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Developing Complex Thinking through Interactive Simulations Applied to Sensor Networks in Higher Education

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***Abstract*—This study addresses the critical issue of fragmented learning in engineering education by framing sensor network design not as a collection of isolated technical problems, but as a multidimensional process. Grounded in Edgar Morin's principles of Complex Thinking, the research implements an interactive simulation experience where students navigate decisions with systemic implications across energy, communications, and data processing. The pedagogical intervention targeted final-year telematics engineering students, transitioning them from high-level Python abstractions to the "friction points" of resource-constrained systems using the Contiki-NG operating system and Cooja simulator. The curriculum was structured across four distinct dimensions: infrastructure (C/IPv6), physical context (spatial emulation), communications (DODAG collective intelligence), and data processing through cloud-integrated protocols. Quantitative results revealed a non-linear learning curve; student performance dropped significantly from a mean of 83.68 to 62.47 points upon encountering the non-unidimensional reality of the simulator, before recovering to 71.57 points as students synthesized the complexity. Qualitative analysis indicated that while 56% found the tasks difficult and 11% considered them very complex in terms of simulator usage, 83% felt the pace was adequate, and the majority agreed the simulation helped bridge the gap between theory and practice. Correlation analysis suggests that student interest and lecturing clarity are primary drivers of successful theoretical integration. Ultimately, simulated environments offer a sustainable, high-fidelity alternative to hardware for mastering real-world network constraints.**

***Keywords*—Sensor Networks, Constrained Systems, Complex Thinking, EdTech, Experiential Learning.**

I. Introduction

The energy autonomy of sensor networks challenges us to rethink traditional design strategies for monitoring physical contexts or real-world environments. Initially, students approach these challenges with fragmented knowledge and one-dimensional solutions that fail to account for the systemic nature of sensor integration.

Overlooking the fact that the intelligence of a sensor network resides within the network itself —rather than the individual sensor— is equivalent to omitting the multidimensionality inherent in complex thinking. This study aims to design and implement an interactive simulation experience that fosters both the integral development of complex thinking and a multidimensional understanding of these networks.

This interactive simulation facilitates a balance between learning development and assessment, reconsidering the relationship between the cognitive and affective aspects of realistic experiences. The study proposes a framework for multidimensional development and evaluation through an interactive simulation that enables students to intertwined multidisciplinary concepts, thereby achieving the integral development of complex thinking.

Throughout this work we identify the challenges and limitations inherent in initial sensor network solutions when multidimensionality is omitted. Subsequently, we transform one-dimensional learning experiences into multidimensional ones using interactive simulations focused on experiential learning. Finally, by designing a series of multidimensional experiences, we evaluate and compare learning outcomes while accounting for student diversity and varying backgrounds.

II. State of the Art

Complex Thinking is a form of reasoning that seeks to understand reality as an interconnected, dynamic, and constantly evolving whole, rather than analyzing it in a fragmented or simplified manner. It recognizes the interdependence between different elements of a system and the uncertainty inherent in complex situations. This paradigm was popularized by the philosopher Edgar Morin, who proposed it as a necessity for addressing the challenges of the 21st century [1], [2].

Analogously, in sensor networks, challenges are interconnected within a complex system where the solution to one problem directly impacts the others. The multidimensional challenges of sensor networks are not isolated problems but rather a system of interdependent and often conflicting constraints, with energy serving as the dimension that permeates and limits all others. These dimensions involve, from the physical phenomena to be sensed up to the analytical decision making based on that factual data. The true multidimensional challenge arises at the points of friction between these dimensions; the optimization of one almost always degrades another [3], [4].

This systemic interdependence mirrors the definition of multidimensionality of Morin, which states that complex units —the human being or the society— cannot be understood by isolating their parts. Moreover, a pertinent knowledge must recognize that the technical dimensions of such units are in a state of permanent inter-retroactivity [1]. In this study, we apply this lens to sensor networks; just a human is simultaneously biological, psychic, and social, a sensor network is simultaneously defined by its physical context, communications, sensed data, and data processing. To overlook these friction points is to ignore the hologramic nature of the system, where a single technical decision (such as increasing sampling rates) carries implications that resonate across all other dimensions. Therefore, fostering complex thinking in higher education requires a pedagogical approach that resists fragmentation, teaching undergraduates students to integrate information into this multidimensional reality rather than treating each constraint as an isolated variable.

