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Student Perception of Construction Problems and their Process Design Strategies*

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The construction process is an ill-structured complex problem that needs to be designed based on multiple constraints. Typically, construction engineering students have difficulties understanding the complexity of the process and treat the problem similar to well-structured problems. This paper has utilized a systems thinking framework to enhance construction engineering students' design thinking. This protocol takes into account critical aspects that students can address in their solutions. The protocol consists of six consecutive levels; each level should be built on the previous levels. Forty-eight construction engineering students participated in this study over five sessions. Student teams designed two construction projects, one with and one without using the introduced framework. They also reviewed and provided feedback on their peers' designs. The results show that the framework reduced the time for most students to reach a higher level of thinking. In addition, students were more successful in connecting different aspects of the project process by using the framework. Thus, it is expected that using the framework helps the students better understand the relationship among materials, systems, structures, and processes, which is the second most important competency for construction management students. In summary, this systematic framework shows potentials to speed up the transformation from novice to expert designers for construction students.

Keywords: construction process; engineering design; design education; systems thinking; novice-experts

1. Introduction

Civil engineering projects typically involve two main decision-making considerations: product and process. The product, or final built outcome, is more often being designed by consultant companies (or individuals) while the contractors are in charge of the decisions regarding the construction process. Although product and process are interrelated, different agencies typically do their designs without adequate communication [1]. Many studies are available on product design, while few scholars have studied construction process design [2].

As a system, the construction process can be very complex to design because it should accommodate many different constraints such as availability of in-house technology, safety, and budget. The early stages of construction design are typically characterized as wicked problems [3–6]. No single algorithm can fully structure and resolve the wicked problems. Addressing wicked problems should be through a process of discussion, debate, and deliberation among the team members [7]. This study looks at construction projects as design problems and examines the effectiveness of a system-based framework, called State Transition Modes (STMs), in enhancing Construction Engineering Management (CEM) students' performance in process design while solving construction problems. In order to develop engineering design expertise, in this study, a system-based scaffolding framework has been introduced and tested.

1.1 Engineering Design

Accreditation Board for Engineering and Technology (ABET) [8] defines engineering design as "the process of devising a system, component, or process to meet desired needs and specifications within constraints." (p. 3). Dym, Agogino, Eris, Frey, and Leifer [9] define engineering design as "a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints." It took a while for "engineering design" to be recognized as a concept [10] and has its own journal in 1979, as previously both design and engineering were seen as one [11]. Although even now, it can be challenging to distinguish these two, design is established as a concept [12].

Design as a noun is defined as "a specification of an object, manifested by some agent, intended to accomplish goals, in a particular environment, using a set of primitive components, satisfying a set of requirements, subject to some constraints" [13]. Ralph and Wand [13] looked at the design process as a project. Similar to projects, design is a human activity within a complex temporal trajectory of a working system toward objectives. Work-

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ing systems are socio-technical systems, including social and machines using information, technology, and other resources to serve the customers' needs [14]. Like other wicked problems, engineering design problems have multiple solutions and varying solution strategies [15–17].

To better understand the design process, methodologies such as protocol analysis, interview, feedback analysis, and observation have been used. These methodologies are categorized differently in research method classification and document different aspects of the practice. Protocol analysis is one of the well-established empirical research tools in studying the design process [18,19]. A protocol is a piece of record of the time path of behaviors [20], which captures the content of the statements rather than the rationale of their occurrence [21]. Although observation and interview are qualitative, feedback and protocol analysis are mixed research methods. Mixed methods [22] are methods that have the potential to combine methodologies, especially qualitative and quantitative methodologies.

Design is a process of co-evolution of the problem and solution space [23]. In other words, designers refine their understanding of the design problem while trying to come up with solutions. Therefore, to the designer, the problem at the end of the design is different from what he started with [24]. Designers try to meet the evolving requirements during the co-evolution of the problem and solution spaces [25]. The solution requirements have different inter-related aspects, such as time, resources, spatial constraints, variation in conditions, and optimality. In this process, some designers may neglect some of these aspects. The main reason for this negligence is a lack of experience. Systems thinking's capabilities in incorporating multiple perspectives [26] can help the students, as novice designers, in that regard by increasing their understanding of the problems' underlying structure [27]. However, to be able to use the systems thinking capabilities, students need systems thinking skills. Stave and Hopper [28] proposed a range of systems thinking skills. Developing these skills help the designer reach a higher level of thinking necessary for attacking wicked problems. Using conceptual models is one of the systems thinking skills that Stave and Hopper [28] proposed. Helping the learners develop the conceptual model skill enables them to explain the systems and use the systems' concept more effectively. The models allow the designer to convey the meanings and share the outcomes more clearly [29]. Previous studies show that models can support the ability to communicate complex systems [30, 31] and increase the structure's clarity and context.

In this study, a system-based conceptual model is introduced and implemented in order to enhance the student's design performance. The performance here consists of understanding the underlying structures and concepts and conveying their solutions clearly. The effectiveness of this framework in improving the student process design was measured. For a meaningful measurement, a protocol was developed, and the results of the analysis were compared. The following section is dedicated to the introduction of the system-based conceptual framework.

