Design of an Evaluation Tool for Decision-Making Strategies in the High-Tech Industry.

A. Koene*

University of Twente, Faculty of Engineering Technology, Drienerlolaan 5, 7522 NB Enschede, The Netherlands.

**Ayu Koene A.Koene-1@student.utwente.nl*

ABSTRACT: Complex system development in the high-tech industry is a long-lasting process marked by decision-making. To gain insight into decision-making strategies without relying on lengthy projects to finish, this paper covers the design of an evaluation tool that quickly reveals the impact of decisions on complex systems. The final design is a workshop prototype where participants physically complete a series of puzzles through strategic decisions. The prototype is tested with experienced Systems Engineers specialising in semiconductor manufacturing equipment. Their decisions and outcomes are documented, quantified through weighted criteria matrices, and finally compared. The results indicate that the tool is capable of evaluating decisions versus outcomes and adapting to strategies. However, more data is required to assess the performance of the tool. Specifically, the accuracy of the analysis models and the adherence to actual system development should be examined. This paper and the prototype can form the basis for further research.

Key words: Systems Engineering, Complex Systems, Decision-Making, Simulation Environment.

1 INTRODUCTION

Within the domain of high-tech engineering, decision-making influences the course of progress and success. In this dynamic industry, complex products with numerous subsystems are developed. To do so, Systems Engineers are required to unify all components and structure them into one functional complex system architecture. This practice is called Systems- Engineering or Architecting. Within this design process, many heuristic and analytical choices are made each leaving a lasting imprint. It requires trade-offs between features of performance, schedule, cost, and risk. It often takes years and involves a great number of people. On top of that, uncertainties play a significant role and decisions are rarely documented and explored in structured ways [1][2].

This poses a problem to researchers investigating the effects of specific decision-making strategies on complex system development. Such studies can be valuable for improving development practices. However, research becomes impractical when lengthy real-life projects are the subject because the decisions taken by Systems Engineers need to be compared with the final result. Thus, for a rapid evaluation of established and novel decision-making strategies, an alternative approach has to be introduced. It should effectively capture and enable analysis of decisions versus outcomes.

The research in this paper concerns the design of a practical evaluation tool in the form of a simulation environment that unveils insights into the impact of decision-making strategies within complex systems. A prototype was developed and tested with the help of experienced Systems Engineers dealing with semiconductor equipment.

2 BACKGROUND

2.1 Decision Analysis

Decision-making processes can be studied through several models described in Decision Theory [3]. Within this field, Decision Analysis (DA) is a practical toolbox for evaluating decisions, while clearly distinguishing them from outcomes. As shown in Figure 1 adapted from [3], good decisions do not necessarily lead to good outcomes, and vice versa.

Fig. 1: Quadrant Chart of Decisions vs. Outcome

In practice, DA makes use of tools like decision trees, influence diagrams, and deterministic & probabilistic analysis. To accurately apply DA to Systems Architecting problems, the set of decisions should be limited, uncertainty should be accounted for through probabilistic analysis, and the system criteria should be clear [1]. Another practical DA concept is Decision Quality (DQ). It is defined as 'the quality of a decision regardless of the outcome' [3]. Figure 2 depicts the six requirements to achieve a high DQ:

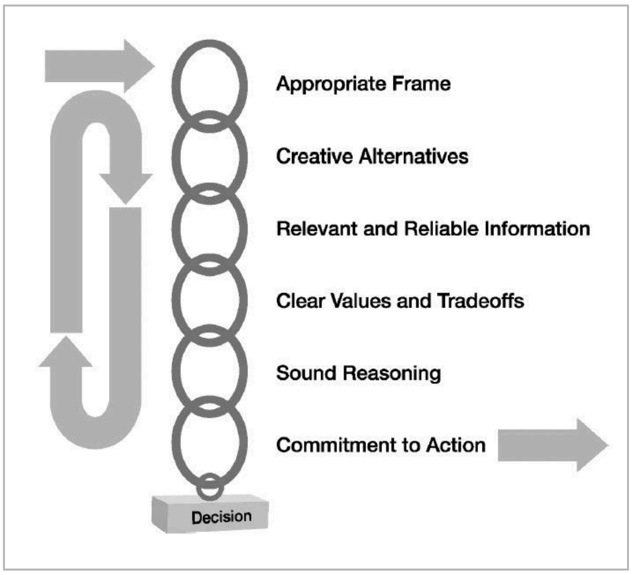


Fig. 2: The DQ Appraisal Cycle [4].