In essence, sensor network design is not a series of technical problems to be solved independently, uni-dimensionally, or in a fragmented way. Rather, it is a single, large-scale multidimensional optimization problem. This study proposes the use of an interactive simulation experience to promote complex thinking, which implies a more sophisticated and pedagogical application of technology [5], [6]. It recognizes the need to move beyond memorization and superficial responses, seeking instead to activate deeper cognitive processes during the development or resolution of a learning experience [7], [8], [9].

We understand that the design of multidimensional experiences facilitates the evolution of sensor network education. By fostering the interconnection of concepts across various disciplines, developing the capacity for synthesis, and promoting the relationship between cognitive and affective domains. By incorporating challenging elements of uncertainty and ambiguity, this approach engages a bilateral cognitive simulation and encourages higher-order thinking, all while remaining firmly rooted in real-world contexts and environments [10].

TABLE I
DIMENSIONS AND MORIN'S PRINCIPLES

N	Dimension	Complexity Principle
1	Infrastructure	Recognition
2	Physical Context	Contextualization
3	Communications	Inter-retroactivity
4	Data and Processing	Multidimensionality

III. METHODOLOGY

The pedagogical intervention was designed for final-year students of telematics engineering who possess experience in high-level embedded prototyping (e.g Raspberry Pi with Python). The course aims to shift their perspective toward Resource-Constrained Systems, utilizing the Contiki-NG operating system and the C/C++ language as multidimensional learning environment. Nineteen students participated in the intervention, including 3 female and 16 male students, reflecting the distribution of the 2025 cohort.

The design follows a structured progression from fragmented to complex thinking. The pedagogical goal is to navigate the points of friction within the simulation to solve specific network challenges. To exemplify, unlike Raspberry Pi environments, where resources are abundant, the Contiki-NG simulation forces students to confront the intelligence of the network. Throughout the simulation we could introduce environmental variables and network failures that are often harder to control or visualize in limited physical hardware setups. The next table present the learning experiences:

The first experience addresses the infrastructure with a focus on fundamental connectivity and the underlying principles of coding logic. Students must transition from the abstraction of Python, interpreted on top of a general-purpose operating system, to the reality of the constrained protocols, such as, IPv6/6LoWPAN stack and C coding. It introduces the communication protocol dimension. By configuring the Border Router, students recognize that, within constrained systems, node detection requires supporting infrastructure, in contrast to the automatic discovery mechanisms provided by Raspberry Pi.

The second experience encompasses the Physical Context. Utilizing the minimalist Cooja Simulator to manage the Sky Mote network, students begin to appreciate the low-level precision of emulation and to visualize the radio environment. Far from replicating fragments of code and resolving coding errors, the learning shift involves interacting with nodes within a spatial reality.

The third experience is centered on routing protocols and the evaluation of performance metrics. Through the analysis of parent-child node relationships, students assess the stability of single or multiple routing trees (DODAGs). Students observe that a change in a node's position or reporting frequency can influence the entire network routing table. The challenge compels students to look beyond the individual node, directing their attention to the collective intelligence of the network.

The fourth challenge integrates advanced protocols, including MQTT and CoAP, along with the Azure Cloud. Students design a simulated sensor network that interfaces with industrial cloud authentication and data ingestion through a gateway, thereby managing simultaneously the physical infrastructure, communications, sensed data and pre-processing dimensions. At this stage, friction can be induced at the gateway level and extended to the payload length, thereby enabling an examination of its effects on the sensor network.

The results are based on mixed-methods research, combining quantitative and qualitative analyses. The learning outcomes are derived from progressive grading and a final perceptive survey. The assumption is that findings based solely on gradual grading will provide only a partial perspective if they avoid the affective-cognitive relationship necessary to complete the critical analysis.

