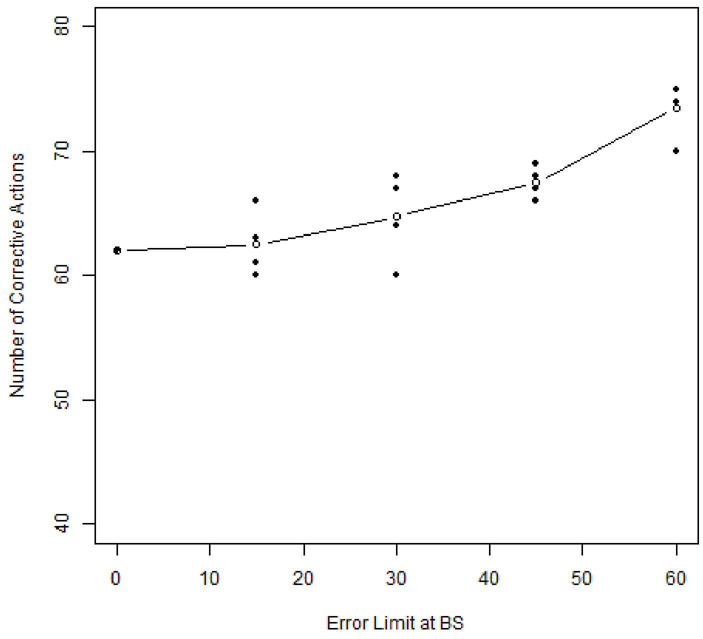

Figure 57 – Number of corrective actions as it relates to the degree of ex ante imperfect information, starting with 'No Error' context (network with 6% fault rate and decision threshold Pb of 2% and perfect information).

The comparison between our four scenarios in terms of channel availability over time (Figure 58) is a simple way to catch the difference at network level between them.

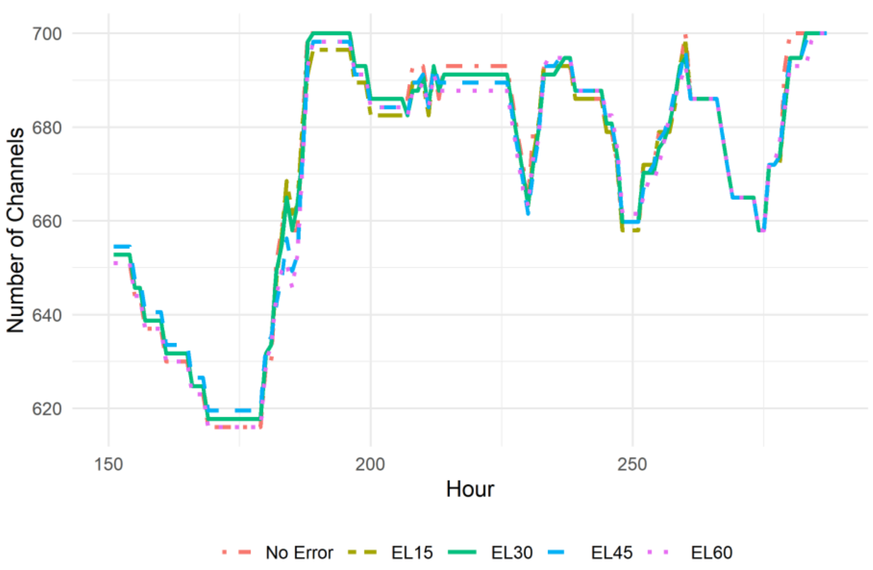

Figure 58 – Comparison of different scenarios (BS Error Limit (EL) of 15%, 30%, 45% and 60%) for the availability of communication channels (average of the maximum number of channels for each hourly period of iterations by scenario), considering an illustrative segment of the simulation period. (plus 'No Error' context: network with 6% fault rate and decision threshold Pb of 2% and perfect information).

Notice that the general pattern of the curves from distinct scenarios are quite similar and the differences, although visible, are fuzzy in terms of visual conclusions in which one is the best performer. This is explained by the aforementioned range of values for the number of corrective actions overlapping between distinct scenarios.

Finally, let us consider the value of (imperfect) information and how the magnitude of imperfection in *ex ante* information impacts its value. Figure 59 illustrates the results obtained for VoII from our experiment considering four iterations per each different scenario (as explained before). The main observation is that the value of *ex ante* imperfect information decreases progressively as the magnitude of imperfection increases. In fact, an increase in the magnitude of imperfection of up to 60% leads to a 45% decrease in the value of information (see Table 19 for numerical values).

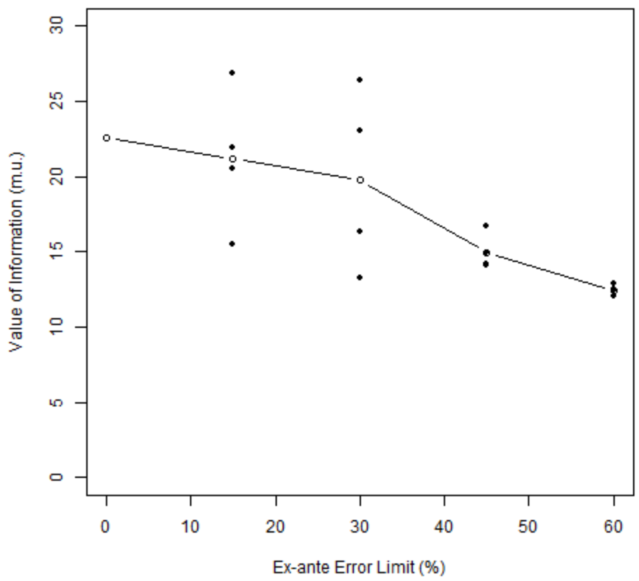

Figure 59 – Value of ex ante imperfect information of different scenarios (Error Limit of 15%, 30%, 45% and 60%) plus 'No Error' context (network with 6% fault rate and decision threshold Pb of 2% and perfect information).

The performance of VoII is explained by the fact that decisions based on false positives (FP) (base station is detected as faulty while base station is operating within performance limits) generate anticipatory reaction, in the sense that the problem is corrected before the business is significantly impacted and also the random magnitude of error (with a maximum limit) means that the net effect of the error is lower than the reference magnitude value used to describe the scenario.

5.3.2 The Relationship between VoII and *Ex Post* Imperfection Magnitude

Our experiment D aims to explore how VoII evolves when the *ex post* imperfection magnitude changes. We used the same baseline and the same paradigm as described in the experience C but in experiment D, the *ex post* imperfection magnitude constitutes our intervening variable, so we consider different *ex post* imperfection magnitudes for each scenario.

Recall that, at simulation level, the *ex post* imperfect information was implemented using an unsuccessful implementation rate (stable during the simulation period), applied randomly to all corrective actions, part of which became ineffective actions.

The net effect of the *ex post* information imperfection is the possibility of unsuccessful corrective actions taken after problem identification impacting the availability of communication channels. In Figure 60 we compare our four scenarios (and the No Imperfect Information) in terms of channel availability over time. Notice that the general pattern of the curves for distinct scenarios are quite different in terms of visual analysis, which anticipate much higher differences in terms of VoII, compared to the previous experiment.

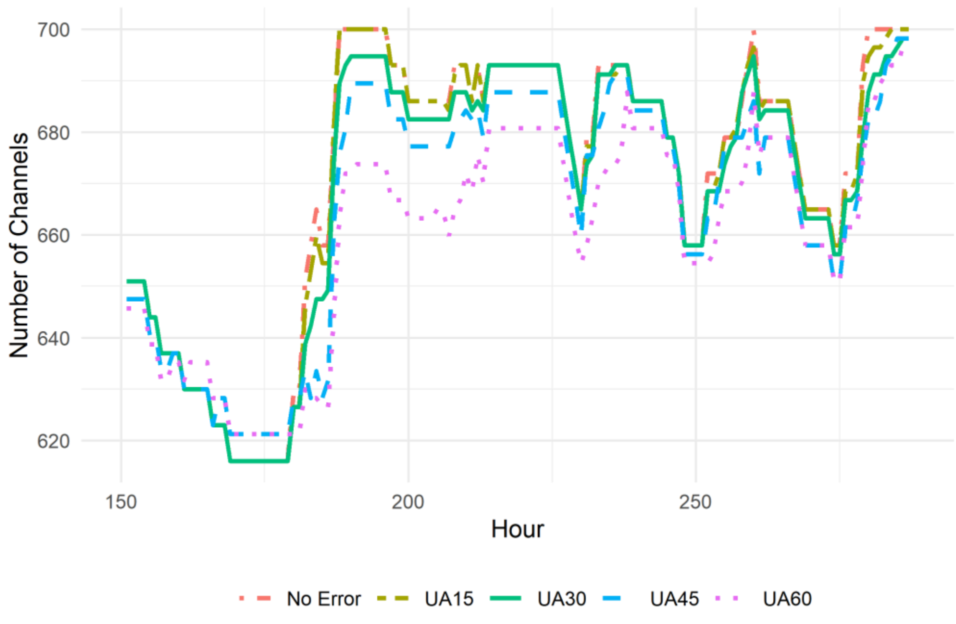

Figure 60 – Comparison of different scenarios (ex post unsuccessful action (UA) rates of 15%, 30%, 45% and 60%) for availability of communication channels (maximum for each hourly period), considering an illustrative segment of the simulation period (6 weeks), plus 'No Error' context (network with 6% fault rate and decision threshold Pb of 2% using perfect information).