3 METHODOLOGY

The tool was developed using the Design Research Methodology framework [5] and applying Design Thinking principles [6]. In the Research Clarification and Descriptive phase, the goals were defined and design requirements were formulated based on the problems' definition and background literature. Then, through diverging and converging phases, solutions for each requirement were explored after which the most suitable were chosen to form a final concept. A prototype was made for the Evaluation phase. In this phase, experienced Systems Engineers participated in an experimental trial to assess the tool. The final prototype and acquired data are presented in Section 4 Results.

3.1 Problem Definition

The overall problem can be defined as the inability to quickly compare decisions with the final outcome within actual complex system development. This makes it difficult for researchers to evaluate different decision-making strategies used by Systems Engineers. A simulation environment representing a condensed version of system development could be a solution. Therefore, the goal is to develop a tool that captures all decisions of experienced Systems Engineers that lead up to a finished complex system in a single workshop session. The environment should accurately model the operation of the real-world process or system over time [7]. However, imitating the real-world process in this way is challenging. Moreover, a structured decision-collection method is often missing within actual processes [2]. For the tool to be effective, the simulation environment should include such a method, accompanied by a DA model. Furthermore, the outcome, i.e. a combination of development- and system quality, should be documented and quantified as well. For actual systems, the quality is defined in terms of customer satisfaction, not system requirements [1]. For actual development processes, productivity is the main measure; An effective process that achieves high customer satisfaction is considered the most desirable outcome [8]. Lastly, it is impractical to experiment with decision-making strategies within the actual process, as discussed in Section 1 Introduction. The tool should facilitate such tests. Solutions to the aforementioned problems should enable researchers to compare decisions, outcomes, and strategies.

3.2 *Design Requirements*

Several design requirements can be formulated for the evaluation tool. These are categorised into simulation and analysis requirements.

An appropriate analogy for actual complex systems is needed for the simulation environment. It requires a dynamic model, initial conditions, specifications on the effects of external factors, and an execution environment to run the model [9]. The dynamic model should accurately mimic the development process. Accordingly, specific criteria and decision-making scenarios leading to an overall problem-solving assignment should be constructed [10]. However, instead of years, the whole process must be covered in one workshop session, also known as the execution environment. This execution environment calls for visual elements. Moreover, the effects of external factors on the dynamic model should be clearly defined. They must be linked to the uncertainties within real-life complex system development. Lastly, the environment should be compatible with- or adaptable to different decision-making strategies.

Additionally, several requirements can be formulated to facilitate research. Decisions should be documented and collected for quantification. The latter requires a limited set of decisions, probabilistic analysis, and clear system criteria as established in Section 2.1. Similarly, the outcome, i.e. the complex system and development process, requires collection and quantification.

In summary, the following is required:

- Simulation Requirements:
  - The dynamic model should mimic complex system development. This requires an analogy for actual systems and specifications on the decision-making scenarios. For an accurate representation, participants need to solve a problem and conform to constraints.
  - The execution environment needs elements fit for a workshop setting in which experienced Systems Engineers participate. The duration is one workshop session of half a day.
  - The external factors should represent the uncertainties within the actual process.
  - It should be compatible with established and novel decision-making strategies.
  - Decisions and outcomes need to be documented.
- Analysis Requirements:
  - Decisions need to be quantified through DA.
  - Outcomes need to be quantified by assessing system and development quality.
  - Decision-making strategies need to be evaluated using the quality of decisions and outcomes.