IV. RESULTS

From a quantitative perspective, students performance began at a relatively high level in the first experience, with a mean score of 83.68 points. Scores then dropped significantly in the second experience with 62.47 points, reflecting the increased difficulty of engaging with a non-unidimensional learning experience. Following this decline, performance improved in the third experience, reaching 69.42 points, and continued to rise in the fourth experience, with 71.57 points. These results suggest that, although students initially struggled with higher complexity, they gradually achieved more effective synthesis in collaborative environments as the course progressed. The following table II provides a detailed overview of these metrics:

TABLE II
METRICS OF THE PERFORMANCE

Metric	Ex1	Ex2	Ex3	Ex4
mean	83.68	62.47	69.42	71.57
min	58.00	0.00	40.00	0.00
max	100.00	90.00	95.00	100.00
std	15.04	30.00	19.63	28.18

From a qualitative viewpoint, the survey results provide an affective dimension of the learning experience, covering 13 questions; 10 of which were compulsory and three optional.

TABLE III
PERCEPTIVE SURVEY SCOPE

N	Description	Responses
1	Interest in the content	18
2	Theoretical difficulty	18
3	Theoretical evaluation	18
4	Lecturing clarity	18
5	Practical difficulty	18
6	Integrated experience	18
7	Simulator complexity	18
8	Pace of the course	18
9	Problem solving	18
10	Dedication time	18
11	Aspects to remark	16
12	Aspects to improve	16
13	Open comments	6

By analyzing the distribution of each response across de five-point Likert scale; from level 1 to level 5, measuring perceived interest, we examine each question sequentially.

In the first question no participants selected categories of no low or none interest. A small proportion of respondents indicated a moderate interest considered (17%). The majority of responses clusters a the positive end of the scale, 50% of the participants rated the subject as interesting and 33% of them rated it as very interesting, as shown in figure 1.

These results suggest a strong overall tendency toward positive perceptions of interest, with the highest concentration of responses at level 4, indicating that most participants found the topic engaging.

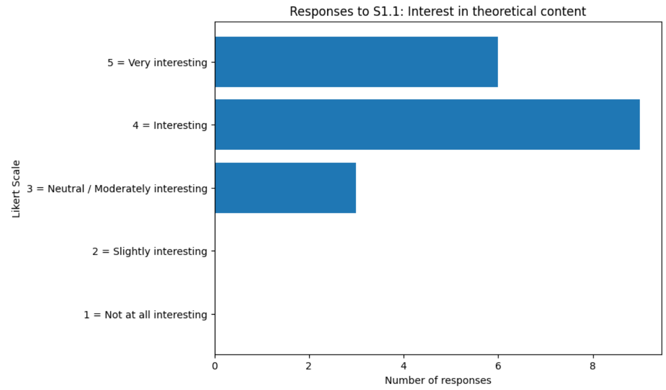

Fig. 1. Question: Perceived interest

Observing the second question regarding perceived theoretical difficulty reveals a concentration at the midpoint of the scale with 78%. No participants considered very easy or easy. The majority of respondents indicated that the literature was adequate, suggesting a balanced perception of difficulty. A smaller group rated the theory as difficult (22%), reflecting some challenges but not an overwhelming level of difficulty. The following figure 2 illustrates the tendency.

Overall, the distribution demonstrates that most participants experienced the theory as manageable, with only a minority perceiving it as somewhat demanding.