Another aspect where there is a clear difference, compared with the first experience, is the number of corrective actions. In this experiment, we observe much higher growth rate as the imperfection of the information increases and thus the range of values for the number of corrective actions is completely different between different scenarios. Combining all the observations from the experiment, a pattern of incremental and significant growth in the number of corrective actions following the increasing degree of *ex post* imperfect information is evident, as shown in Figure 61.

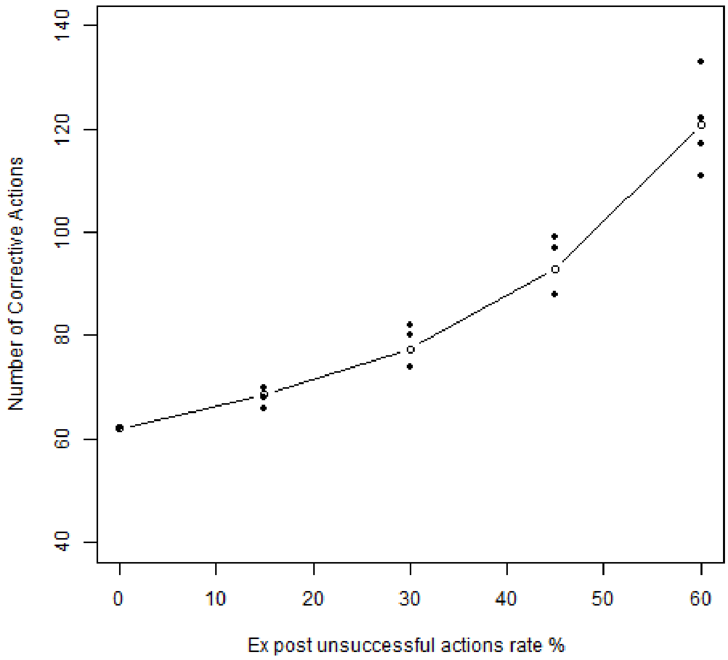

Figure 61 – Number of corrective actions as it relates to the degree of ex post imperfect information (ex post unsuccessful action (UA) rates of 15%, 30%, 45% and 60%), plus starting point of 'No Error' context (network with 6% fault rate and decision threshold Pb of 2% and perfect information).

Let us now turn to the value of the (imperfect) information and how the magnitude of imperfection of *ex post* information impacts it. Figure 62 shows the results obtained in our experiment for multiple iterations (four) of different scenarios in terms of value of information.

The main conclusion is that the impact of imperfect *ex post* information on value is much higher than was seen in the *previous experiment (ex ante* information case). The value of *ex post* imperfect information falls at a higher pace (compared to the first experiment), as the degree of imperfection increases, reaching near-zero values when imperfection magnitude is close to 50%. Whether the information is used or not is always optional, which ensures that the value of information is always positive (or one would otherwise assume that it would be disposed of and not used).

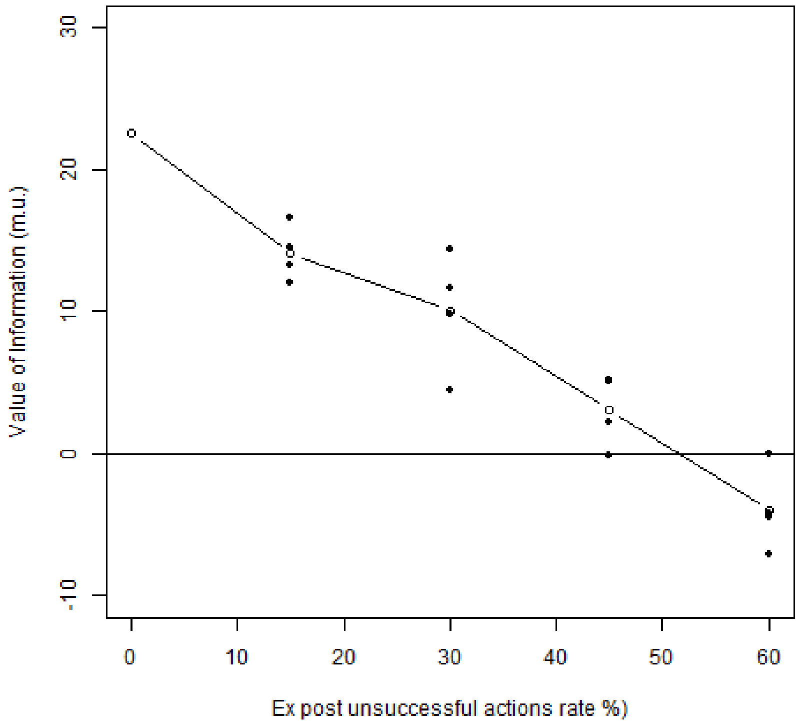

Figure 62 – Value of imperfect information of different scenarios (ex post unsuccessful action rates of 15%, 30%, 45% and 60%) plus 'No Error' context (network with 6% fault rate and decision threshold Pb of 2% and perfect information).

But this experiment shows that the value added by information should be evaluated and positive contribution to the business should not be taken for granted (as a general rule and specially when information is imperfect). Our extreme scenario (imperfection magnitude of 60%) is one of those situations where management should ignore the information, since it does not add value to business and should use the 'No Information' option of conducting operations. Keep in mind that the value of information is always contingent on the outcomes (in our case the financial performance) associated with the 'No Information' alternative.

5.3.3 Qualitative and Quantitative Views on Ex ante and Ex post VoII Estimates

Our broad context is the estimation of the value of the information used in network management activities. In this context, imperfect information can emerge before or after the 'Problem Identification' step, which we considered as the pivotal moment.

We emphasized that information imperfection differs significantly between the *ex ante* and *ex post* contexts. For *ex ante* information, accuracy issues are the main source of imperfection, whereas if management reaches the conclusion that ex post information needs improvement, other information attributes and quality criteria, such as completeness, correctness and clarity, rather than accuracy, would need improvement.

Thus, the following comparative analysis is conducted with caution and using magnitudes of imperfection on *ex ante* and *ex post* context as reference, useful for a macro analysis of the decision process and the impact of imperfect information used along it, but recognizing that such comparison does have limitations in terms of detailed interpretation.

We conducted two complimentary experiments designed to research the value of imperfect information *ex ante* and *ex post* that pivotal moment, using the same baseline. For each experiment we built four scenarios with increasing level of imperfection of the same magnitude (15%, 30%, 45% and 60%) in both experiments. Individual results of those experiments were presented in the last sections and now, in Figure 63, we put those results into perspective, thus setting the stage for qualitative and quantitative analysis. The main observation is that the value of information is consistently decreasing as the degree of imperfection of information increases, but the pace of the value decay is completely distinct between experiments.

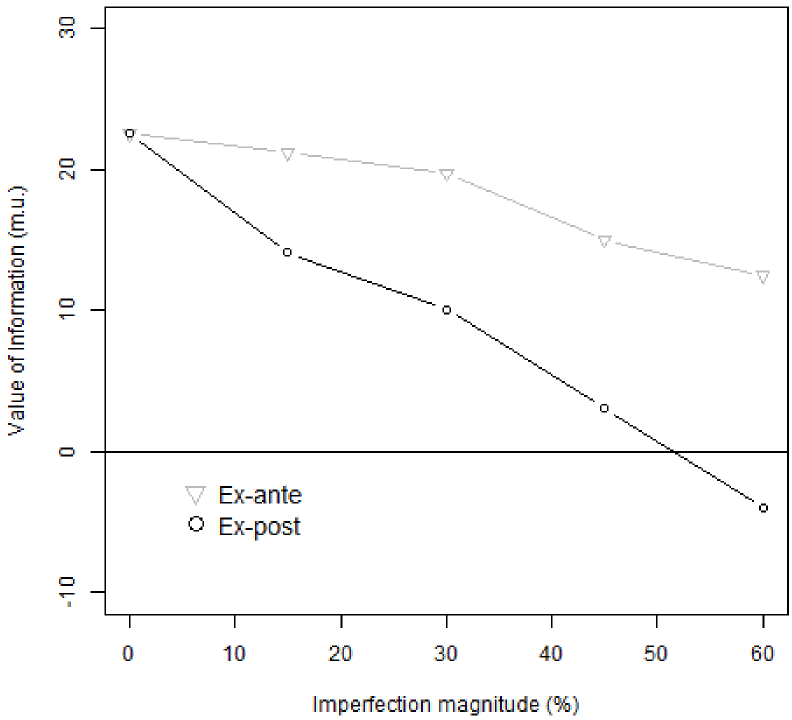

Figure 63 – Value of imperfect information in different scenarios (imperfection magnitude of 15%, 30%, 45% and 60%) plus 'No Error' context (network with 6% fault rate and decision threshold Pb of 2% and perfect information).