3.3 *Conceptualisation*

Based on the requirements, concepts are formulated with the aid of a generic morphological diagram described in Table 1. It covers the design requirements and possible solutions.

Table 1: Morphological Diagram - Possible solutions for the requirements.

	Option 1	Option 2	Option 3
Simulation Requirements			
Analogy-type Dynamic Model	Realistic 31	Abstract 31	Simplified 57
Medium & Resources Execution Elements	Virtual 40	Physical 56	Combination 50
Decision-Making Scenarios Analogy-type	Realistic 48	Abstract 26	Simplified 52
Uncertainty External Factors & Effects	Real-time Feedback Mechanism 50	Planned Consequences 55	Probabilistic Modelling 35
Analysis Requirements			
Documentation Decisions & Outcome - Medium	Digital 47	Analog 56	Combination 43
Evaluation Quantification Method	Mathematical Models 36	Weighted Scoring Mechanisms 49	Combination 38

Through a weighted scoring scheme, the solutions are rated and the best options are derived as indicated in Table 1. The following criteria and corresponding weighting factors were considered:

- Feasibility (5): Scores are assigned based on resource requirements.
- Effectiveness (4): Scores are assigned based on the ability to effectively and accurately acquire data for the comparison of decisions and

outcomes.

- Adaptability (3): Scores are assigned based on the solutions' adaptability to novel and established decision-making strategies.
- Flexibility (2): Scores are assigned based on the solutions' flexibility to other applications and other areas within the high-tech industry. This criterion also considers scalability.

The weighting factors correspond to the goal and timespan of this research.

The solutions that scored the highest are used for designing the final concept. First, the dynamic model is an analogy displaying a simplified but recognizable system. Secondly, physical execution elements are most feasible and align with the predefined workshop setting. Consequently, the simulated system outcome is physically documented. The decision-making scenarios are simplified and do not display the variety of scenarios within actual system development [1]. Accordingly, uncertainties are included through planned consequences to keep the analysis manageable by enabling an ideal configuration. For the documentation of decisions, a simple form or survey is sufficient for a prototype. The concepts' initial analysis makes use of a weighted scoring mechanism.

4 RESULTS

4.1 Final Simulation Environment

The final concept is a simplified analogy of complex system development going back to the basic principles of Systems Architecting [1]. The complex system is represented by a certain surface area made up of physical building elements, i.e. subsystems, that appear as puzzle pieces or tiles. The pieces need to be connected and structured to fit into the constraints, thus fully covering the surface area. In this simulation, Systems Engineers develop the system by deciding on desired pieces and the positioning of pieces. The external factors, or uncertainties, are introduced by revealing the pieces stepwise and alternating mandatory- and optional pieces. In this way, their effects are defined, the simulation is controlled, and the analysis is manageable. For the documentation of decisions, the Systems Engineers are asked to write down their reasoning while researchers observe their approach. For the documentation of the outcome, a photo of the system is taken and completion time is tracked. By keeping the analogy simple, the simulation can be adapted to various applications and decision-making strategies.

4.2 Game Mechanics

The simulation works similarly to a tiling match game or puzzle mechanics [11]. When comparing it to the well-known videogame Tetris [12], the players are required to match or cover the whole board instead of one row. The mechanics are summarised in a workshop manual used for the final prototype's trial session as displayed in Figure 3.

