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Complex Scenario Design for Investigating Cognitive Process in Problem-Solving Collaboration

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ABSTRACT

Complex problem solving (CPS) has been a field that uses computer-simulated scenarios and has been applied in problem-solving-related studies. However, the problem scenario has not been thoroughly discussed as an essential factor in determining the reliability of the studies. Consequently, there are no systematic principles for scenario design in CPS studies. This study was performed to establish fundamental standards for complexity analysis in the CPS scenario design. We created a high-fidelity problem scenario to investigate the cognitive processes in CPS discussions. The reliability of the system and scenario was validated by five industrial experts. The findings of this study can be applied to future experiment designs, meta-analysis methods, and study replications.

Keywords: Cognitive process, Complex problem-solving, Problem complexity analysis, Scenario design, Taxonomy, Dynamic problem-solving

INTRODUCTION

In complex problem-solving (CPS) studies, the problem scenario design may directly influence the quality of data collection. Computer-simulated scenarios have been used in problem-solving-related studies; however, the problem scenario has not been thoroughly discussed as an essential factor in determining the reliability of these studies. Consequently, there are no systematic principles for analyzing problem scenarios or the scenario design in CPS studies. In addition, when studies need to be cross-compared, there are often no adequate metrics to refer to. Hence, only general comparisons can be made using the number of variables (Funke, 1991) or structure of the task (Stadler *et al.*, 2015).

This study falls under a project that aims to propose a platform-versatile CPS discussion guideline. This paper documents the steps taken to design a complex experimental scenario. We proposed a set of standards that enable an in-depth analysis of the problem complexity. We further designed a complex, high-fidelity, computer-simulated scenario using the proposed standards and verified it with expert knowledge. The results presented in this paper

Table 1. Taxonomy for fundamental scenario complexity analysis.

Taxonomy	Dimensions	Basic factor	Complex factor
Time-related	Time-dependency	Event-driven	Clock-driven
	Decision making	Discrete	Continuous
	Feedback interval	Immediate	Delayed
System behavior	Information availability	Transparent	Opaque
	Randomness	Deterministic	Stochastic
	Variable's values	Discrete	Continuous
Individual-related	Interaction type	Reactive	Predictive
	Representation forming	Learning	Non-learning
	Problem-solving behavior	Search-based	Understanding-based
Scenario features	Knowledge requirements	Lean	Intensive
	Inter-links	Linear	Nonlinear
	Uniqueness	Well-defined	Ill-defined

contribute to future experimental designs, meta-analysis methods, and study replications.

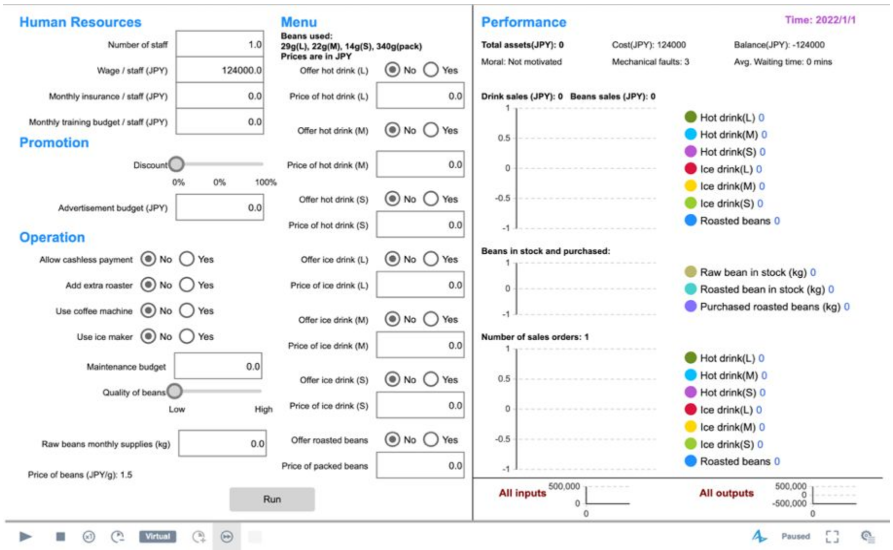
METHOD

Taxonomy for Fundamental Complexity Analysis

"Complex problem" as a general term covers various topics. Jonassen (2000) proposed a typology comprising 11 types of problems and, correspondingly, a set of high-level strategies to support problem-space construction. Although the researcher suggested criteria for problem categorization, it was still difficult to design a complex scenario with descriptive content. For instance, abstractness, which is also interpreted as domain specificity, has several values including problem-, context-, case-, issue-situated, etc. However, these values are not necessarily mutually exclusive, and do not have standard interpretations without further definitions. To define complex problems, previous studies have proposed lists for complexity analysis (Quesada, Kintsch and Gomez, 2005; Grösser, 2017). We revised the captioned lists into a taxonomy: time-related, system behavior, individual-related, and scenario features. Each characteristic can be identified through either complex or basic factors that can be used as Boolean parameters in a simulated scenario design (refer to Table 1. The definition of each dimension can be found in the two literatures). Thereafter, we created a quantitative interpretation of the fundamental scenario complexity, which is the number of complex factors to be considered. We emphasize the term "fundamental" because Boolean parameters are regarded as extremes, whereas in the real world, representations could be intermediate between these parameters (Miller, 1988).