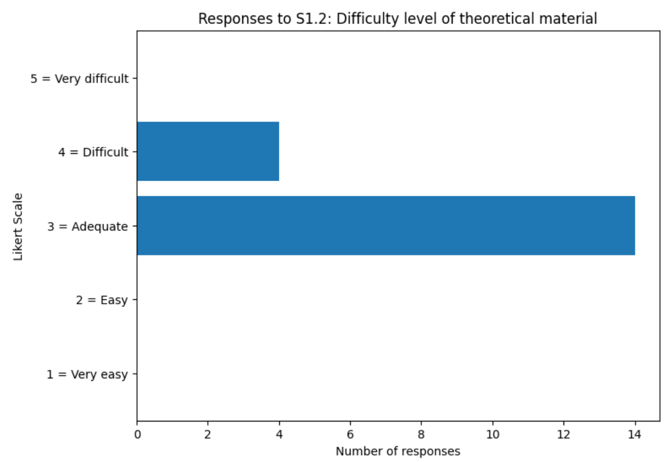

Fig. 2. Question: Theoretical difficulty

The third question captures the perceived helpfulness of quizzes demonstrates the absence of negative perceptions. A moderate number of respondents (28%) reported a neutral stance, identifying the quizzes as somewhat helpful. Yet, the largest proportion of responses (50%) fell within the quite helpful category, while a 22% of participants rated the quizzes as very helpful. The following figure 3 shows the results.

Taken together, these results suggest that the majority of participants perceived the quizzes as beneficial, with the highest concentration of responses reflecting a strong endorsement of its helpfulness.

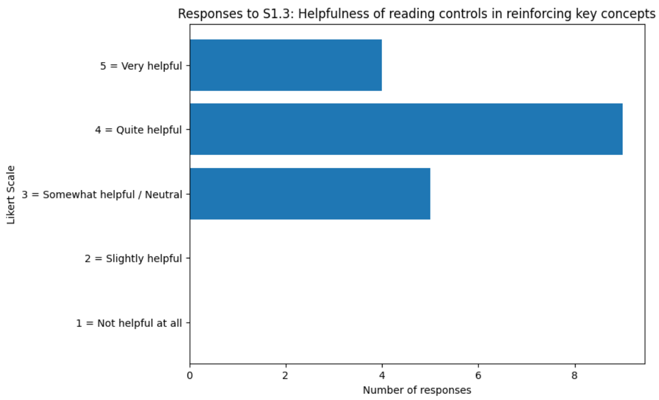

Fig. 3. Question: Quizzes helpfulness

The results of the fourth question concerning clarity of the lecturer indicates a predominantly positive evaluation. None of the participants selected categories not clear or not very clear, suggesting the absence of negative perceptions. A minority of respondents (22%) reported a neutral or moderately clear impression. The largest proportion of responses identified the experience as clear (50%), while an additional 28% of participants rated it as very clear, as shown in the next graph 4.

Overall, the distribution demonstrates that the majority of participants perceived the experience as clear, with substantial concentration of responses at the higher end of the scale.

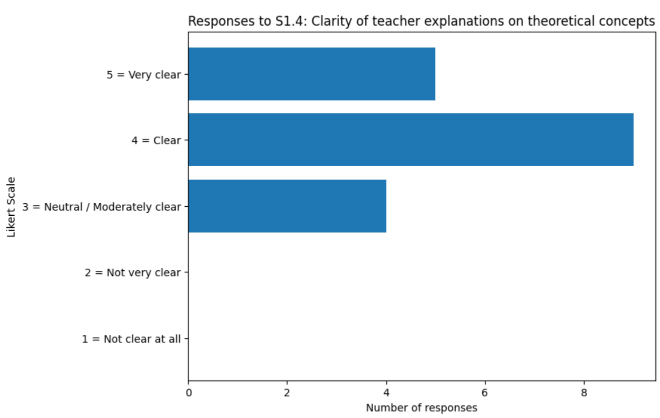

Fig. 4. Question: Lecturing Clarity

The fifth question asked about the overall level of difficulty of the practical tasks, and reveals a distribution concentrated toward the higher end of the Likert scale. No participants rated the tasks as very easy or easy. A minority of respondents (28%) considered the experiences to present an adequate difficulty. The largest proportion of responses (56%) indicated that the experiences were difficult, while an additional 18% of participants rated them as too difficult. The following figure 5 exhibit the results.

Overall, these results suggest that the majority of participants perceived the simulator tasks as challenging, with most evaluations falling between adequate and difficult, and a smaller but notable group identifying them as excessively demanding.