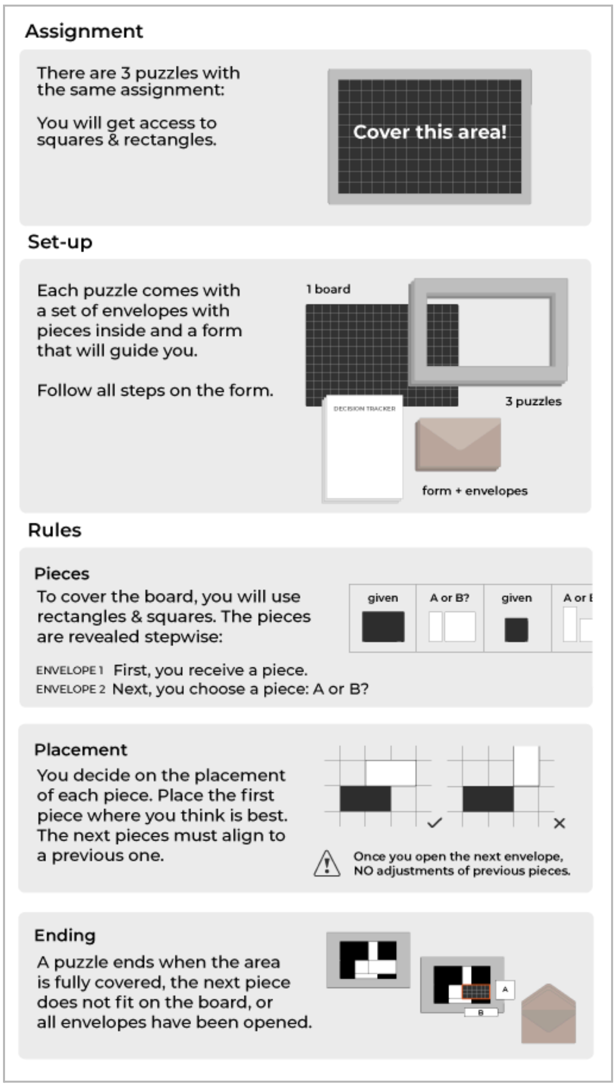


Fig. 3: Workshop Manual used within the trial.

The static rules, as defined by Bailey [11], are described by the resources. For the prototype, a board with a rectangle grid and a square cell topology is used. The puzzle pieces are monochromatic rectangles revealed stepwise through a predefined spawning algorithm. For the dynamic rules, players are tasked to place and choose pieces. They receive a maximum number of pieces. Odd-numbered pieces are determined, while even-numbered pieces are chosen from a limited set. The goal is to fully cover the board. The game ends when the players run out of resources, fully cover the area, or cannot fit the upcoming piece onto the board.

4.3 Analysis Method

Through weighted criteria matrices, the overall quality of decisions and outcomes are evaluated separately and finally plotted for further assessment. To explain the analysis, quality decisions and outcomes are defined. First of all, a quality decision adheres to the six DQ requirements in Figure 2 applied to the game mechanics in Section 4.2. Players make decisions on piece placement and piece choice. Secondly, a quality outcome is the combination of a quality- system and development process. A quality system is described as an efficient neat structure of puzzle pieces. A quality development process is time efficient, which means time is compared to the number of decisions and surface area coverage. The outcome quality can be linked to decision-making strategy quality [8].

4.3.a Weighted Decision Criteria Matrices

Each decision on both piece placement and piece choice is separately scored based on the following criteria. The accompanying weighing factors are shown in brackets:

- Adherence to strategy (2): Scores are assigned based on the extent to which decisions align with participants' strategies.
- Sound reasoning (3): Scores are assigned based on the logical coherence and reasoning communicated by the participant.
- Compatibility with known (5): Scores are assigned based on compliance with apparent information like previous pieces, their placement, and the remaining number of pieces & surface area. For piece choice, the size and shape compatibility is taken into consideration. For piece placement, alignment is assessed.
- Adaptability to unknown (5): Scores are assigned based on the decisions' strategic flexibility or adaptability to uncertain factors like upcoming piece size and shape. For piece choice, size and shape ability to account for uncertainties is taken into consideration. For piece placement, the positioning is assessed.

The weighting factor of 5 is assigned to criteria crucial for achieving full coverage. The other weights mark general criteria for good decision-making.

Additionally, for quantifying the quality of piece choices, probability analysis is introduced. Specifically, the Expected Value, that is the probability of a piece leading up to the ideal solution [13], was added to the criteria with a weighting factor of 1. This modest weight can be explained by the hypothetical nature of the calculations. The criterion is of interest but its accuracy should be reexamined when more data is gathered. Moreover, this probabilistic approach has not been applied to placement decisions due to its complexity and the scope constraints of this initial analysis.