In Table 19, we present the summary of results comparing *ex ante* and *ex post* imperfect information experiments. The *ex ante* cumulative loss of 45% in value of information after error magnitude of 60% means that *ex ante* information is able to add value even when it is significantly imperfect while, by contrast, ex post information with similar magnitude of imperfection is useless (it would generate loss if used). Taking a more general (albeit conservative) interpretation, the increment in value of improving *ex post* imperfection one order of magnitude roughly doubles the value of information from improving *ex ante* imperfection in equivalent magnitude. This is a huge difference, since it means that hypothetical equivalent projects (in terms of investment), reducing with similar magnitude the imperfection of information *ex ante* and *ex post*, would generate completely different return-on-investment.

Table 19

Value of imperfect information (VoII) of different scenarios (imperfection magnitude of 15%, 30%, 45% and 60%) complemented with incremental differences between scenarios.

Imperfection magnitude	**VoII Ex ante**	**Cumulative % Loss Ex-ante**	**VoII Ex post**	**Cumulative % Loss Ex-post**
0	22.55		22.55	
15	21.18	6%	14.09	38%
30	19.77	12%	10.10	55%
45	14.98	34%	3.07	86%
60	12.45	45%	0*	100%

* We assume information is not used, thus its value is 0.

The imperfection of *ex ante* information is fundamentally different from its *ex post* counterpart. Therefore, the imperfection magnitude, although nominally identical in both experiments, should be interpreted carefully, since scenarios with the same magnitude of imperfection imply information imperfections that are completely different in nature. Recall that *ex ante* imperfection is commonly due to measurement (or computation) inaccuracy, while *ex-post* imperfection is much more complex and might include limitations in alternative identification and alternative selection or even at the implementation stage.

The difference in nature and complexity of *ex ante* versus *ex post* information might explain *per se* the huge differences in terms of value of the imperfect information. However, the implication for practitioners is significant since, under limited budgets, investing in improving the *ex post* information seems to have more impact and relevance for information value than investing in improving *ex* ante information.

5.3.4 VoII Estimate Considering Real-life Rate Plans

In order to put these results into the perspective of the practitioner, we will now extrapolate the results to a realistic business situation. We carry out this exercise considering a publicly-available rate plan for prepaid mobile communication service by UZO,[8] a Portuguese service provider, which charges €0.099 per minute of communication. Table 20 summarizes this extrapolation exercise considering only working days (250 in a fiscal year). This should be considered a conservative, although very insightful, estimate of the financial benefits that one should expect from such information usage.

Table 20

Value of imperfect information (VoII) in different scenarios (imperfection magnitude of 15%, 30%, 45% and 60%): extrapolation of revenue by a service provider with 1 million active customers adopting a flat rate plan of €0.099.

Imperfection magnitude	**VoII (1)** **Ex ante**	**1Day & 1M users VoII (2) Ex-ante**	**1Year & 1M users VoII (2) Ex-ante**	**VoII (1)** **Ex post**	**1Day & 1M users VoII (2) Ex-post**	**1Year & 1M users VoII (2) Ex-post**
0	22.55	€ 25 513.71	€ 6 378 428.57	22.55	€ 25 513.71	€ 6 378 428.57
15	21.18	€ 23 963.66	€ 5 990 914.29	14.09	€ 15 941.83	€ 3 985 457.14
30	19.77	€ 22 368.34	€ 5 592 085.71	10.1	€ 11 427.43	€ 2 856 857.14
45	14.98	€ 16 948.80	€ 4 237 200.00	3.07	€ 3 473.49	€ 868 371.43
60	12.45	€ 14 086.29	€ 3 521 571.43	0(3)	€ 0	€ 0

(1) Default rate plan of 1 cent of the monetary unit per minute of mobile communication, applied to scenario population of 8750 users

(2) UZO's charging plan of 9.9 cents of a Euro per minute of mobile communication.

(3) We assume information is not used, thus its value is 0.

The extrapolation to one million users gives practitioners *proxies* to real life contexts of decision-making in terms of data management, analytics projects and information usage to support decisions. In this example we have calculated our financial estimate from information improvements in the level of imperfection for both ex ante and ex post information.

These results challenge us to acknowledge that the magnitude of savings resulting from information usage and action taken to improve information imperfection in the telecommunications context are significant from a financial perspective, and thus improvements in this area seem to have good potential for return on investment for many projects.

[8] https://www.uzo.pt/tarifarios/carregamento, accessed on 19th December 2021.

5.4 Combining Network and User Sourced Information to Increase Value

In this section we present experiment E based on two types of information: user device sourced information and network sourced information (in both cases, only perfect information is considered). We only consider the potential usage of this information by the network management team to improve service performance; any other prospects and opportunities to monetize such information are out of our research scope.

We present some limited results to discuss how the information coming from different sources (network and user device) can be combined and also to set the stage for new lines of research, since customer experience is at the heart of telecommunications industry innovation and all the processes related with customer information management are critical to improve customer experience. Crowdsourced network measurements are available as commercial services and products (Hirth et al., (2015). Hirth et al. discuss mainly internet service monitoring, but there are systems dedicated to monitor mobile communications services, thus we believe that the ability to estimate VoI with applications in ensuring high quality experience and reducing churn is critical to decision making related to investments in this field. The business reason to undertake this kind of investment may vary from simple and genuine search for better service for all customers to differentiated high quality service offered to high-end market segments while the rest of the population receives massive, undifferentiated and lesser quality service. For example, if the business decides to reduce resources dedicated to network monitoring (and field actions), having the user perspective of the delivered service might simply help to prioritize where to apply the resources available according to information collected at user device (obviously the user must agree to share that information, thus there must be some compensation).

Our initial questions that drove the extension of NIESIM to include user device information in the decision-making process were the following:

a) Does user device sourced information (used to improve service level) add value on top of existing network monitoring information?

b) What is the improvement in terms of performance and value?

c) If we have different population segments (in terms of expected service level and also in terms of willingness to pay an additional fee for higher service level), what are the implications in terms of value of information and information sourcing strategies?

There are many other possible questions, but we had to limit the scope of the research. We created a new baseline, with different geographical conditions and higher population to explore these topics, although the computational costs have limited the extension of the results obtained.

For this experiment, our basic assumption is that (a) the business decides adopt less stringent criteria for general grade of service (thus we choose Pb=6% as decision criterion for information collected from the network) while (b) it selects a group of users (20% of the population) to source user device information to use as complementary input for decision support (adopting a high user CSSR, CSSR=98%, for problem identification from the user perspective). These reference values are only based on educated guessed, and they are chosen for experiment purpose only, without allowing further extrapolation.

5.4.1 Experiment Setting

In this subsection, we introduce the general characteristics of a business setting used as a reference for the experiment E. We have already discussed the creation and characteristics of an experiment baseline, thus we go straight to the point: this is essentially an extended version of the baseline used for experiments A, B, C and D, doubling the size of the geographic area, considering significantly higher population and also a few additional differences that we present in Table 21 and Table 22.

Table 21

Technical summary of experiment E baseline

Modelling concept or input	Units/Values
Total geographical zones	50
Longitudinal range	10
Latitudinal range	5
Total users	12750
Average number of users per zone	255
Mobility rate during ‘leisure period’	1%
Mobility rate during ‘working period’	1%
Total base stations	50
Average communication channels by base station	21
Total communication channels	1050
The price of one minute of communications	0.01
Fault rate	6%

A distinctive change of this baseline (in contrast with former baselines presented) is the geographic area modelled. Figure 64 shows the user distribution per zones during the working period (considering the average number of users in each area), which corresponds to a completely different pattern of geographic distribution trends of experiment E (when compared with the former experiments, which assumed higher mobility rates and thus presented higher variability in the number of users in the different zones).

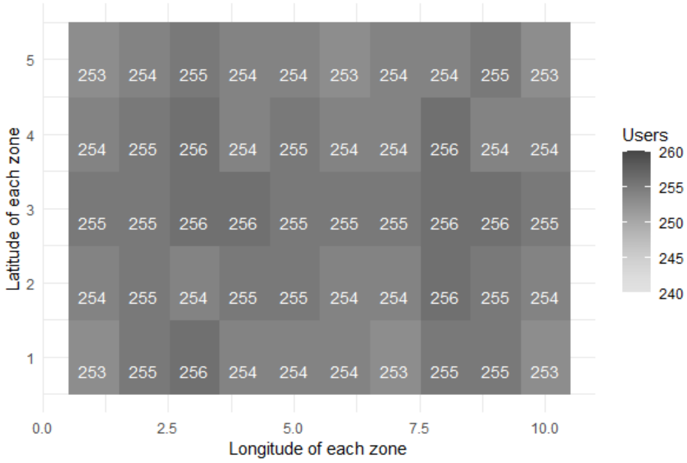

Figure 64. Average number of users in each zone, during the working period, in experiment E.

The service usage profile and the call duration profile used in this baseline are those presented in Figure 27 (Subsection 4.5.2) and Figure 25 (Subsection 4.5.1), respectively. Those profiles are based on data from a real service provider, to get as close as possible to a real-life scenario.