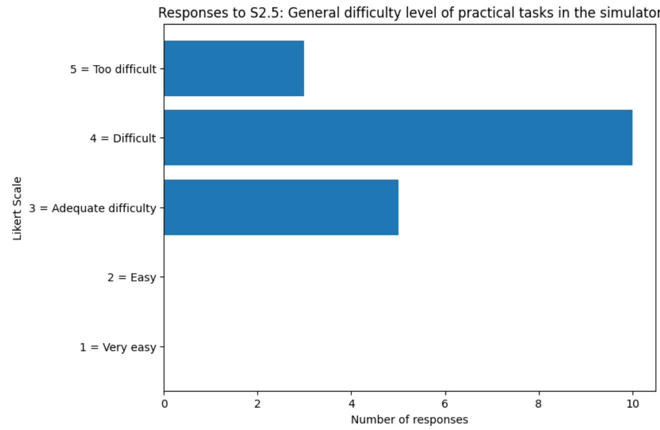

Fig. 5. Question: Difficulty of practical tasks

In the question six is assessed whether the practical tasks helped participants connect and apply theoretical concepts in an integrated manner, showing a predominantly positive trend. No respondents selected strongly disagree, while only a 11% expressed disagreement. A considerable proportion of respondents (33%) adopted a neutral position, indicating neither agreement nor disagreement. An equal number of participants agreed with the statement, and 22% strongly agreed. The next figure 6 illustrates the results.

Overall, these findings suggest that most participants perceived the practical tasks supportive in bridging theory and practice, with the majority of responses clustering around agreement and neutrality, and very few expressing disagreement.

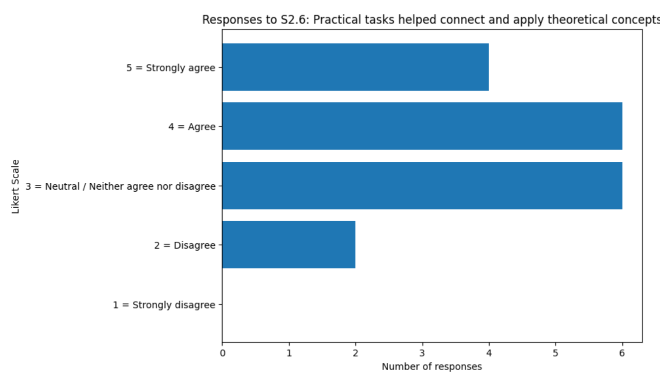

Fig. 6. Question: Integral practice and theory

Examining the seventh question regarding the perceived complexity of the simulator usage reveals a distribution skewed toward moderate to high levels of difficulty. Only 6% of the participants rated the process as very easy, and 17% of the respondents considered it easy. A larger group represented by the 33% indicated that the tasks involved a moderate or adequate difficulty. An equal number of participants perceived the process as complex, while 11% rated it as very complex, as shown in the figure 7.

Overall, these findings suggest that while a minority found the tasks straightforward, the majority experienced them moderately to highly complex, highlighting the technical demands associated with engaging with the simulation environment.

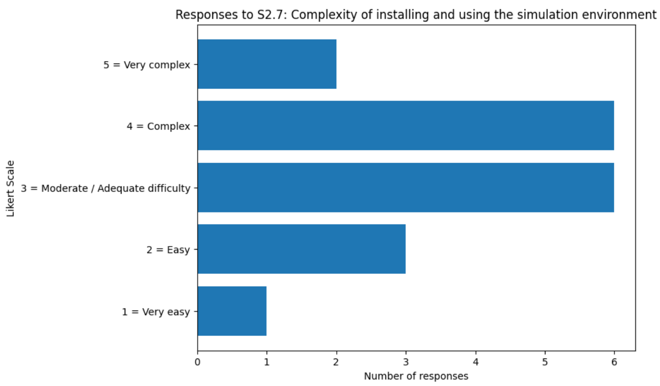

Fig. 7. Question: Simulator usage complexity

In the eighth question asked participants to evaluate the overall pace of the course, and it indicates a strong consensus around adequacy. None the respondents rated the pace as too slow or too fast. A small minority (11%) perceived the course as slow, while 6% of participants considered it fast. The overwhelming majority (83%) rated the pace as adequate, suggesting that the course rhythm was generally well-balanced and aligned with participants' expectations, as is illustrated in figure 8.