After the decisions on piece placement and choice are individually assessed, the average is taken and scaled to conform to a grading scale ranging from 0 to 10.

4.3.b Weighted Outcome Criteria Matrix

When rating outcomes, the quality of the system and development process is rated. The outcome for each puzzle is examined based on the following criteria and weighting factors:

- System - Coverage (5): Scores are assigned based on the percentage of the total area covered.
- System - Efficiency (5): Scores are assigned based on the outcome's average surface area/piece versus the perfect systems' average surface area/piece.
- System - Simplicity (2): Scores are assigned based on the outcome's shape or circumference. As simplicity is desired, a high deviation from the perfect solution means a low score.
- Process - Completion time (3): Scores are assigned based on a time scale where quick completion is scored high. This evaluates the development process.

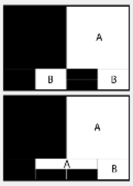
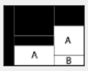
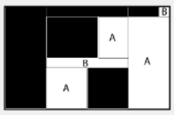
The weighting factors for coverage and efficiency are highest because these correspond to the goal of the assignment. The criteria with lower weighting factors are important, but the participants did not specifically design for it.

The resulting quantity for each outcome is scaled to conform to a grading scale of 0 to 10.

4.4 Trial

To assess the prototype, a workshop session with experienced Systems Engineers was held to explore two aspects. First of all, the tool's ability to compare decisions to the outcome is of interest. Like Figure 1, the results are plotted by scoring decisions and outcomes through the weighted criteria schemes in Section 4.3. Secondly, the tool's ability to compare decision-making strategies is investigated. To examine this aspect, each group received different decision-making guidance.
The experimental trial was performed with four participants, specifically experienced Systems Engineers. In pairs, they were asked to carry out three puzzles. Both pairs were given identical puzzle sets. The ideal solutions and corresponding data of the puzzle set are summarised in Table 2, where *c* is one cell in the grid.

Table 2: Ideal Outcomes of the Puzzle Set.

Puzzle	1	2	3
Ideal Solutions			
Surface Area [c^2]	96	48	160
Avg Area / Piece [c^2]	10.66	8	16
Circumference [c]	40	28	52
Total Decisions [n]	10	10	15
Chosen pieces	B A B, A A B	A B A	A B A A B
Placement Examples			
Quality of Outcome - 10 min	10	10	10

The Systems Engineers were asked to think about their decisions and write down their reasoning carefully. Additionally, their approach and reasoning were observed by surveillants. The participants were aware that their decisions, system, and development process would be analysed. However, they were not informed about specific analysis criteria, because it would influence their approach.
Furthermore, Group 0 did not receive any additional guidance besides the workshop manual of Figure 3. They were given freedom in their approach. In contrast, Group 1 received extra decision-making guidance. They were asked to keep in mind the DQ appraisal chain [4] as depicted in Figure 2 and received corresponding information throughout the game:

1. Appropriate Frame: A list of available pieces within each puzzle set is provided.
2. Creative Alternatives: Prompts are given.
3. Relevant & Reliable Information: Information on i.e. piece recurrence and upcoming pieces is provided.
4. Clear Values & Tradeoffs: Prompts are given.
5. Sound Reasoning: Prompts are given.
6. Commitment to Action: Prompts are given.

Due to the different guidance, it is expected that Group 1 will obtain higher quality decisions than Group 0, but better outcomes are not guaranteed [3].

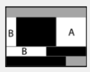
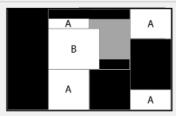
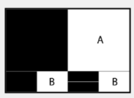
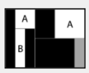
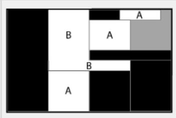
4.4.a Experimental Data

An overview of the acquired data is displayed in Tables 3 and 4. Table 3 provides the data and resulting grades, i.e. Quality of Decisions, obtained through the matrices in Section 4.3.a. Table 4 reviews the actual solutions. The grades, i.e. Quality of Outcome, are calculated by using the criteria in Section 4.3.b.

