# Barriers and Challenges of Network Simulation Tools: A Case Study on CORE/EMANE

Manal Ghanem[1], Nicholas Micallef[1], Sara Correia-Hopkins[1], and Jonathan-Lee Jones[2]

[1] Swansea University
2200761@swansea.ac.uk;nicholas.micallef@swansea.ac.uk;s.correia@swansea.ac.uk
[2] ITSUS Consulting jonlj@itsusconsulting.com

**Abstract.** Network simulation tools provide advanced simulation solutions. These tools reduce costs and simplify the testing of scenarios to mitigate risks before deployment. However, many of these tools still possess shortcomings that hinder their usability and widespread adoption. Notably, many tools cannot accommodate dynamic scenarios, thus limiting the scale and complexity of simulations they can support. Our study explores professionals' experiences with network simulation tools, with a focus on CORE/EMANE, aiming to understand their shortcomings and future potential. While existing research highlights technical drawbacks, our mixed-methods approach, uses a questionnaire to gather perspectives on network simulators and a design workshop to explore both technical and usability barriers associated with CORE/EMANE from an industry perspective. Our research highlights critical technical and usability barriers and challenges as perceived by industry professionals who frequently use these tools. Our work improves the understanding of the technical and usability requirements of network simulation tools. More importantly, we provide features that are grounded in participants' feedback, aiming to streamline user interfaces and align tools capabilities with the evolving network simulation landscape for improved project outcomes. These insights are key for informing future development, emphasising the need for tools that address technical requirements while ensuring user-friendliness.

**Keywords:** Network Simulation Tools · CORE/EMANE · User Experience · GUI Design · Interface Design.

## 1 Introduction

A wide range of network simulation tools, including NS-2 [2], NS-3 [22], OPNET Modeler [3], QualNet [15], and OMNet++ [43] have enabled the modelling of various types of networks, ranging from local area networks (LANs) to wide area networks (WANs). These tools play a pivotal role in developing and evaluating modern communication systems, allowing controlled testing and optimisation of networks without extensive physical setups. Real-time simulation, replicating

the timing behaviour of real-world targets, is significant in this field, enabling cost-effective experimentation.

As wired and wireless networks continue to grow, the importance of evaluating network performance through simulation becomes more essential [17, 4]. While network simulation tools offer a cost-effective alternative for performance evaluation, the increasing reliance on them raises concerns about accuracy and validation issues, including technical and usability aspects. Despite the emphasis on developing high-performance network simulation tools, there are significant challenges in accurately representing real-time networks. The precision of wireless network simulations is crucial for both accuracy and scalability [25, 35]. The limitations often arise from the inherent constraints of the simulator supplied with the operating system, directly impacting the accuracy of results. Additionally, the abundance of choice further complicates the selection of the most suitable simulation tool [37]. Many tools rely on abstract simulation models, which, though useful for specific analyses, may not fully capture the intricate behaviour and performance of wireless networks, resulting in less accurate outcomes compared to real-world implementations [27].

To the best of our knowledge, no prior research has undertaken a comprehensive examination of the usability of network simulation tools from a user's perspective. Our research builds upon the existing body of comparative reviews and technical evaluations of network simulation tools, expanding the scope to study user experiences with CORE/EMANE. This research, conducted in collaboration with ITSUS Consulting, a technology solutions provider specialising in ICT solutions for critical communication systems, aims to understand how network simulation tools are used, with the ultimate goal of designing solutions that could address current limitations of these tools. The study focuses on technical and usability challenges faced by users, aiming to enhance the tools' effectiveness and efficiency by compiling a list of requirements that can be used by the wider community to improve the development of next-generation network simulation tools. The research contributes to improving network infrastructure design and deployment processes. Our research is guided by the following research questions:

[RQ1] What are the key features of network simulation tools according to professionals?

[RQ2] What are the strengths/weaknesses of network simulation tools according to professionals?

[RQ3] How would professionals who use these tools like to see them evolve in the future?

To answer our research questions, we employed a mixed-methods approach, utilising a questionnaire for an overview followed by a design workshop focused on one tool, CORE/EMANE, involving six professionals in each activity. Our findings reveal technical and usability issues associated with network simulation tools, emphasising the importance of considering specific operational contexts when selecting, designing or upgrading these tools.

In the rest of the paper, we begin by presenting related work in Section 2. Section 3 details the methods employed for the research. The results of the

study are presented and discussed in Sections 4 and 5. Finally, Section 6 offers our concluding remarks and avenues for future research.

## 2 Related Work

Network simulators, emulators, and testbeds are three distinct tools and approaches used in network evaluation and experimentation [16]. Each approach offers unique strengths and limitations. In this research, the term *'simulation'* refers to the use of any of the tools discussed; specific tool categories are mentioned as necessary. Simulation tools' development serves as an indispensable resource in the research community, enabling the development and evaluation of new protocols, and facilitating comparisons between novel and existing protocols. Many of the comparative reviews shed light on the technical aspects and performance metrics of these tools [42, 12, 9, 24, 26, 37, 39]; however, they rarely focus on the user experience and usability challenges encountered by day-to-day users and non-experts.