Overall, these findings highlight participants' experienced the ace as appropriate, with only minimal variation toward slower or faster perceptions.

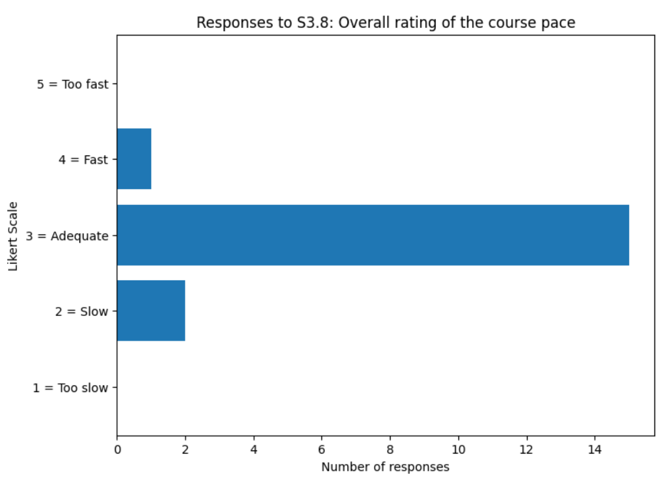

Fig. 8. Question: Course pace

The results of the ninth question regarding the course challenges participants to think differently when solving problems compared to other subjects, reveals a varied distribution across the Likert scale. Only 6% of respondents perceived the course as following a traditional approach. A group represented by the 33% indicated that the course presents some small differences but remains mostly traditional. The 28% of participants adopted a neutral stance, describing the course as somewhat different. The 22% of respondents considered the course to be considerably different, while 11% of participants strongly affirmed that it is definitely a different approach, as is exhibited in the next graph 9.

Overall, these findings suggest that while a portion of students view the course as largely traditional, the majority recognize at least some degree of difference, with a notable subset perceiving it as considerably or definitively distinct in its approach to problem-solving.

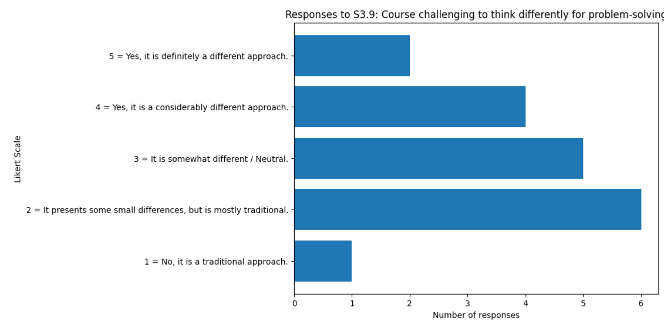

Fig. 9. Question: Think differently in problem solving

In the question tenth asked to the participants reporting the average amount of time dedicated to the course per week, which reveals a distribution concentrated in the lower to moderate ranges of study time. The 11% of the respondents indicated spending less than 2 hours per week. The largest proportion of participants (50%) reported dedicating two to three hours per week, followed by 39% of respondents who reported four to six hours per week. Notably, no participants selected the higher categories of seven to then hours per week, or more than ten hours per week. The following figure 10 illustrates the results.

Overall, these findings suggest that most students dedicate between two and six hours weekly to the course, with no evidence of extensive time investment beyond this range.