Table 3: Experimental Data of Decisions.

Puzzle	1	2	3
Group 0 - Zero guidance			
Adherence to Strategy	8.88	9	9.7
Sound Reasoning	8.81	7.83	8.2
Compatibility with Known	7.94	5.67	8.1
Adaptability with Unkown	8.88	9.17	8.45
Quality of Decisions	**8.41**	**7.6**	**8.34**
Group 1 - DQ guidance			
Adherence to Strategy	10	9.67	10
Sound Reasoning	9.69	8.27	9.55
Compatibility with Known	9.66	8.52	8.35
Adaptability with Unkown	9.26	9.09	9.5
Quality of Decisions	**9.39**	**8.68**	**9.04**

Table 4: Experimental Data of Outcomes.

Puzzle	1	2	3
Group 0 - Zero guidance			
Surface Area [c^2]	85	38	147
Avg Area / Piece [c^2]	9.44	6.33	14.7
Circumference [c]	55	26	68
Total Decisions [n]	13	9	15
Time [min]	31	26	27
Pieces	B B A A	B B A	A A B A A
Placement			
Quality of Outcome	**8.17**	**8.04**	**8.56**
Group 1 - DQ guidance			
Surface Area [c^2]	96	45	147
Avg Area / Piece [c^2]	10.66	6.42	14.7
Circumference [c]	40	28	58
Decisions [n]	10	10	15
Time [min]	87	40	43
Pieces	B A B	B A A	A B B A A
Placement			
Quality of Outcome	**8.42**	**8.85**	**8.52**

4.4.b Analysis

To analyse the trial results, the data from Tables 3 and 4 is used to plot Figure 4. Overall, it is apparent that both teams made good decisions that led to good outcomes. However, when zooming in, it becomes clear that Group 1 scored higher on the quality of their decisions as expected. Despite this, they achieved only slightly better outcomes, Puzzle 3 (P3) being the exception. Nevertheless, the differences are minimal.