In the subsequent sections, we explore the design and usability issues by investigating research in data processing and decision-making, human-computer interaction design, and the usability of network management tools, and introducing the benefits and drawbacks of CORE/EMANE the tool used in our design workshop. By exploring these areas, we aim to shed light on the usability challenges and opportunities within network simulation tools, ultimately contributing to the development of more effective and user-centric solutions.

### 2.1 Data and Decision-Making

Modern network implementation facilitates the collection of a vast and growing volume of data. Leveraging simulation tools to make informed decisions about the appropriateness of a particular implementation or protocol heavily relies on utilising this data. Schroder et al. indicated that the quality of decision-making improves with the increasing volume of data available [36]. However, the potential to make better decisions through the processing of huge datasets comes with challenges. Cognitive overload may arise if the proper processing and display of the data are not well-suited for the task at hand [28]. Ensuring the data is presented in a meaningful and easily comprehensible manner is crucial to avoid overwhelming users with information.

Falschlunger et al. demonstrated that the relationship between task complexity and decision-making outcomes is mediated by information overload [18]. The researchers found that when faced with complex tasks, individuals may experience information overload, which can negatively impact their decision-making abilities. This highlights the importance of managing information effectively in decision-making processes. The study reaffirmed Gettinger et al. conclusions that well-implemented visualisations serve as an effective aid in the comprehension of large amounts of information, suggesting an improved ability to detect trends

and patterns, ultimately leading to better decision-making [19]. Given the critical role of data in modern network implementation and decision-making, the efficiency and effectiveness of decision-making using simulation tools heavily depends on the tools' ability to handle data in a user-friendly manner, reducing cognitive load, and facilitating informed choices based on data-driven insights. Therefore, improving the way network simulation tools present and process data can increase the tools' efficiency. Our research aims to create an actionable list of features to facilitate decision-making.

### 2.2 Human-Computer Interaction for Data Visualisation in Network Tools

Human-Computer Interaction (HCI) research, recognising the potential of visualisation and usability resources in advancing user interfaces for network management applications, is the most relevant to our research [34, 18, 8, 21]. These resources offer benefits to both non-specialists and experts, enhancing productivity in daily monitoring tasks [21]. Consequently, recent initiatives have proposed HCI-based usability guidelines, or heuristics, to aid in the design of user interfaces for network management tools [44]. Researchers developed guidelines for network monitoring tools through experimental studies involving network administrators [38, 44]. They introduced "guidelines for usability design in network monitoring tools" [38, 44]. However, these guidelines have yet to be evaluated by network management tool developers to assess their usability benefits and potential need for refinement.

Graphical representations can provide a visual and intuitive understanding of the simulated network environment and alleviate the cognitive load [14]. The limited visualisation in many of these tools can make simulating complex network topologies and scenarios challenging for users to understand the interactions between nodes, links, and traffic [33]. Inadequate or complicated visualisations may lead to difficulty in identifying potential issues, bottlenecks, or inefficiencies in the network design. This in return makes debugging network simulations a specialised task that requires expert users. It also would lead many users to identify errors or anomalies in the simulated network using log files and textual outputs, which can be cumbersome and time-consuming.

Pretorius et al. utilised Eye Tracking as an evaluation method, to highlight significant challenges in the usability of the implemented graphics. Their results revealed issues in data visualisation legibility, user preferences for graphical representations, and issues of presented visualisation in some parts of the screen [33]. Based on these findings, it is evident that poorly designed graphical interfaces can significantly hinder the user experience. Users may find it challenging to create, modify, and manage network configurations. Limited customisation options can present another issue, restricting users from tailoring the visualisation according to their specific needs. This can be directly linked to simulation tools, especially when trying to analyse and evaluate the impact of various protocols or network settings on the simulated environment. Our research explores user-centred design of network simulation tools to enhance their usability.

### 2.3 Usability of the Tools

Yang et al. found that usability issues in network monitoring and management tools for both network administrators and non-expert users are related to technical knowledge requirements and lack of visualisations for the tools [45]. Inconsistent user interfaces were also identified due to the absence of guidelines, leading to variations among suppliers, devices, and operating systems [45]. Similar issues were discussed in recent research [42], where researchers surveyed six simulation tools to be used by students in classrooms. The tools had issues with their interfaces and ease of use [42]. Issues with time investment to learn and use the tools were also discussed [42].

While specific literature that directly addresses the usability challenges of network simulation tools was not identified, our review of related studies has provided valuable insights into the design and usability issues common to network management tools. These findings can be extrapolated to potentially impact network simulation tools as well. The usability research has highlighted various aspects, such as the importance of catering to different user profiles [45], effectively handling collected data for generating meaningful insights [28], mitigating cognitive loads associated with learning and comprehending these tools [45, 18], and addressing issues concerning poor interfaces [45].