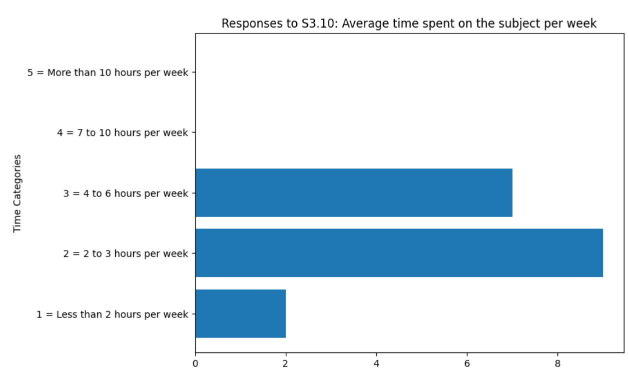

Fig. 10. Question: Study time

V. Analysis

Learning outcomes are evaluated based on both scores and perceptions, which are analyzed here in combined manner. The scoring metrics, including averages, minimums, and maximums, are presented per student in the figure 11, where the range of performance is clearly observed. There is no evidence of a collapse into a single dimension of evaluation, as variability remains across iterations. From the second task onward, the complexity increases, and the pace of delivery is not consistently assured. Nevertheless, the majority of the students adapt to the simulated scenario, maintaining performance above the threshold of 55 points required to pass the course.

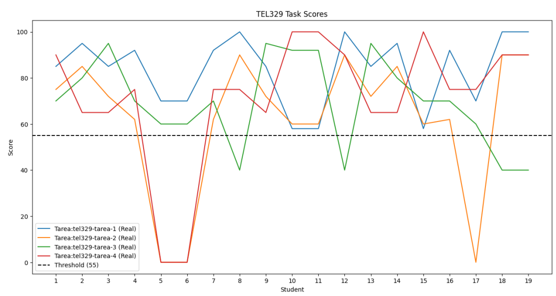

Fig. 11. Scoring Metrics

The correlation analysis of the survey questions (1 to 10) reveals several direct relationships based on Pearson correlation coefficients. A summary of the most notable correlation (absolute value > 0.4) is presented below, indicating potential associations between participants' perceptions.

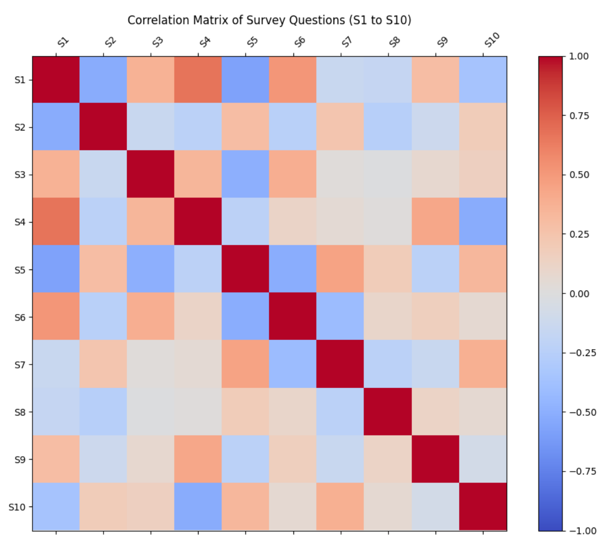

Fig. 12. Correlation Questions 1 to 10

Strong Positive Correlations ($r > 0.5$)**:** Higher interest in theoretical content is strongly associated with perceiving the teacher's explanations as clearer (Fig. 1 interest in content and Fig. 4 clarity of explanations; $r = 0.67$). Students who found the content more interesting also tended to agree that practical tasks facilitated the integration of theoretical concepts (Fig. 1 and Fig. 6 practical tasks helping integrate theory; $r = 0.51$).

Strong Negative Correlations ($r < -0.5$)**:** Greater interest is associated with lower perceived difficulty in practical tasks (Fig. 1 and Fig. 5 difficulty of practical tasks; $r = -0.57$). Clearer explanations are correlated with less time dedicated to the subject (Fig. 4 and Fig. 10 time spent per week; $r = -0.52$). Higher perceived difficulty in practical tasks is associated with lower agreement that they facilitate the integration of theory and practice (Fig. 5 and Fig. 6; $r = -0.51$).