In experiment E, we model management activities and their decisions considering two different sources of information with distinct workflows, as discussed in Subsection 4.2.3 and particularly depicted in Figure 15 (simplified decision model for mobile communications network management activities using monitoring information from the network infrastructure) and Figure 16 (simplified decision model for mobile communications network management activities using information coming from the users' device monitoring branch). In Table 22 we present a summary of the values of the simulation parameters related to the process of decision making and subsequent actions (those parameters only apply to the 'Information Available' context), including parameters specific to the user device sourced information usage in the decision process, such as the 'sampling group dimension', the 'user expected service level' (in our case measured in terms call success rate experienced by the user considering an historical time window), the 'historical time window' used to compute user CSSR and finally the 'service relevance threshold' (the dimension of the group of people experiencing low performance, within the population sampling, which signals the existence of a problem – beyond this threshold, a problem is considered identified).

Table 22

Simulation parameters related to the process of decision making and subsequent actions

Modelling concept or input	**Units/Values**
Pb Decision Threshold (network information decisions)	6%
Decision to field action delay	1h
Elapsed time for a field action team solve a problem	1h
Number of field action teams	Unlimited
Limitation on field teams work periods	NO
Time granularity of computation of performance indicators	1h
Management evaluation of KPIs and decision-making period	1h
Sampling group dimension (% of population)	2549 (20%)
User expected service level (User CSSR)	98%
Historical time window	4 Days
Service relevance threshold (% of the sampling group)	319 (12,5%)

Decisions based on user device information are daily decisions (planned for 8:00 am of each day) using the user CSSR computed for the historical time window considered: in this case, four (4) days. This means that the first week is useless in terms of valid simulation results, so in experiment E we add one extra week to the simulation (it ran for 7 weeks), but the first two weeks are ignored (thus we retain a similar number of results as in previous experiments).

In case of positive problem identification, the base stations frequently used (by the users experiencing low performance) are the target of corrective actions considered in the implementation phase of the decision-making process.

Note that the problem identification, when we use user device sourced information, is more complex (compared with the network sourced information), since the individual user perspective has to be combined with the systemic perspective. The implicit process of screening the population of users and collecting their user experience towards a problem identification (part of the decision-making process) is represented in Figure 65.

The experiment E results shows that with a sample of users that share their device information (related to service performance), it is possible to improve the service of the global population.

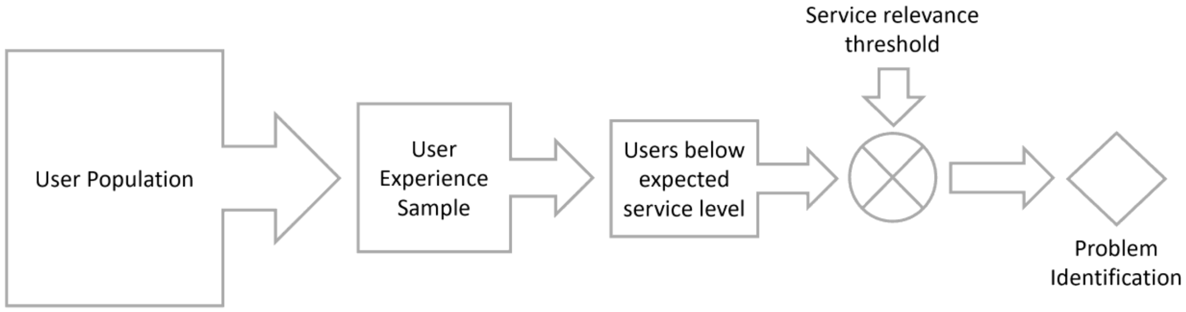

Figure 65 – Problem identification process when user device sourced information is the decision-making process.

5.4.2 Exploratory Results

Results of experiment E presented in this section are exploratory in the sense that it is possible to address a new class of questions. When information from users are part of the experiments, new variables and perspectives are open to research and more extensive and robust experiments are recommendable. We acknowledge that limited results can be gathered from this specific experiment and yet relevant insights are presented here.

The first question we address regards the added value of the user device sourced information (on top of existing network monitoring information). In Figure 66 we present the data showing the net effect of this extra information to improve the available channels to provide the service (this Figure roughly shows the results for weeks 3 and 4 of the simulation period). We use acronym NW to identify network monitoring information and acronym MIX to identify the combination of network and user device sourced information.

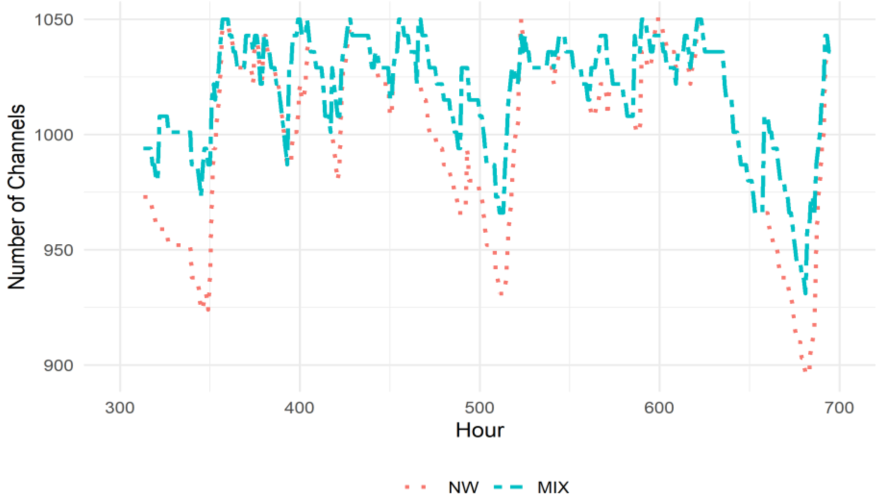

Figure 66. Comparison of available channels using network monitoring information (NW) versus combination of network and user device sourced information (MIX) supporting decisions towards corrective actions considering experiment E baseline.

Since our focus is actually the value in financial terms, in Figure 67 we compare the revenue of both contexts (network monitoring information and user device sourced information) for the same time period and we confirm a small increment in revenue when we combine information from network and user devices.

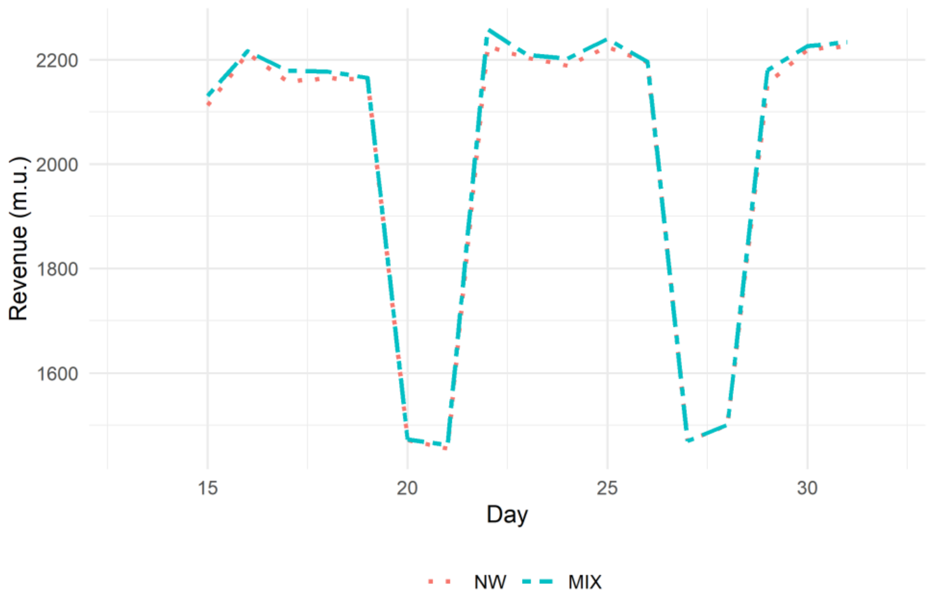

Figure 67. Comparison of revenue when using network monitoring information (NW) versus combination of network and user device sourced information (MIX) supporting decisions towards corrective actions considering experiment E baseline.

We define the Added Value of the User Device sourced Information (UDI Added Value) as the difference between the revenues showed in Figure 67 (thus 'UDI Added Value'=MIX-NW). In Figure 68 we present the Added Value of the User Device sourced Information (UDI Added Value) on top of existing network monitoring information for the complete simulation period (after the initial two weeks ignored to prevent initialization bias). Figure 68 is like a zoom on Figure 67 but with a value of information perspective, since in one hand 'UDI Added Value' is the difference between the revenue of both contexts (network monitoring information and user device sourced information) but on the other hand it is important to put 'UDI Added Value' into perspective of the value of the information used (network monitoring information (NW VoI) and the combined information of network and user devices (VoCI)).