Utilising the insights from these studies, we devised a comprehensive approach to further probe and directly understand changes that need to be implemented while working with users of these tools. This involved the development of a questionnaire and a design workshop. These methods were employed to collaboratively engage with end-users, allowing us to gain a more nuanced understanding of the necessary enhancements to be integrated into these tools. Through this approach, we aimed to bridge the gap between the challenges identified in the literature and the practical implementation of upgrades, ensuring that the proposed upgrades would meet the requirements and usability expectations of current users.

### 2.4 CORE/EMANE

In the literature on network simulation tools, the Common Open Research Emulator (CORE) is often highlighted for its open-source framework and capability to emulate networks across multiple machines, including integration with live networks [20, 41, 6, 5]. CORE provides a graphical interface to manage network topologies and offers Python bindings for scripting, enhancing its adaptability for various research needs. It visually represents wireless connections with antennas and green lines, which helps in effectively demonstrating the layout of wireless networks.

Similarly, the Extendable Mobile Ad-hoc Network Emulator (EMANE) is noted for its modular MAC and PHY layer architecture that supports varied network emulation [6, 1]. EMANE allows for the development of different radio interface models through its Network Emulation Modules (NEMs), facilitating

real-time, distributed network emulations when used in conjunction with CORE, thus enhancing the realism and scope of network simulations.

According to comparative studies comparing various simulation tools [20, 41], CORE/EMANE has limitations, particularly in detailed event execution and the lack of support for capturing wireless packets, including complex packet exchanges. This limitation restricts the tool's efficacy in studying real-world wireless networking scenarios. Additionally, CORE's focus on the physical and data link layers without built-in support for wireless security protocols poses significant restrictions, especially when deploying comprehensive system configurations without manual adjustments.

The real-time emulation feature of CORE allows for observing protocol and application behaviours in a temporally accurate environment. It also offers prebuilt network models that researchers can adapt and expand to construct intricate network topologies [5]. However, the necessity for elaborate configuration scripts and the high computational demands for running extensive network scenarios make CORE less accessible for many researchers and increase the complexity and learning curves for new users [29]. In our work, we use CORE/EMANE as a case study because it is the most popular tool among our participants.

## 3 Methods

We employed a mixed-methods approach, utilising a questionnaire and a design workshop, to address our RQs. The mixed-methods approach was used to gain a more nuanced understanding of the use of these tools. The questionnaire offered a broad perspective, which was subsequently refined during the design workshop to extract more in-depth qualitative data focused on CORE/EMANE to design the features required to improve such tools. All study procedures were approved by our University's Institutional Review Board (IRB). The online questionnaire targeted ITSUS Consulting employees who regularly use or have previous experience with simulation tools. A convenience volunteer sampling technique, facilitated by contacts at ITSUS Consulting, invited participants meeting our inclusion criteria, specifically individuals working directly with simulation tools, leading projects that use simulation tools, or working with clients' projects utilising simulation tools. Participants' backgrounds included expertise in software engineering, cybersecurity, and data science, along with educational backgrounds in computer science, cybersecurity, physics, and astrophysics.

To better understand tool usage patterns, client requirements, and visualisation preferences, the questionnaire was designed with open-ended questions to allow participants to provide detailed, qualitative insights. The questionnaire contained 24 questions, organised into three main sections to align with the study's research questions and typically required about 30 minutes to be completed. The first section collected general information on the tools participants used, including their experience levels, common features, and tool limitations. This section aimed to address RQ1 by identifying the core functionalities that professionals consider essential, as well as any client requirements that current

tools do not meet. The second section focused on clients' perceptions, common pain points, and usability challenges, exploring how these tools are used in various scenarios. Aligned with RQ2, this section provided insights into the strengths and weaknesses of these tools, capturing client expectations and highlighting areas for improvement in usability and functionality.

The final section investigated visualisation needs and preferences, exploring current limitations and future expectations for visualisation components in network simulation tools. This section was aligned with RQ3 and examined participants' views on emerging trends, necessary enhancements, and the importance of visualisation for effective decision-making.

The questionnaire analysis informed the design of the subsequent workshop. Participants recruitment for the design workshop used a purposive sampling technique, facilitated by our project partners. Since participants were recruited from the same partners, some participants have participated in both studies because participants of the design workshop reported expertise similar to the ones who participated in the initial questionnaire. Besides exploring CORE/EMANE's usage experiences and challenges, the design workshop, conducted in an open and collaborative environment, involved two design activities: (1) listing interface additions to improve CORE/EMANE; and (2) suggesting important data visualisations to incorporate into the tool to aid analysis and decision-making. Two researchers moderated discussions to maintain focus and ensure productivity. The design workshop lasted for two hours.

For both activities, we recruited six participants in total, with the possibility of some overlap among participants. The questionnaire participants reported a collective experience ranging from 1 to 20 years, indicating a mix of experienced and novice professionals. Similarly, the design workshop included participants with experience ranging from 1 to 5 years, enriching discussions on the challenges and opportunities in this domain.