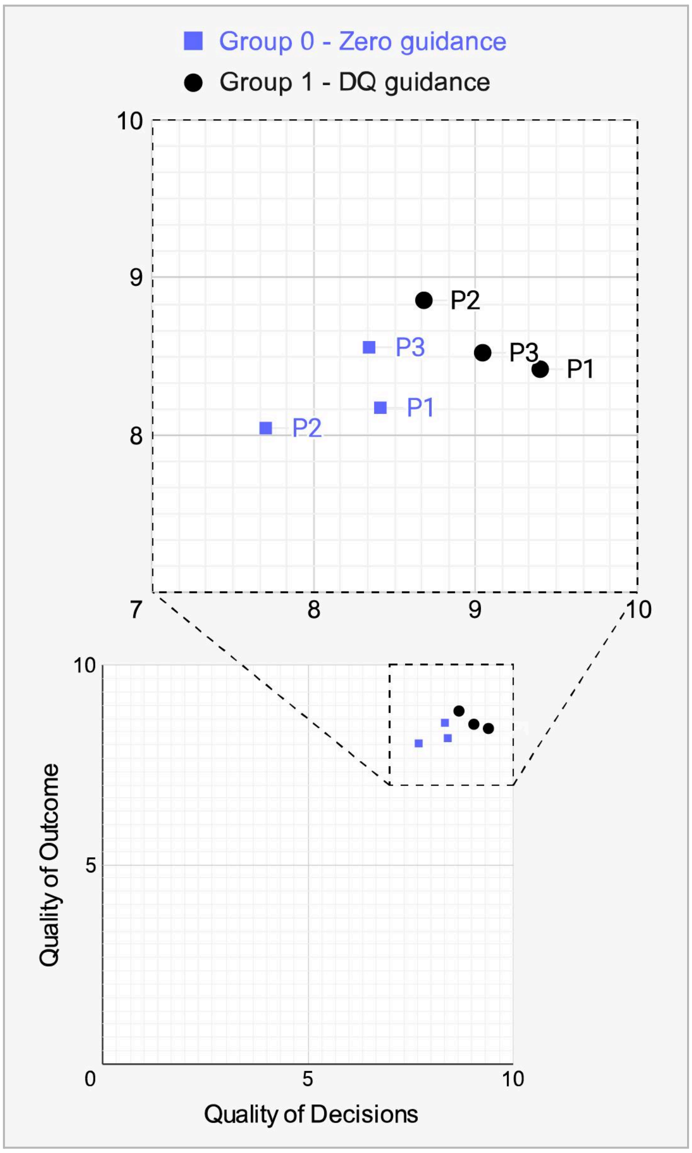


Fig. 4: Workshop Results - Quality of Decisions vs. Outcome.

The results can be explained by the distinct priorities of the participants. Group 1 prioritised perfect solutions. They started a relatively long-lasting study to achieve this, which caused high-quality decisions, but an inefficient process compared to Group 0. For Puzzle 1 (P1), they developed the ideal system, but it took them 87 minutes as seen in Table 4. Consequently, there is a decrease in the overall quality of the outcome of Group 1. Meanwhile, Group 0 scored lower on their decision quality and system quality, but higher on the development process. They used an intuitive approach while attempting to assess risks, which led to faster completion of the puzzles. Therefore, the two groups performed alike in the end.

The difference in approach and priorities could be assigned to the distinct decision-making guidance. Still, the quality outcomes and decisions correspond to what one might expect from experienced Systems Engineers. The results may also be a consequence of the individuals' general problem-solving- or Systems Architecting approach.

5 DISCUSSION

Several aspects of the results can be reflected upon.

First of all, the experiments' conditions should be reviewed. Within the experiment, the Systems Engineers were unaware of the analysis criteria described in Section 4.3. This enabled the review of their priorities: an efficient or a quality solution. However, informing the participants about all evaluation criteria, specifically on the outcomes, would have caused different and arguably more accurate results. To research such effects, experiments with varying available information should be conducted. The appropriate conditions might vary depending on the application or goals.

Secondly, the simulations' adherence to complex system development should be reviewed. The prototype and trial conditions might not sufficiently mimic the actual process. For example, risks might decrease towards the completion of actual system architectures and iterations can be made throughout [1]. This was not implemented in the trial puzzles. Also, the current design might be too simplistic for certain applications, fields, and strategies. However, the existing basic game mechanics and resources allow for necessary alterations and scaling.

Thirdly, the analyses of decisions, outcomes, and strategies should be reviewed. Processing the data was a somewhat tedious but manageable operation forming seemingly reasonable results. For future research, a digital version could refine the analysis process and ease data gathering. Still, the comparison of decisions and outcomes was attainable. However, other DA methods might be necessary to improve the analyses. Given the small-scale data set, validating and assessing the data and methods is unsubstantiated.

Lastly, the experimental results, as described in Section 4.4.a and 4.4.b, are analytically analysed. However, within the workshop trial, it became apparent that the tool is potentially valuable for empirical research as well.

Overall, it is essential to further test the tool. Its performance has not been fully validated because it requires more data. Once this is determined, the tool's adherence to system development, its analysis accuracy, and ease of use can be enhanced accordingly.

6 CONCLUSION

A workshop prototype of an evaluation tool for decision-making strategies was designed, created, and tested with Systems Engineers. It simulates the basic elements of Systems Architecting by utilising tiling match game mechanics. The first trial shows the tool is capable of comparing decisions with outcomes and is adaptable to different decision-making strategies. However, it is difficult to draw well-founded conclusions with the limited amount of acquired data. For an accurate assessment of the tool's performance, more experiments should be carried out. Afterwards, improvements can be made accordingly, ultimately leading to an efficient and precise examination of decision-making strategies in the high-tech industry.

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