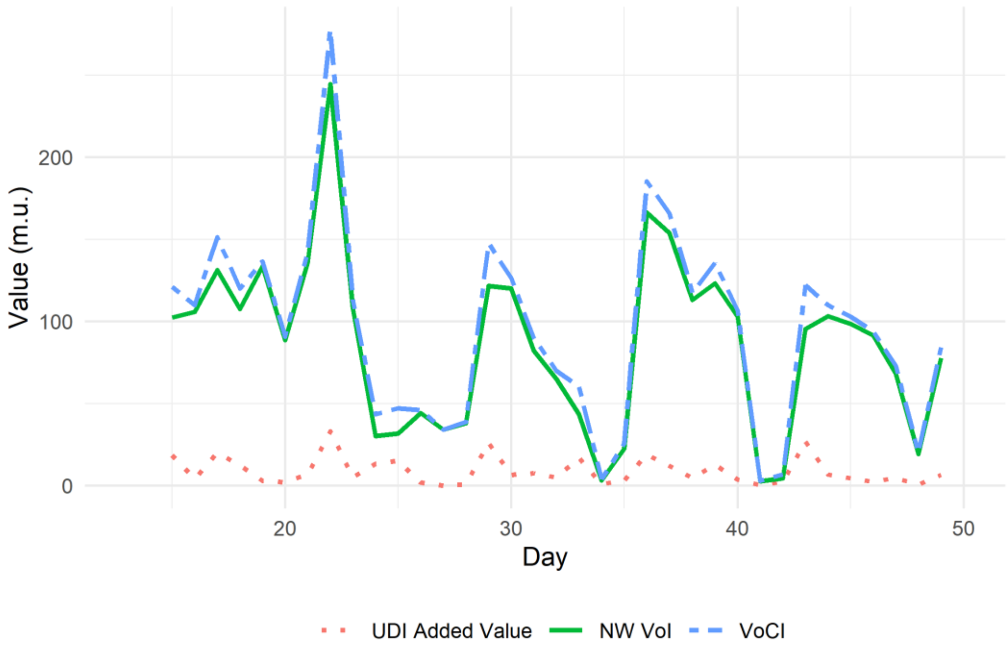

Figure 68. Comparison of added value of the user device sourced information (UDI Added Value) with VoI of network monitoring information (NW VoI) and the value of combined information (VoCI) computed as aggregation of former variables.

In Table 23 we gather a summary of the basic descriptive statistics of the daily values presented in Figure 68 (25 values were retrieved from the scenario and used in the analysis). Following the approach to estimate the daily value (subsection 5.1.3), thus using the using the median value, we conclude that the added value of the user device sourced information (UDI Added Value), is 7.7 u.m., while the VoI of network monitoring information (NW VoI) is 103.2 u.m. and finally the Value of Combined Information (VoCI) is 112.6 u.m.. Note that, since we use the median value to adopt a daily value, those values do not sum up.

Table 23

Descriptive statistics of daily values from Figure 68 (only working days considered).

Context*	**Min**	**1Q****	**Median**	**Mean**	**3Q****	**Max**
NW VoI	30.1	82.1	103.2	103.4	121.6	244.4
UDI Added Value	1.9	4.7	7.7	11.4	16.9	33.2
VoCI	43.4	89.9	112.6	114.9	135.8	277.6

* Added value of the user device sourced information (UDI Added Value); VoI of network monitoring information (NW VoI) and the value of combined information (VoCI).

** 1Q is the first quartile (25th percentile); 3Q is the third quartile (75th percentile)

The extrapolation exercise to estimate VoI (of network monitoring information) for a 1 million users scenario (with the same charge plan of € 0.099 per min of mobile communication) would lead us to € 80 132 for VoI on a daily basis (+€20M per year) which is a higher value than the one obtained in the comparable scenario in experiment B (fault rate of 6% and Pb of 6%), thus suggesting the VoI might correlate with network infrastructure (e.g., number of base stations for which KPIs are computed and granular decisions are made). Table 24 summarizes this extrapolation exercise considering only working days (250 per fiscal year).

Table 24

Extrapolation to daily and annual amounts considering a service provider with 1 million active customers adopting a flat rate charging plan of €0.099.

Description	NW VoI*	VoCI*	UDI Added Value*
Value captured on a daily basis considering 1 million users	€ 80 132	€ 87 431	€ 5 979
Value captured in 250 working days considering 1 million users	€ 20 433 600	€ 22 294 800	€ 1 524 600

* Added value of the user device sourced information (UDI Added Value); VoI of network monitoring information (NW VoI) and the value of combined information (VoCI).

With that, we have (a) confirmed user device sourced information (used to improve service level) adds value on top of existing network monitoring information and (b) the improvement in terms of financial performance for the service provider is relevant (estimated as €1.5M per million users on year basis, given the particular options we made for the decision criteria and baseline definition).

The previous discussion was developed with the assumption of all users treated equally both in terms of service expectations and pricing (using the baseline value in m.u and the Uzo charge plan for the extrapolation exercise)

Now let us explore the implications of differentiated groups of the population of users, considering that the population is segmented in two groups, one group having higher service level expectations and willingness to pay a premium price for that higher service level (we label this group of users as segment A), while the general population receives regular service (labelled as segment B). Moreover, for the purpose of this explorative endeavour, we assume regular users pay € 0.10 per minute of communication (similar price as Uzo provider) and that a *premium* price of 50% above the regular charge is paid for high level service by customers of Segment A (0.15 Euros per minute). We also assume that the users sharing their information are those of segment A.

The values represented in the in Figure 69 are obtained when we apply the price segmentation just described. We present the same comparation between concepts used before for comparability and explanatory reasons (although different pricings are involved). We observe very similar shapes (as compared to Figure 68) but with higher separation of the curves which is aligned with expectations (the general population price is 10 times higher in the new scenario).

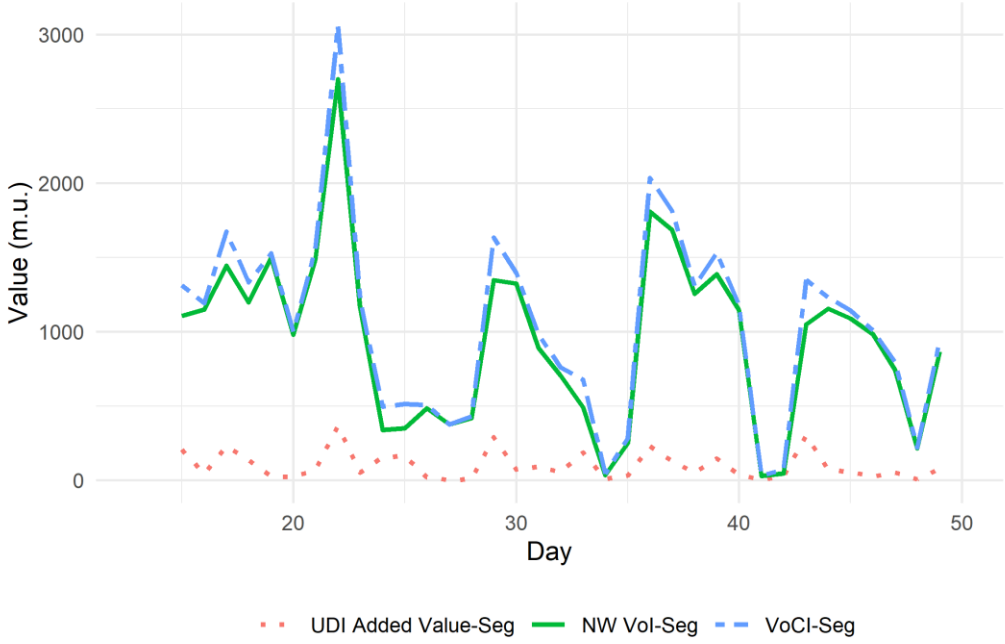

Figure 69. Impact of adopting customer segmentation: Comparison of added value of the user device sourced information (UDI Added Value – Seg) with VoI of network monitoring information (NW VoI – Seg) and the value of combined information (VoCI-Seg).

In order to better express the impact of adopting customer segmentation on value of information we proceed comparing the VoI of network monitoring information with and without customer segmentation (Figure 70). In case of customer segmentation, we apply the pricing differentiating for Segment A (50% increase, as described) and the curve is labelled ‘NW VoI – SEG’ while in case of no segmentation, all population is charged € 0.10 per minute of communication and the curve is labelled ‘NW VoI – STD’. Under these conditions, Figure 70 presents the impact on the value of network sourced information when we have customer segmentation. Using the same conditions, in Figure 71 we compare the added value of the user device sourced information (curves tagged ‘UDI Added Value – SEG’ and ‘UDI Added Value – STD’ respectively).

Our conclusion is that, adopting a pricing differentiation between segments of users will increase the value of the information sourced in the network and also in the added valued from user device information.