### 3.1 Data Analysis

Data analysis of the qualitative information gathered from both the questionnaire and the design workshop followed an inductive thematic analysis approach, as outlined by Braun and Clarke [10, 11]. This analysis consisted of two primary stages: open coding and axial coding. During the open coding phase, the data was carefully reviewed multiple times by the lead author. This iterative process allowed the researcher to form initial impressions of the data and identify distinct ideas, which were then coded. A second researcher went through these codes and in most instances confirmed the impressions of the lead researcher. There were only a few cases in which the second researcher suggested different codes. Conflicts were resolved through discussion to arrive at a consensus between coders. Subsequently, in axial coding, these codes were organised and grouped based on their connections and relationships.

### 3.2 Limitations

While the study aimed to provide insights into the use of simulation tools among ITSUS Consulting employees, certain limitations were acknowledged. Reliance on self-reported data might lead to recall bias or subjective interpretations. An overall small sample ($N \approx 9$) of ITSUS Consulting employees limits the generalisability to other organisations. However, as the findings of this research are intended as exploratory, they lay the groundwork for future research. Expanding the sample in future studies to include a more diverse group of participants across industries—such as telecommunications, defense, academia, and commercial IT—would ensure generalisability of the results.

To enhance the robustness of future studies, larger-scale quantitative approaches, such as online surveys distributed across industry networks and professional organisations, could be employed to validate the observed patterns and trends statistically. Additionally, a longitudinal approach could provide insights into how user needs evolve as new technologies, like 5G, 6G, and AI-driven automation, become more integrated into network simulation tools. Despite the constraints of a smaller sample, the richness of the collected data is evidence that we managed to extract meaningful insights. Ethical considerations, a mixed-methods approach, and expert review enhanced the study's rigour. The small sample size suggests the list of strengths and shortcomings may not be exhaustive, but can still be relevant for end-users who use network simulation tools.

## 4 Results

In this section, we present results from the questionnaire and the design workshop, aiming to understand participants' perspectives on network simulation tools. The questionnaire results provided initial answers to our research questions, while the design workshop provided a more nuanced understanding of the identified themes. A summary of key findings from the questionnaire and the design workshop is listed in Table 1.

### 4.1 Questionnaire Results

Participants' responses shed light on the technical and usability needs in their work, addressing clients, projects, and colleagues.

**Key Features, Needs, and Challenges.** CORE/EMANE was the most frequently used tool among participants, followed by other tools like OPNET Modeler, Cisco CML, and GNS3. In terms of selection criteria, the answers included testability (3/6), open-source options (1/6), and managerial preferences (1/6).

Our Participants identified essential features for effective simulation, addressing our first research question. These features include the ability to replicate scenarios, isolation from operating systems, noise introduction, and dynamic manipulation of parameters. They stressed that for clients, the capability of

**Table 1.** Key Findings from Questionnaire and Design Workshop

| Category | Questionnaire Findings | Design Workshop Findings |
|---|---|---|
| Requirements | Need for better performance and scalability to handle large, complex simulations.<br>Importance of accurate radio propagation modeling for wireless signal behaviour.<br>Essential need for an improved, user-friendly interface for efficient simulation. | Clear and effective data visualisation is crucial, with CORE/EMANE's GUI needing more parameter representations.<br>Open-source development affects data quality, with inconsistent dataset contributions impacting usability. |
| Challenges | Technical limitations include scalability issues, compatibility challenges, and limited software configurability.<br>Usability challenges such as a steep learning curve, leading to ineffective use and fewer conducted tests.<br>Frequent reliance on workarounds due to limited configurability and complex setup. | Challenges in client engagement, especially during ad hoc, command-line-based demos.<br>Weak visualization in mobility scenarios, with difficulties in real-time parameter adjustments.<br>Development challenges including complex GUI, steep learning curve, and limited documentation.<br>Fragmentation due to reliance on multiple tools across projects. |
| Tools Evolvement | Anticipated evolution to include advanced technologies like 5G and improved scalability.<br>Suggestions for a user-centered design approach to improve initial user experience, reduce complexity, and enhance configurability.<br>Interest in future enhancements like virtual reality integration, dynamic routing, and mesh networks. | Recommendation for intuitive data visualisation and dynamic user profiles.<br>Increased customisability, including easier configuration and enhanced visual tools for data interpretation.<br>A unified simulation tool with features that reduce reliance on workarounds and multiple tools. |

these tools to mirror real-world scenarios and measure essential network metrics is fundamental. Additionally, the need for virtual topologies, modular architecture, scalability, and effective integration was highlighted.

"Common key features would include generic network would be bandwidth, packet loss (and distributions), Latency and Jitter." - (QP1)

Participants expressed a need for better performance and scalability in simulation tools to handle larger, intricate simulations while maintaining optimal performance. They emphasised the significance of accurately modelling radio propagation to represent wireless signal behaviour in varied environments. The anticipation of tool evolution in line with upcoming technologies like 5G was noted, pointing to the need for continuous adaptation. Additionally, the importance of an improved user interface was stressed to make the simulation process more streamlined and user-friendly.