Scenario Design

Based on a widely used scenario, the Tailor shop (Danner *et al.*, 2011; Süß and Kretzschmar, 2018), we designed a complex scenario based on the aforementioned taxonomy. The scenario simulates coffee booth operations, where



Human Resources

Number of staff: 1.0
Wage / staff (JPY): 124000.0
Monthly insurance / staff (JPY): 0.0
Monthly training budget / staff (JPY): 0.0

Promotion

Discount: 0% (0% – 100%)
Advertisement budget (JPY): 0.0

Operation

Allow cashless payment: ● No ○ Yes
Add extra roaster: ● No ○ Yes
Use coffee machine: ● No ○ Yes
Use ice maker: ● No ○ Yes
Maintenance budget: 0.0
Quality of beans: Low (Low – High)
Raw beans monthly supplies (kg): 0.0
Price of beans (JPY/g): 1.5

Menu

Beans used:
29g(L), 22g(M), 14g(S), 340g(pack)
Prices are in JPY

Offer hot drink (L): ● No ○ Yes
Price of hot drink (L): 0.0
Offer hot drink (M): ● No ○ Yes
Price of hot drink (M): 0.0
Offer hot drink (S): ● No ○ Yes
Price of hot drink (S): 0.0
Offer ice drink (L): ● No ○ Yes
Price of ice drink (L): 0.0
Offer ice drink (M): ● No ○ Yes
Price of ice drink (M): 0.0
Offer ice drink (S): ● No ○ Yes
Price of ice drink (S): 0.0
Offer roasted beans: ● No ○ Yes
Price of packed beans: 0.0

Performance

Time: 2022/1/1

Total assets(JPY): 0
Cost(JPY): 124000
Balance(JPY): -124000
Moral: Not motivated
Mechanical faults: 3
Avg. Waiting time: 0 mins

Drink sales (JPY): 0 Beans sales (JPY): 0
Beans in stock and purchased:
Number of sales orders: 1

Figure 1: Simulation interface.

problem-solvers make operational strategies each month, in a course of one simulated year with the goal of maximizing the monthly balance.

The scenario adopted in this study has a fundamental complexity of six factors, including opaqueness, predictive interaction, search-based problem-solving behavior, continuous variables, non-linear inter-links, and knowledge intensity. Its system has 27 intervention variables, 25 non-modifiable variables, 19 hidden variables, and 122 interlinks. To reduce the variability due to knowledge intensity, an video was created to inform general participants about basic café operational knowledge, before they operate the system.

The reliability of the scenario was validated by expert participants with more than five years of experience in café operational management. The evaluation was conducted in two steps: first, the participants were asked to complete the entire simulation in a 60-minute one-on-one online interview; thereafter, they were required to answer a questionnaire regarding their problem-solving process. The questionnaire evaluates three aspects using a five-point Likert scale: participants' problem-solving ability, scenario fidelity, and system usability (refer to Table 2). "Problem-solving ability" measures the ability to understand a problem, devise a plan, execute the plan and review (Polya, 1945). "Scenario fidelity" evaluates whether the simulated situation is intuitive enough for the experts to apply their theoretical knowledge and practical experience rationally (Chen, Kanno and Furuta, 2021). Finally, "System usability" evaluates the ease of use of the simulation UI (Barnum, 2021). The scenario is considered reliable if the average score of each category exceeds three.

RESULTS

Five industrial experts evaluated the simulated scenarios. The problem-solving performance of the simulated system is illustrated in Figure 1 The

Table 2. Question for problem-solving process evaluation.