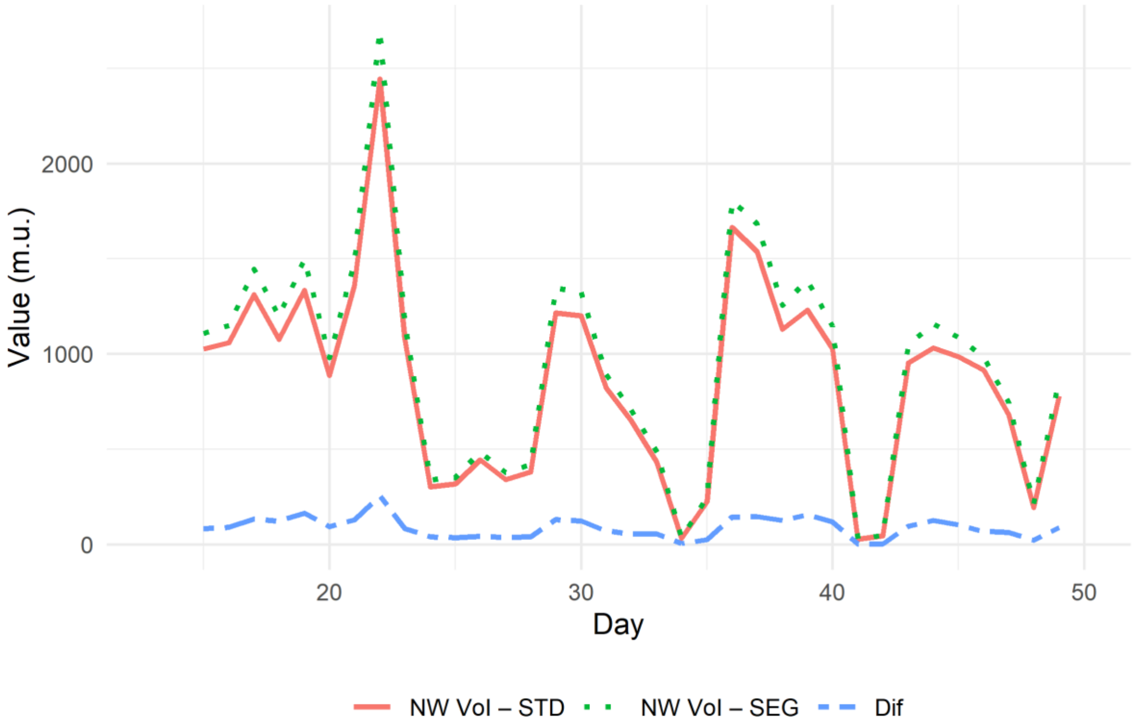

Figure 70. Impact of adopting customer segmentation on the value of network sourced information: comparison of the application of price differentiation for Segment A (curve labelled 'NW VoI – SEG') with the case of no segmentation (curve labelled 'NW VoI – STD').

In Table 25 we gather a summary of the daily values of key concepts for relative comparative analysis (based on data presented in Figure 70 and 71, using the median value to estimate the daily value).

Table 25

Impact of adopting customer segmentation (analysis using estimated daily values).

Context*	**Median**	
NW VoI – STD	1031.9	
Dif NW VoI=SEG-STD	102.8	10% Increase
UDI Added Value – STD	76.9	
Dif UDI Added Value = SEG-STD	9.0	12% Increase

* VoI of network monitoring information with no segmentation (NW VoI-STD); Added value of the user device sourced information with no segmentation (UDI Added Value – STD); difference between these contexts with and without pricing differentiating for Segment A.

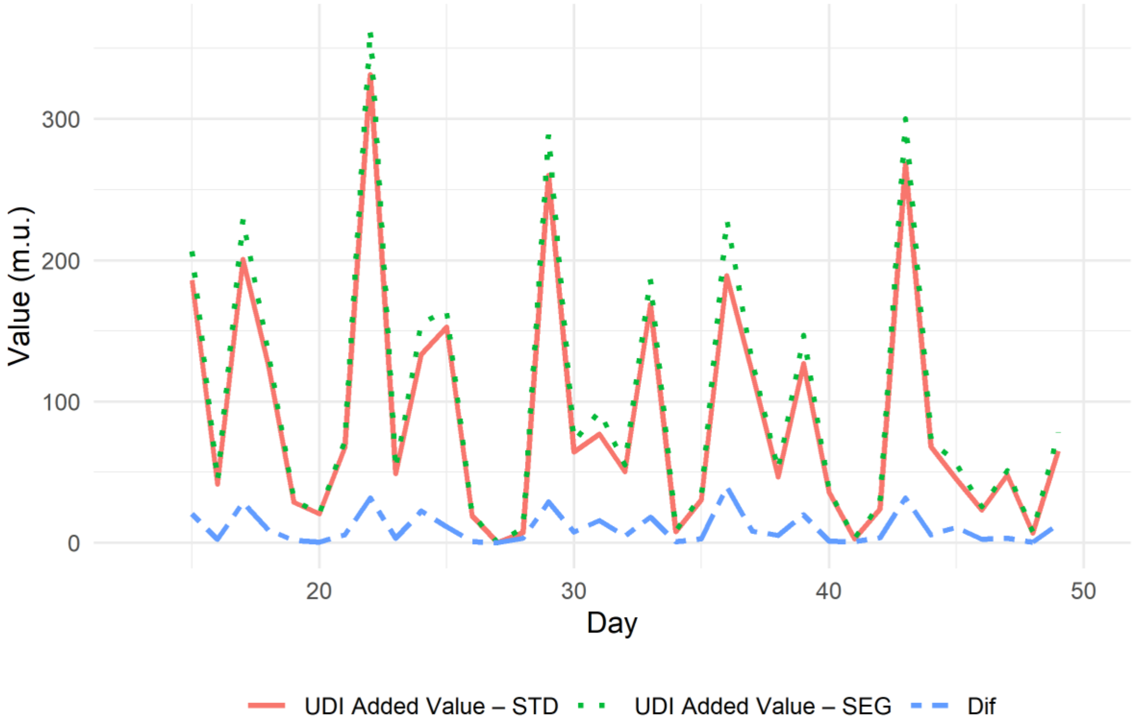

Figure 71. Impact of adopting customer segmentation on the added value of the user device sourced information: comparison when we apply the pricing differentiating for Segment A (curve is labelled 'UDI Added Value – SEG') with the case of no segmentation (curve is labelled 'UDI Added Value – STD') and the difference between these contexts (Dif=SEG-STD).

In conclusion, this analysis confirms the impact of adopting customer segmentation on the value of information but with similar relative impacts regardless of information sourced in the network or information sourced in users' devices.

Until this point, we assumed that users sharing their information are all those of segment A, which might be considered an unrealistic assumption, since many high-end users probably have privacy concerns and refuse to share their data.

If we accept the alternative of sourcing user device information outside of Segment A, we might face uncertainty on the ability to obtain similar results from those showed in Figure 69. Although, in our experiment, users sharing information are randomly spread in all the geographic area under simulation, we expect to observe nuances in terms of value added of this information according to the alignment between the group of users from segment A and the group of users sharing information.

Thus, we decided to explore the implications in terms of revenue and value of information emerging from higher or lower aligning the user device sourced information with population segments that have higher service level expectations and willingness to pay premium price (segment A).

For this exercise we adopt the pricing described before (regular users pay 0.10 Euros per minute of communication (similar price as Uzo provider) and users from Segment A pay 0.15 Euros per minute) and we investigate the following scenarios:

a) Segment A users are randomly distributed with no special alignment with the group of users sharing their device information to the service provider;

b) Users sharing their device information to the service provider are selected with the goal of aligning them with the number of Segment A users in the working period reference zones (three alignment levels are considered: 100%, 66% and 33%);

Note that we pick users of Segment A randomly, without any restriction (leading to a very high probability of all zones having segment A users, in every iteration). So, before going forward we explain how we defined the 66% alignment (as an example). We check the Segment A user distribution per zones (let us consider zone 1 has 12 users, while zone 5 has 6 users) then we source a proportion of 2/3 (66%) of the users from those same zones (in this case, 8 from zone 1 and 4 from zone 5), while the remaining users are providing information are chosen randomly across the population.

In Figure 72, we present the results from implementing the experiment, comparing added value of the user device sourced information (UDI Added Value) for different scenarios and considering that the group of segment A users has similar dimension to group of users sharing information. The four scenarios of alignment between groups included in the experiment are the following: (a) Full alignment between groups; (b) 66% alignment (meaning 2 out of 3 elements of the groups are chosen from the same zones); (c) 33% alignment (meaning 1 out of 3 elements of the groups are chosen from the same zones); (d) groups are both selected in an independent and random way.