"We need greater performance/scalability, more accurate/realistic radio propagation, more diverse mobility models, 5G and beyond, and improved user interface." - (QP6)

Participants expressed concerns about the tools, providing insights that addressed our second research question. They highlighted technical limitations, scalability issues, and compatibility problems. The focus was more on technical aspects than usability, with a need for enhanced software configurability, better interfaces, and advancements in radio propagation modelling, mobility models, and real-time adaptability. The importance of scalability in line with emerging technologies was also reported.

**User Experience and Usability.** Participants' perceptions of client experiences varied, emphasising the impact of individual backgrounds. The diversity of viewpoints underscores the complexity of this domain and its intersection with

the evolving landscape of technology. A common theme among the responses was the acknowledgement of the uniqueness of each tool and the influence of individual backgrounds in shaping their experiences.

Several participants reported the difficulties encountered while using these tools, requiring workarounds to navigate through them (2/6). Participants also pointed out that tools with poor usability could lead to fewer people being able to use them effectively, ultimately leading to fewer tests being conducted (2/6), this also can be linked to another answer describing the steep learning curve associated with these tools, noting that users might focus on learning a single feature that they perceive as essential, missing out on other valuable functionalities due to usability issues.

"Complex and frustrating tools lead to avoidance or limited usage, with users often mastering only essential features due to a steep learning curve, leading to missed opportunities to explore and benefit from other valuable features." - (QP5)

Usability and user experience of the visualisation component of wireless network simulation tools were considered highly important. When asked about how the current visualisation is perceived by their clients, our participants reported that their perception of visualisation features varied. While some clients find the visualisations acceptable but not exceptional (3/6), others feel the visualisation is not very good, lacks clarity, and may not effectively convey important information (3/6).

"The user experience of these tools is not great. It's a hard thing to get across as the spectrum may not always be visualised." - (QP1)

All participants agreed about the importance of well-implemented visualisation. They highlighted the need for aids for configuration, ease of understanding, efficient analysis, faster decision-making, and higher adoption rates.

"Visualisations that are well-utilised are important for ease of understanding, efficient analysis, faster decision making, higher adoption, training and a competitive advantage." - (QP6)

**Emerging Trends and Next Steps for Design.** Participants recommended a user-centred design approach, focusing on improving initial user experiences, reducing complexity, and enhancing configurability. Integration of virtual reality, dynamic routing, and mesh networks were suggested for future enhancements. Simultaneously, they also emphasised the importance of improving initial user experiences, reducing complexity, and enhancing configurability to make the tools more accessible to a broader user base.

"users needs should be at the centre of experience, not technology." - (QP1)

### 4.2 Design Workshop Results

Informed by the questionnaire results, the design workshop discussions were focused on participant-client collaboration using network simulation tools, exploring both positive and negative aspects. Discussions unveiled development

challenges in meeting clients' demands. Afterwards, to answer our third research question, two design activities were conducted using CORE/EMANE as a case study, to compile feature lists addressing usability and reducing complexity. Participants emphasised that a human-centric approach to enhance usability and realise the tool's potential is crucial.

**Challenges of Simulation Tools.** Starting the discussion, participants shared challenges and frustrations in utilising simulation tools, particularly focusing on CORE/EMANE, the primary tool used by our participants. Challenges highlighted in clients' engagement when using simulation tools include simulation demonstrations that often appear to be ad hoc and unprofessional, leading to difficulties in conveying information to clients. Participants expressed difficulties when urgent changes are requested by clients during demos which can be time-consuming and involve command-line operations, disrupting the workflow and coming back with results that cannot be verified.

"It always looks ad hoc and unprofessional ... Stakeholders may ask for changes to the simulation, which can take 15 minutes of fiddling around with command-line commands. It may or may not work, and even when it does, because the tool does not provide visual outputs, it can be difficult to understand what is happening." - (WP3)

The tool's visualisations were criticised for their lack of clarity. Participants emphasised that the tool sometimes leaves stakeholders to interpret data independently. Mobility-related scenarios, which involve the dynamic movement or changing locations of entities within a network, were identified as particularly problematic, causing crashes and difficulties in altering parameters on the fly.

**Open-Source and APIs.** A strong theme that emerged from the design workshop was the impact of open-source development on data quality and library usability, with tool choices influencing dataset quality. CORE/EMANE, while recognised for extensive datasets, posed challenges due to varying quality dependent on contributors' efforts. Participants expressed concerns about datasets ranging from well-structured to hastily created ones, emphasising the impact on project outcomes.