1. Problem-solving ability	2. Scenario fidelity	3. System usability
a. I understood the meaning of all given elements in the simulation scenario. b. I became aware of some not-given elements in the simulation scenario. c. I could explain the reasons regarding the changes in performance. d. I established my goal in the simulation scenario. e. I determined the appropriate actions to take to achieve my goal in the simulation scenario. f. I executed these actions that I determined to achieve my goal in the simulation scenario. g. I kept checking the effectiveness of my actions. h. I revised my planned actions by reviewing the overall effectiveness of my approach.	a. I could provide specific rationales for my actions during the simulation scenario. b. The simulation scenario allowed me to apply my knowledge reasonably. c. The simulation scenario allowed me to apply my practical experience reasonably. d. My actions were based on the knowledge and skills I acquired from my professional training. e. My actions were based on the experience I acquired from daily life experiences. f. The introduction video and texts reflected real-world scenarios reasonably g. The results of the simulation reflected real-world scenarios accurately.	a. I was able interact with the system without difficulties. b. I was able to understand the numbers in the system without difficulties. c. I was able to understand the graphs in the system without difficulties. d. I was able to interact with the system without stress.

monthly balance ranged from $-1.12E + 06$ to $7.29E + 05$. Two out the five participants had negative average balance (Participant A and E), and the other three managed to obtain a positive balance (Participant B, C, D). Participants were able to achieve their first break even by the eighth month; only Participant C consistently recorded profit.

The results of the scenario evaluation are listed in Table 3. The problem-solving-ability scores exhibited a moderate positive correlation with the monthly balance (0.52). Moreover, among all sub-questions, 1c, 1h, and 2f had strong positive correlations with the monthly balance (0.71, 0.78, and 0.71, respectively); as a reliability indicator, the means of all three values exceeded three (4.40, 3.88, and 4.50, respectively). Similarly, the mean of all the sub-questions in each category also exceeded three. Questions 1c, 2c,

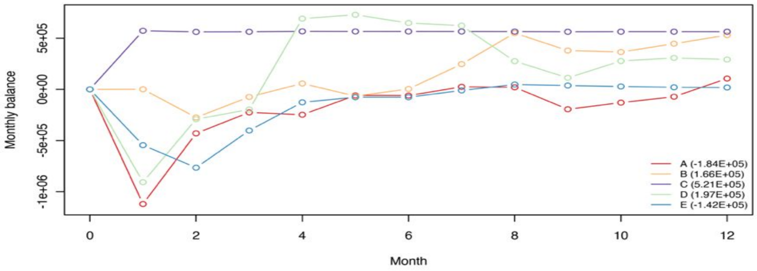


Figure 2: Problem-solving performance of expert participants.

Table 3. Problem-solving process evaluation.

Participants	A	B	C	D	E	Corr. with monthly balance
Problem-solving ability	3.88	4.25	4.50	5.00	4.38	0.52
Scenario fidelity	3.63	3.75	3.50	5.00	3.50	0.14
System usability	5.00	4.75	3.75	5.00	4.00	−0.40

2e, and 2f all yielded an average score of 3.6, the lowest among all sub-questions. In contrast, Questions 1d, 1f, and 1g yielded 4.8, the highest among all sub-questions. System usability had a significantly higher interquartile range (1.00) compared to those of problem-solving ability and scenario fidelity (0.25, 0.25).

DISCUSSION

Experts determined that the system was reliable overall. The positive correlation between the monthly balance and problem-solving ability indicated that the simulation result was a valid measure of the participants' reasoning ability. Meanwhile, the overall scenario fidelity exerted less influence on the monthly balance than the introductory video solely. These results demonstrate the practicability of designing a less biased knowledge-intense scenario for problem-solving investigations.

The weaknesses of the designed scenario can be obtained from the questions with the lowest scores (1c, 2c, 2e, and 2f). These questions indicated the impossibility of reflecting expert experience. This problem is also reflected in the problem-solving performance. When expert participants defined a scenario based on the situation of their own shops, rather than a logical analysis of the scenario, they were less likely to obtain a positive monthly balance (see A, D, and E at Month 1 in Figure 2). However, we expected such bias to be less likely when the task was assigned to general participants whose problem representation was based on the introductory video and experience as consumers. Moreover, solely relying on expert experience in the simulated scenario could negatively impact problem representation. For example, Participant C established a strategy from Month 1 based on personal experience. However, he was not motivated to improve his strategy because his business was already profitable. Consequently, he failed to discover some hidden elements, which led him to rate the scenario fidelity lower.

In future research, a troubleshooting task may be used instead of a performance-neutral beginning to motivate users to extend the problem representation. In addition, the influence of interdependency between months on performance should be investigated. Finally, we were unable to quantify the complex and basic factors using a standard scale; this should be attempted in future research to achieve more comprehensive scenario comparisons.

CONCLUSION

We proposed standards for CPS scenario design and documented the steps taken toward designing high-fidelity computer-simulated complex scenarios. Furthermore, we designed a taxonomy for fundamental complexity analysis and questionnaires for expert validation and result analysis. The scenario was a simulated coffee booth for which problem solvers crafted operational strategies each month over the course of one simulated year with the goal of maximizing the monthly balance. Experts determined that the system was reliable and accurately reflected their reasoning ability. The findings of this study can be used in future experiment designs, meta-analysis methods, and study replications.

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