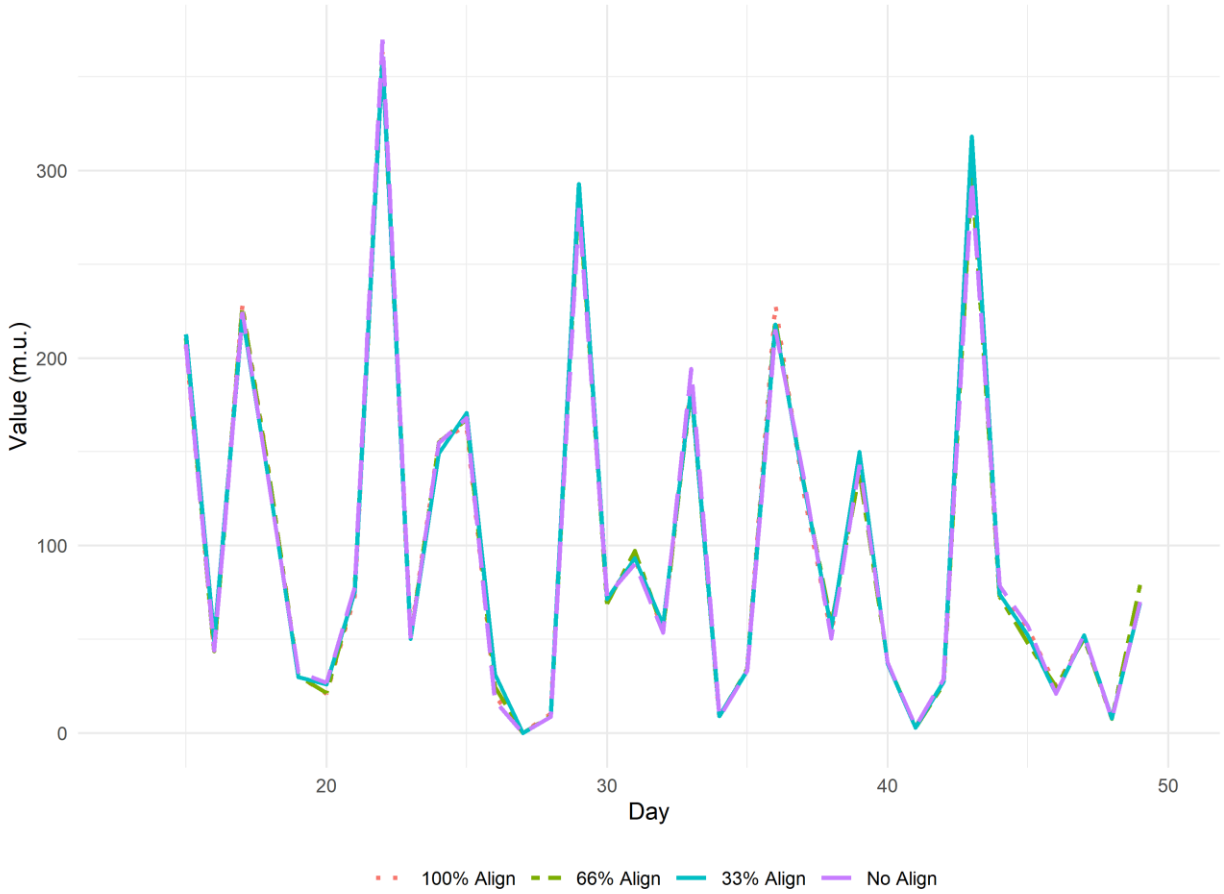

Figure 72. Comparison of 'UDI Added Value' for different scenarios from higher to lower aligning between the users sharing their information and users of segment A (scenarios considered are: alignment of 100%, 66% and 33% and finally 'No Alignment').

Our results show very low differences between different alignment scenarios in terms of value added of user device information. We expected higher differences, but several explanatory reasons have to be further investigated, for example:

a) The group of users sharing information is spread all over the geographic area and is very significant (20% in terms of all population of users), thus ensuring good representation of the general experience of the population (thus segment A users are as much beneficiaries of the additional information as the remaining population). What if the group sharing information is significantly smaller and also smaller than the segment A? What would be the impact of the alignment in that case?

b) Segment A group is not concentrated in a subset of zones (neither the users sharing information) but spread in all the geographic area, so our attempt to find a mismatch between groups is doomed to failure. What if we have asymmetric distribution of segment A (probably a more realistic reproduction of business settings) and also asymmetric willingness to share information? What is the minimal viable alignment between those groups? What is the minimal dimension of the group sharing information to achieve a significant value added of this user sourced information?

These exploratory results are just a glimpse of the multitude of questions the user sourced information might present to practitioners, questions that we believe are important applications of value of information in the telecommunications industry and worth of higher academic and applied research.

6 Conclusions

This thesis represents the first steps towards measuring the financial value of information used within the network monitoring activities in a mobile communications setting, with the possibility of combining internal information with information obtained from service users' devices, to deliver higher performance and higher customer experience. It is a contribution to a non-trivial problem of developing a modelling approach and then implementing and operationalizing it in a simulation software designed to create reproduceable and meaningful experiments, aiming to provide insights to practitioners and academia alike.

It is important to note that we do not explore monetization opportunities emerging from the abundant information collected by telecommunication providers (and other companies such as Google, Facebook and others) with potential market value either through exchange or value-added services, but rather focus our attention on the value of using information sourced in the network (and on users' devices) to achieve operational performance improvement.

We propose a method to estimate financial value of the information used at the management level, with a broad systemic perspective of the mobile communications setting. While value of information (and other information metrics) are often used in the engineering component of communications and related systems (used as guide to automatic action embedded in algorithms and engineering solutions), our structured literature review showed a reduced number of articles related to, or aiming to, estimate the value of the information in financial terms (monetary quantification) in the telecommunications industry, and none of those articles were dedicated to VoI estimation in financial terms in the mobile network setting. Thus, we believe that this work will contribute to reduce this research gap.

6.1 Overview

This work represents a first step towards estimating the Value of Information (VoI) used in mobile network management, specifically the information required to act on correcting or preventing network failures resulting in service denial. We use a Discrete Event Simulation (DES) approach to simulate a mobile communications setting (keeping the service management perspective in mind and simplifying the engineering aspects as much as possible) to capture and measure information value in financial terms.

We developed experiments to understand and quantify VoI and how VoI is impacted by management options (e.g, service level adopted as desired state of affairs for regular operations and service delivery) but also by technical circumstances and failure events (e.g., impact of increasing level of fault rates on performance and VoI).

We have explored the impact of imperfect information used in the decision cycle of the mobile communications setting. We have considered the problem identification as the pivotal step of the operational decision-making process and explored the usage of imperfect information *ex ante* and *ex post* problem identification step.

We have extended our model and software implementation to include information from users' devices (assuming exclusive usage for operational purposes), thus providing additional inputs to the decision process. This information is commonly perceived as valuable but our model makes it possible to assess the additional value on top of internal network information in financial terms, thus allowing practitioners to make better decisions regarding this type of investment.

6.2 Research Contributions

Before presenting the research contributions, we recall the research questions used as guidance to drive our research:

> Q1: What is the VoI required to act on correcting or preventing a specific telecommunications network failure event?
>
> Q2: How does the VoI change for different service level options from the management?
>
> Q3: How does the VoI change with different operational conditions (e.g., different fault rates affecting the network equipment and functions)?

Q4: What is the VoI potentially provided by end users as complement to the VoI gathered through traditional methods (performance from the network standpoint)?

These research questions are addressed by the experiments presented in the text (and summarized below) and they are the corollary of broader work. Our contributions include contributions to answer the questions and also the conceptual approach to tackle to challenge of measuring VoI in the network monitoring setting (including the information from users' devices) and the practical instruments (software and methods) to develop experiments and put forward our estimate for specific use cases. The conceptual contributions are summarized as follows:

i) We developed a simulation-based model of the essentials of the mobile communications service delivery that incorporates the information produced and used to manage this delivery;

ii) We put forward a procedure to estimate the VoI in the setting of mobile network management which is able to isolate and measure (in financial terms) the information contribution to the network management efforts;

iii) The model was instantiated through a software development (named NIESIM) thus creating a tool to perform tailored simulations according to the procedures necessary to isolate information contribution to the network management activities;

iv) The model (and the software implementation) distinguishes the VoI gathered internally by traditional network monitoring versus the information coming from service end users;

v) We presented the methodology to set up the experiment (using NIESIM) so that only the contribution of information explains the differences in the financial outcome, thus providing material criteria for the measurement of the value of information used to manage the mobile communications network.

As tangible results (beyond the software artifacts and the documentation) we have developed a series of experiments considering perfect information and imperfect information using information from the network infrastructure. We also developed experiments combining it with information from users' devices (in this case only perfect information is considered). The obtained results can be structured as follows

First, the experiments A and B, were experiments conducted to estimate the value of perfect information (VoPI). We explored two distinct perspectives: (i) how VoPI evolves when the fault rate affecting the network infrastructure changes and (ii) how VoPI evolves when the decision thresholds change. The main conclusion in the first experiment (variable fault rate while the decision threshold is kept constant) was that, below the exhaustion limit of the model, there is a positive relationship between the VoI and the fault rate impacting the network and the service delivery.

We undertook an extrapolative exercise, adopting real world service plans, to estimate VoI per million users, thus providing tangible insights for management. In this first experiment, even with low fault rates affecting the network, the value of information easily reaches into the millions of euros on an annual basis per million customers and, even at a low fault rate of 2%, VoI will surpass €3.6M. The impact of any increment in failure rate might result in increasing the VoI as much as 16% for each 1% increase in the fault rate (with a nominal VoI of €685 151 for each additional 1% in the fault rate per one million users).

In the second experiment (variable decision threshold while fault rate is kept constant) the Probability of Blocked Traffic (Pb) value used as decision threshold shows a nonlinear relation with VoI with a convex type of curve with a maximum value of €10.9M for VoI (per million users, with fault rate of 6%).

The absence of general correlation between the number of corrective actions and the VoI is another significant insight since this observation is not obvious. Note that such correlation would be reasonable from a common-sense perspective considering the results from experiment A.

The following two experiments explored the Value of Imperfect Information (VoII) used in decision making: one (experiment C) considers imperfect information *ex ante* 'Problem Identification' and the other one (experiment D) addresses imperfect information *ex post* 'Problem Identification'. We considered the 'Problem Identification' step as the pivotal moment of the operational decision-making process (we assumed this step to be neutral, in terms of information quality) and developed experiments to understand the impact of imperfect information emerging before and after this pivotal moment.