"Some tools may look better but have limitations, focusing on specific aspects like Cisco. CORE/EMANE tends to have more comprehensive data. The quality of datasets can vary, ranging from well-done ones to incomplete ones crafted for specific projects." - (WP3)

**Development Challenges.** The challenges discussed while working with clients transitioned into development challenges, particularly concerning the graphical user interface (GUI) limitations in exposing essential parameters for network conditions. While the GUI was praised for user-friendliness in node representation, manipulating critical parameters remained obscure, requiring a balance between flexibility and usability. Additionally, beginners face a steep learning curve and

insufficient documentation. To address this challenge, the development team has resorted to collaboratively developing internal documentation. This has helped to improve the documentation, but some challenges still remain.

"The CORE/EMANE GUI is visually straightforward, depicting node types and network topology. However, crucial parameters for network conditions are obscured, especially in complex radio models with numerous tweakable parameters. Balancing flexibility with simplicity poses challenges for developers, as more parameters enhance flexibility but make explanation and consistency more difficult." - (WP1)

Participants noted that while standard routing algorithms were easy to use, customising the tool to meet specific clients' requests was a challenge. Customisation can be difficult and time-consuming, as it requires substantial research efforts by developers to identify the appropriate parameters and learn about the many parameters available in CORE/EMANE. Some parameters are not intuitive, and it can be difficult to understand their impact on the simulation.

While simulations present numerous advantages, they aren't without challenges, including integration complexities, manual setup steps, data sharing limitations, and adapting to future requirements. Many projects involve multiple tools, leading to fragmentation. Participants acknowledged these challenges but noted the difficulty in creating a single tool with all features. They prefer to develop workarounds for diverse projects until a unified tool becomes available.

"Many of these projects are proof-of-concept, aiming to demonstrate an idea's feasibility. As a result, it is not always important if it is a kludge or a quick/dirty solution. This approach can result in a patchwork of kludges. Each project caters to specific client needs, making a comprehensive system challenging without anticipating all customer requirements. Quick solutions remain essential." - (WP1)

**Data Visualisation.** During the discussion, CORE/EMANE's GUI design was praised for its ease of use but deemed in need of new features. However, the absence of visual representations for many parameters was noted. Addressing data visualisation challenges, a participant stressed the importance of clear and visually appealing visuals, crucial for conveying complex simulation results to non-technical stakeholders. Participants emphasised the significance of clear data visualisation and the challenges posed by raw, unprocessed data in complex simulations. Emphasis was placed on user-friendly interfaces for intuitive data interpretation, aligning with the questionnaire results advocating for dynamic user profiles. CORE/EMANE lacks built-in visualisations for various data types, prompting users to rely on third-party tools for desired visualisations.

"My role involves speaking to customers and ensuring they can easily interpret and visualise the data. The data must be presented in a clear and visually appealing way... This can be challenging when dealing with non-technical customers who simply want to know if something will work in a given situation. So, presenting data in an easily understandable way is a priority for us." - (WP5) Following the initial discussions, participants engaged in two design activities to propose enhancements for simulation tools, addressing our third re-

search question. The subsequent subsections will detail these activities and the list of features our participants recommended to improve CORE/EMANE and other simulation tools.

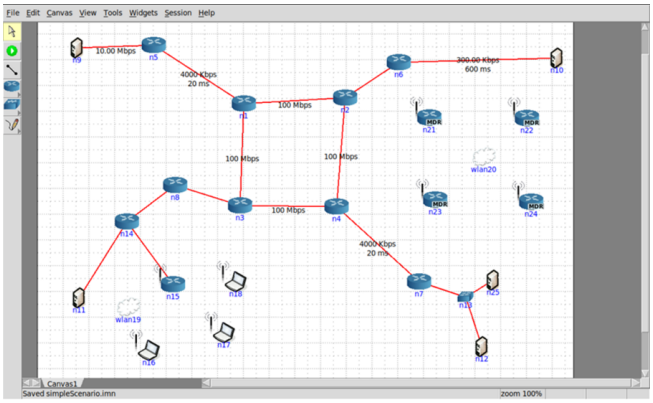


**Fig. 1.** CORE/EMANE interface used in activity 1.

**Activity 1: Designing the GUI Interface.** In the first design activity, participants were presented with a screenshot of the CORE/EMANE interface, shown in Figure 1, and asked to identify positive features. Our participants highlighted several positive features, including the clear and user-friendly design, emphasising the ease of dragging nodes and customising the interface for improved usability. Icons were considered representative enough for users to quickly understand their functions, even with minimal prior knowledge. The interface effectively distinguished wireless nodes with a small antenna icon, facilitating easy identification. Moreover, the editing capabilities, such as modifying connections, adjusting bandwidth, adding labels, and managing properties, were acknowledged for providing users with convenient and flexible options.

Afterwards, participants were given the task of designing the added features and functions they would like to see added to the tool's interface. Participants were given the choice to jot down on the printed interface or use blank papers to complete the task. One of these designs is displayed in Figures 2. Following are the features our participants suggested to be added to the interface:

- Toggle visual indicators for identification of network conditions like congestion or bottlenecks.
- Switch between full and simplified network topology views.
- Show areas of overlap between wireless nodes to identify potential interference or connectivity issues.
- Quickly identify nodes connected to a WLAN.
- Colour coding to visualise network connectivity, segments, & vulnerabilities.