Moderate Correlations ($|r| = 0.3 - 0.5$)**:** Greater interest is associated with lower perceived theoretical difficulty (Fig. 1 and Fig. 2 theoretical difficulty; $r = -0.52$). Interest positively correlates with perceiving quizzes as helpful (Fig. 1 and Fig. 3 helpfulness of reading controls; $r = 0.36$). Clearer explanations are associated with perceiving the course as more challenging in problem-solving (Fig. 4 and Fig. 9 challenging to think differently; $r = 0.43$). Greater practical difficulty correlates with higher perceived simulator complexity (Fig. 5 and Fig. 7 complexity of simulator; $r = 0.45$). Higher simulator complexity is associated with more time spent on the subject (Fig. 7 and Fig. 10; $r = 0.38$).

Weak or No Correlations ($|r| < 0.3$)**:** Most pairs involving course pace (Fig. 8) and challenging to think differently or time spent (Fig. 9 or Fig. 10) exhibit low correlations, suggesting that pace is perceived independently. In terms of helpfulness of quizzes (Fig. 3) is shown moderate associations but is not strongly linked to most other variables.

These correlations suggest that positive perceptions of content interest and clarity may foster better integration of theory and practice while reducing perceived difficulty. Conversely, practical challenges (difficulty and complexity) appear to be interconnected and may contribute to increased time investment.

Complementarily, all elements written in the open and optional questions were processed descriptively using a word cloud. This visualization highlights the frequency of meaningful terms. At first glance, the favorable appreciation of the course lies in the practical experiences; however, the underlying interpretation relates to its closeness to the physical and realistic world. Embedded systems tend to carry a bias among students, particularly regarding physical interaction with robots. Nevertheless, understanding robots and the wide variety of integrated components requires resources that often exceed the common budget of universities. Therefore, simulators represent the most sustainable and affordable means of learning about them.

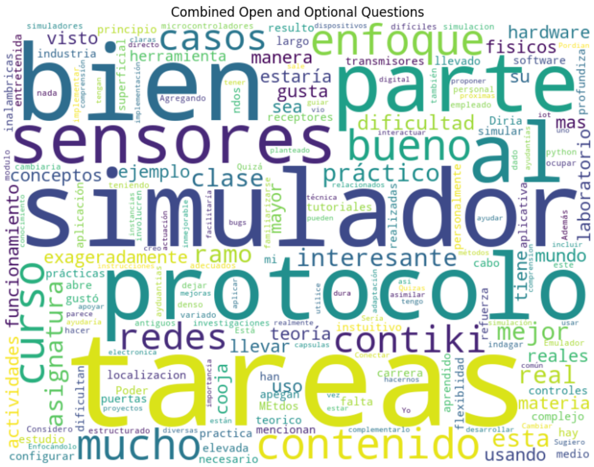

Fig. 13. Word Cloud of Open and Optional Questions

VI. Conclusions

This study addresses the issue of fragmented learning by framing a sensor network learning experience not as a collection of isolated technical problems, but as a multidimensional educational process. By applying Edgar Morin's principles of Complex Thinking through interactive simulations, students make decisions with implications across energy, communications and data processing, thereby confronting the inherent challenges of constrained systems.

To foster complex thinking, the intervention transitions final-year students from high-level Python abstractions to the friction points of resource-constrained systems using Contiki-NG and Cooja. The curriculum integrates four dimensions: infrastructure (C/IPv6), physical context (spatial emulation), communication (DODAG collective intelligence), and data processing through cloud-integrated protocols.

The results reveal a non-linear learning curve that validates the challenge of complex thinking. As seen at the second experience, students performance dropped significantly (from 83.68 to 62.47 points) when introduced to the non-unidimensional reality of the simulator, reflecting initial friction with higher complexity. Scores improved in subsequent experiences (reaching 71.57 by the last experience), suggesting that students successfully synthesized the multidimensional concepts. While 56% found the tasks difficult and 11% considered them very complex in terms of simulator usage, 83% felt the pace was adequate, and the majority agreed the simulation helped bridge the gap between theory and practice.

Analysis reveals that student interest and lecturing clarity significantly enhance theoretical integration while reducing perceived difficulty. Despite hardware biases, simulators offer a sustainable, realistic alternative for mastering complex network constraints. Navigating simulated friction points successfully bridges the gap between fragmented learning and real-world multidimensional systems.

As future work, complementing simulators with hard and soft real time operating systems would be of interest.

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