In our model, the *ex ante* imperfect information is introduced through measurement error rate, assigned to each base station (stable during the simulation period) and with impact on the corresponding KPIs. Imperfect information, when present in this step ('Stimulus'), will produce false negative and false positives in terms of 'Problem Identification' outcomes and, ultimately, lead to useless actions (because they intend to correct one illusional failure) and absent actions (because there is a real failure that requires action). The *ex post* imperfect information (which in theory could emerge both at either the ‘Alternative Selection’ or at the ‘Implementation’ steps) was implemented using an unsuccessful implementation rate (stable during the simulation period), applied randomly to all corrective actions, part of which became ineffective actions. The net effect of the *ex post* information imperfection is the possibility of unsuccessful corrective actions taking place (following the ‘Problem Identification’ step) impacting the availability of communication channels.

From a qualitative perspective, our experiments of *ex ante* versus *ex post* VOII indicate significant differences in terms of VoII sensitivity to the magnitude of information imperfection before and after the pivotal moment of ‘Problem Identification’ in the decision-making process. The results indicate that *ex ante* imperfect information might still add value even if it is severely inaccurate, while the value of *ex post* imperfect information rapidly falls as the magnitude of imperfection increases, and actually such information becomes useless (roughly at 50% imperfection magnitude). Moreover, the increment in value from improving *ex post* imperfect information by one order of magnitude is roughly double that which comes from improving the accuracy of *ex ante* imperfect information by an equivalent magnitude. This is a huge difference, since it means that hypothetical equivalent projects (in terms of investment), reducing with similar magnitude the imperfection of *ex ante* and *ex post* information would generate completely different return-on-investment.

Finally, experiment E is based on two types of information: information from users’ devices and internal information from the network (in this case only perfect information is considered). The added value of the information from users’ devices in the improvement of the operational decision-making process, on top of existing network monitoring information, is demonstrated and measured along with the impact from having different pricing segments in the population of users.

Since the group of users sharing their device information does not necessarily match the higher end segments of the population, in terms of service level (and also in terms of willingness to pay additional fee for higher service level), we explore the implications in terms of revenue and VoI emerging from aligning the information from users’ devices with population segments that have higher service level expectations, and also show willingness to pay a premium price for that higher service level. Our initial assumption was to consider that users are spread regularly throughout the considered geographical area, despite their socio-demographic and service user profile. Given this assumption and the fact that users sharing information are randomly spread across all the geographical area under simulation, our results show very low differences between different alignment scenarios in terms of value added of user device information.

6.3 Proposed Future Directions

Estimating the value of information used in mobile network management proved to be a complex endeavour, but we believe this work and the insights from our experiments have the potential to 'start the ball rolling' in terms of opening conversations on the value of information and return on investments within the network management field. We hope these insights will give managers useful benchmarks for their daily activities, such as evaluating data and analytics initiatives (or the systems and applications they might be considering buying to manage those initiatives), putting the value of information at the core of the business case.

The modelling alternatives already supported by NIESIM open the door to many exciting albeit sometimes complex possibilities due to the simulation's costs (in computational resources and time). Examples of questions to explore in near future include:

a) How does the network deployment and configuration impacts VoI? Does the number of base stations increase the VoI? While we expect a direct positive relationship, we have yet to develop experiments to prove it and garner insights on the magnitude.

b) How about the geographic and mobility factors, what impacts should we expect in VoI and how to model asymmetric or high mobility settings?

c) How about the response time from decision to implementation? We adopted a very idealistic response time and fast decision making. What happens to VoI as response time increases?

d) Many technical failures are not easy to identify, some of them are somehow intermittent and take long periods of time to be spotted and eventually solved. In these types of setting, what is the magnitude of VoI? For example, if we have the opportunity to buy/develop a solution with cost X to increase the probability of spotting problem Z in K%, is it worthwhile proceeding and to buy/develop that solution?

e) What is the minimal dimension of the group of users sharing information to ensure a good representation of the general experience of the population? What is the optimal dimension of the group sharing information to achieve a significant value added of this information from users' devices?

f) What if we have an asymmetric distribution of high-end segments of users (probably a more realistic reproduction of the business settings) and also an asymmetric willingness to share information? What is the VoI impact from higher/lower alignment between those groups? What is the minimal viable alignment between those groups?

In terms of future directions, we have plenty of ideas, but the key element is the engagement of the practitioners to significantly improve the adoption of VoI in the telecommunications industry. So, we therefore look forward to developing VoI estimation experiments tailored to specific use cases (and practitioners' needs), both using network information and information from users' devices.

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APPENDIXES

Appendix 1: Examples of queries for each engine

Example of query Q4 tailored for SCOPUS search engine with complementary category filters included (in this example only journal published articles):

TITLE-ABS-KEY (value W/3 information AND networks) AND (LIMIT-TO (DOCTYPE , "ar")) AND (EXCLUDE (SUBJAREA , "ENVI") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "EART") OR EXCLUDE (SUBJAREA , "AGRI") OR EXCLUDE (SUBJAREA , "PHYS") OR EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "MATE") OR EXCLUDE (SUBJAREA , "ENER") OR EXCLUDE (SUBJAREA , "NEUR") OR EXCLUDE (SUBJAREA , "CHEM") OR EXCLUDE (SUBJAREA , "MULT") OR EXCLUDE (SUBJAREA , "CENG") OR EXCLUDE (SUBJAREA , "ARTS") OR EXCLUDE (SUBJAREA , "PSYC") OR EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "HEAL") OR EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "NURS") OR EXCLUDE (SUBJAREA , "VETE") OR EXCLUDE (SUBJAREA , "DENT") OR EXCLUDE (SUBJAREA , "Undefined")) AND (LIMIT-TO (EXACTKEYWORD , "Value Of Information"))

Example of query Q4 tailored for Web of Science search engine with complementary category filters included (in this example only journal published articles):

(TI=((“value of information” and (networks))) OR AB=((“value of information” and (networks))) OR AK=((“value of information” and (networks)))) NOT (DT==("BOOK CHAPTER") OR DT==("PROCEEDINGS PAPER") OR DT==("CORRECTION" OR "EDITORIAL MATERIAL") OR TASCA==("ENGINEERING CIVIL" OR "WATER RESOURCES" OR "ENVIRONMENTAL SCIENCES" OR "GEOSCIENCES MULTIDISCIPLINARY" OR "HEALTH CARE SCIENCES SERVICES" OR "INFORMATION SCIENCE LIBRARY SCIENCE" OR "ENGINEERING ENVIRONMENTAL" OR "HEALTH POLICY SERVICES" OR "MEDICAL INFORMATICS" OR "MEDICINE RESEARCH EXPERIMENTAL" OR "TRANSPORTATION SCIENCE TECHNOLOGY" OR "CHEMISTRY ANALYTICAL" OR "CONSTRUCTION BUILDING TECHNOLOGY" OR "ECOLOGY" OR "ENGINEERING CHEMICAL" OR "INSTRUMENTS INSTRUMENTATION" OR "MATHEMATICAL COMPUTATIONAL BIOLOGY" OR "MEDICINE GENERAL INTERNAL" OR "BIODIVERSITY CONSERVATION" OR "BIOLOGY" OR "DENTISTRY ORAL SURGERY MEDICINE" OR "ENERGY FUELS" OR "ENGINEERING MECHANICAL" OR "GEOGRAPHY PHYSICAL" OR "PUBLIC ENVIRONMENTAL OCCUPATIONAL HEALTH" OR "SOCIAL SCIENCES INTERDISCIPLINARY" OR "SOCIOLOGY" OR "ANESTHESIOLOGY" OR "ANTHROPOLOGY" OR "BIOCHEMICAL RESEARCH METHODS" OR "BIOTECHNOLOGY APPLIED MICROBIOLOGY" OR "CHEMISTRY MULTIDISCIPLINARY" OR "CRIMINOLOGY PENOLOGY" OR "CRITICAL CARE

MEDICINE" OR "EDUCATION EDUCATIONAL RESEARCH" OR "ENGINEERING BIOMEDICAL" OR "ENGINEERING OCEAN" OR "ENGINEERING PETROLEUM" OR "ETHICS" OR "GEOCHEMISTRY GEOPHYSICS" OR "GEOGRAPHY" OR "HOSPITALITY LEISURE SPORT TOURISM" OR "HUMANITIES MULTIDISCIPLINARY" OR "IMAGING SCIENCE PHOTOGRAPHIC TECHNOLOGY" OR "INTERNATIONAL RELATIONS" OR "LIMNOLOGY" OR "MATERIALS SCIENCE MULTIDISCIPLINARY" OR "MECHANICS" OR "MEDICAL ETHICS" OR "METEOROLOGY ATMOSPHERIC SCIENCES" OR "OCEANOGRAPHY" OR "PHARMACOLOGY PHARMACY" OR "PHYSICS APPLIED" OR "PHYSICS MATHEMATICAL" OR "PHYSICS MULTIDISCIPLINARY" OR "PLANT SCIENCES" OR "POLITICAL SCIENCE" OR "PSYCHOLOGY APPLIED" OR "PSYCHOLOGY EXPERIMENTAL" OR "PSYCHOLOGY MULTIDISCIPLINARY" OR "RADIOLOGY NUCLEAR MEDICINE MEDICAL IMAGING" OR "SOCIAL ISSUES" OR "SOCIAL SCIENCES BIOMEDICAL" OR "SOCIAL SCIENCES MATHEMATICAL METHODS" OR "TRANSPORTATION"))

Appendix 2: Articles surveyed in the structured literature review

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