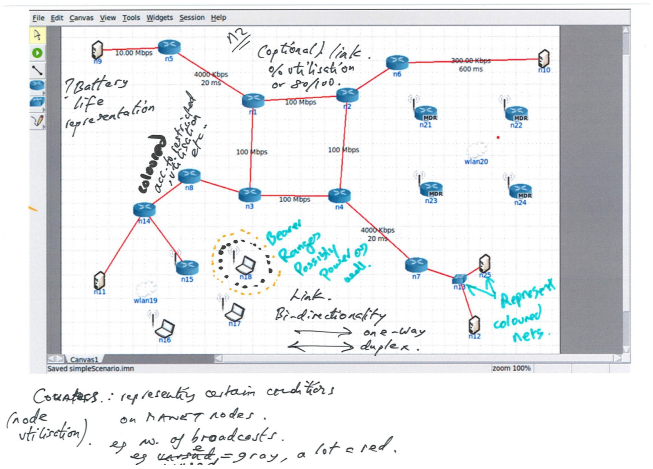


**Fig. 2.** Participants added features in activity 1.

- Display battery life of network devices or nodes.
- Provide alternative data transmission paths to increase network reliability.
- Add sliders to adjust and visualise different parameters.
- Select and display specific properties or details of nodes.
- Assign different icons to nodes to distinguish their types.
- Add controls to simulate network events, as traffic changes.
- Set performance thresholds for varying conditions.

**Activity 2: Required Visualisation and Data Types.** After the first activity, the participants were asked to draw visualisations they would like to see in the tool. One of these designs is displayed in Figure 3. After the activity, our participants discussed their visualisation and agreed that the following features should be added to enhance the visualisations of network simulation tools:

- Show available and utilised bandwidth on network links, identifying potential bottlenecks.
- Use colours to represent link delays for better optimisation.
- Represent different network paths graphically, including the best path to a destination.
- Provide a visual indicator of network devices' health status, identifying potential faults.
- Use colours to show network reachability and connectivity.
- Display frequency of node transmissions, identifying traffic bottlenecks or security risks.
- Show link between network traffic and throughput over time.
- Highlight areas with poor connectivity on a map, pinpointing areas needing improvement.

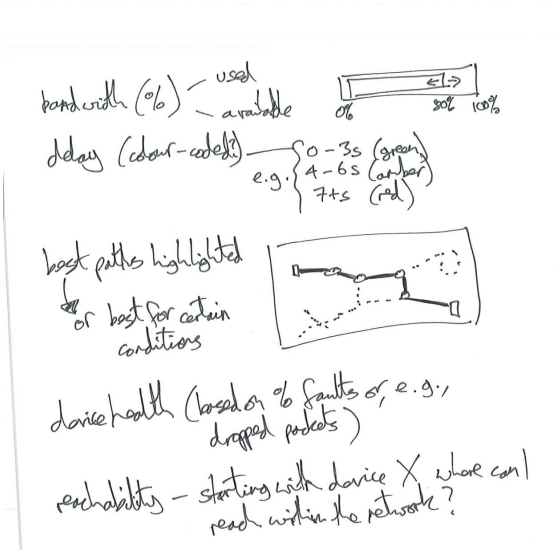


**Fig. 3.** Example of the designed visualisations.

- Show bandwidth utilisation over time, with moving average.
- Visualise significant network events using a bar chart.
- Generate interactive graphs to visualise network data.
- Enable personalised dashboards and reports, with configurable widgets and content.

## 5 Discussion

Participants' insights, gathered through the questionnaire and the design workshop have provided an understanding of both technical and usability requirements and challenges in network simulation tools. The following section will discuss the key findings of our research.

### 5.1 Usability Shortcomings

Our findings, in alignment with related research in network management tools research, explore the crucial issue of usability faced by users and clients when implementing projects [34]. Participants' experiences reveal diverse client perceptions of user experiences with these tools, emphasising the complexity of this domain amid technological advancements. Non-technical end-users commonly struggle with interfaces to comprehend numerical outputs, requesting simpler means to manipulate simulation scenarios. These sentiments align with the conclusions that handling significant data for decision-making is challenging without tailored processing and presentation methods [28].

Our findings reveal a common agreement among participants about the integral connection between user-friendliness and the effectiveness of tool usage, emphasising the pivotal role of usability in determining the efficacy and impact of network simulation tools. The potential hindrance of usability issues resonates with findings from usability research indicating that perceived ease of use and output quality were associated with perceived usefulness [31, 13].

The challenges highlighted in our study emphasise the significance of the GUI in these tools. While the GUI in CORE/EMANE was commended for simplicity and user-friendly clarity, participants observed that essential parameters controlling network conditions are not easily accessible. This lack of customisation makes manipulation and visualisation of these parameters challenging through the GUI, resulting in a steep learning curve and limiting accessibility for users with varying technical proficiency [34].

### 5.2 Fragmentation and Multi-Tool Utilisation

Our findings reveal persistent challenges in network simulation tools like CORE/EMANE, originally developed for a military context, reflecting shortcomings common in general-purpose network simulation tools. Our findings align with prior research highlighting the persistence of challenges across various simulation platforms when used for specific domains and industries [46]. The identified fragmentation issues hinder project consistency, causing disjointed simulations and requiring substantial time and effort. Incompatibility can lead to time-consuming workarounds and may even require custom development to bridge the gaps between tools. It is not uncommon for simulations to produce outputs that are incompatible with each other, making analysis and interpretation difficult.

In addition to compatibility challenges, the increased learning curve associated with multiple tools can slow down project progress. Team members must invest time in learning how to use each tool effectively. This complexity may result in a knowledge gap within the team, where some members are proficient in one tool while others are experts in another, further complicating collaboration. As projects grow in complexity or scale, the challenges associated with using multiple tools become more pronounced. Scalability becomes an issue when juggling multiple tools, data sharing and results across multiple tools can be cumbersome; this can lead to data loss, errors, and additional manual work.

### 5.3 Open-Source Nature of the Tools

Unlike commercial simulators, open-source projects often suffer from insufficient resources and contributions dedicated to documentation [7]. As a result, understanding and tracing codes across different versions can become challenging, hindering efficient development and troubleshooting. This aligns with prior work conclusions that although these tools benefit from openness and community contributions, they are affected by the lack of proper documentation [37, 32]. With

a broader range of contributors, maintaining systematic and complete documentation becomes more difficult, leading to potential gaps in understanding and utilising the tools.

Another related shortcoming is the lack of robust version control support and API integration. As open-source simulation tools evolve with new features and updates, the lack of version control can make it hard to manage changes and ensure backward compatibility [23, 30]. Users may find it challenging to migrate from older versions to newer ones, impacting the longevity and applicability of open-source simulation tools.

### 5.4 Emerging Technologies Integration

Integrating emerging technologies like AI, 5G, and 6G into CORE/EMANE presents significant opportunities for enhancing the tool's adaptability and scalability. For instance, incorporating AI could enable real-time automation of network parameters, making simulations more responsive to dynamic conditions. This approach has already been explored in other tools, such as NS-3, where ns3-ai toolkit enhances data transmission speeds and supports complex AI-driven tasks, such as Channel Quality Indicator (CQI) prediction [47]. This setup lays the groundwork for the potential use of applications to optimise network parameters and resource allocation, thereby improving the responsiveness and efficiency of network simulations. Additionally, support for advanced network standards like 5G could expand CORE/EMANE's utility in simulating ultra-low latency and high-throughput environments, aligning it with the capabilities found in simulators like NetSim [40]. Incorporating these technologies into CORE/EMANE, alongside user-centered design improvements such as interactive visualisations, could enhance user experience and streamline the simulation process, meeting the needs of both novice and experienced users.

## 6 Conclusion

Addressing the growing demand for network simulations, our research offers key insights into professionals' needs, challenges, and opportunities when working with these tools. Addressing technical and usability issues is crucial, necessitating the integration of new technical capabilities alongside enhanced usability considerations. Our mixed-methods approach, involving both a questionnaire and a design workshop, addressed three key research questions regarding the essential features, strengths and weaknesses, and future expectations for network simulation tools. The findings provide insights into the shortcomings and future potential of these tools, particularly from a user-centered perspective.

In response to RQ1, professionals highlighted essential capabilities such as real-time adaptability, scalability, and accurate modeling of network scenarios. CORE/EMANE's strengths in offering open-source, flexibility, and extensive customisation were valued. However, limitations in usability and GUI design, as well as challenges with radio propagation modeling, restricted its applicability.

Subsequently, RQ2 addressed the strengths and weaknesses of network simulation tools. While CORE/EMANE was praised for its adaptability, the study revealed significant weaknesses in terms of steep learning curves, fragmented tool functionality, and the lack of robust visualisation features. These limitations make it challenging for both novice and experienced users to fully leverage the tool's potential, often resulting in workarounds or dependence on additional tools to meet specific needs.

Finally, RQ3 focused on how professionals envision the evolution of these tools. Participants expressed a clear need for the integration of emerging technologies to improve both usability and scalability. Suggestions for future improvements included user-friendly interfaces, enhanced visualisation capabilities for real-time tracking, and automation features that reduce manual configuration time. A more intuitive, customisable interface and dynamic visualisations were highlighted as priorities for addressing both technical requirements and enhancing the user experience.

Our study highlights the need for network simulation tools that not only meet technical demands but also prioritise usability. By addressing the challenges identified and incorporating user-centered design principles, future developments can improve accessibility and efficiency, making tools like CORE/EMANE more adaptable to evolving professional needs.

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