1.2 The State Transition Modes (STMs) Framework

The framework used in this study is referred to as State Transition Modes (STMs) developed by Shafaat and Kenley [32] to model the project process. The primary purpose of developing this framework was to make automated project design possible in the presence of variations. Utilizing this framework, it is possible to develop algorithms to design a project. This algorithmic nature also acts as a scaffold for students; therefore, it can be used as a pedagogical framework. Scaffolding reduces the cognitive loads for both designers and assessors [33, 34] and enhances peer-assessment accuracy and reduces assessors' mental effort. Scaffolds offer support to learners to face task complexity gradually [33] and enhance learning [35] and help students learn from their peers' works [36].

In STMs, a project system breaks down a project into a combination of transitional sub-systems, called modes. Each sub-system (modes) includes activities that start from the beginning or any time before the transition is over. Each sub-system starts from a stable state, called the evaluation state (EVS), and ends up in another stable state. In the current study, stable states are introduced as snapshots of the project at a specific time when the project is stable enough (not changing too much) to be evaluated (e.g., end of the week). Therefore, evaluation states are not just for checking the physical progress; they also check the performance of the system interface and update the designed system interfaces for the following functional requirements (for more information regarding the STMs, look at [2, 32]). In the current study, evaluation states were introduced to the students as pictures they could take from the project at a specific time for evaluation.

An example of a stable state is at the end of the week when the weekly evaluation of the projects is being done. Fig. 1 shows part of the designed project timeline with three evaluation states and four sub-systems, AKA system modes. A simplified version of this method is introduced to the class

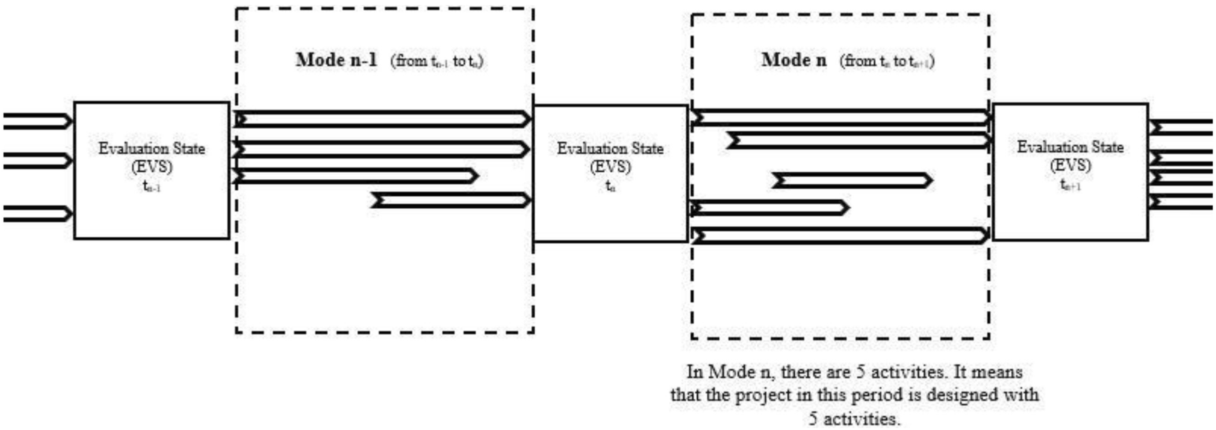

Fig. 1. STMs model Evaluation States (EVS).

based on its ability to help the students look at a project as a set of states rather than interrelated processes. A system designer is supposed to consider possible deviations (i.e., possible problems) from the designed system and try to fix them (back to the baseline) in the future steps.

The simplified concepts, including systems and subsystems, states, transitions, inputs, and outputs, were introduced to students. For example, the idea of sub-systems was introduced. In addition, it was described how a designed combination of activities can build a project sub-system. Later the discussion shifted back to the input-output idea that the presentation started with. Students were told to design what they wanted to have at each evaluation state. Then find out what is needed to be included in the sub-systems to reach the goals (outputs) and what inputs would make such a transition possible. These inputs include human, material, and machinery resources. Students agreed that designing the output and input makes it possible to understand the construction process better. The presentation and discussion ended with an example of a small activity due to the time limitation. A schematic representation of the example is shown in Fig. 2 in which:

- States are snapshot views of the project;
- Outputs are results of the activities that had been performed during the previous week; and
- Inputs are resources the project needs for the coming week.

To avoid making the students biased, keywords such as variations, optimization, high-level thinking, nonlinearity, and so on were dropped as much as possible from the presentation.

1.3 Research Questions

This study aims to investigate the construction engineering management (CEM) students' perspectives on construction problems and find solutions to enhance their design skills, expediting their journey to become experts. The following research questions were investigated in this paper:

1. Do students see construction problems as design problems? The answer to this question implies whether or not students, as novice designers, see the process of construction as a wicked problem.
2. Does the system-based framework (STMs) influence the quality of design communication?
3. How much can the system-based framework (STMs) improve the students' ability to see problems' underlying structure?

The findings are generalizable to students in other disciplines dealing with construction, such as civil engineering, construction management, and architecture engineering.

2. Methods

To answer the aforementioned questions, this study was designed and conducted accordingly. The study targeted construction engineering and management students as novice project designers. A design workshop was developed for CEM 280 class (professional development course). A mix of sophomore and junior students, as well as a few senior students in construction engineering and management, were enrolled in the course.

2.1 Protocol

To evaluate and compare the outcomes of the process design, a conceptual framework referred to as Dimensional Process Design (DPD) protocol was proposed and adjusted to fit the needs of this analysis (Table 1). This protocol took into account the critical aspects that students can address in their solutions. This protocol consisted of six consecutive

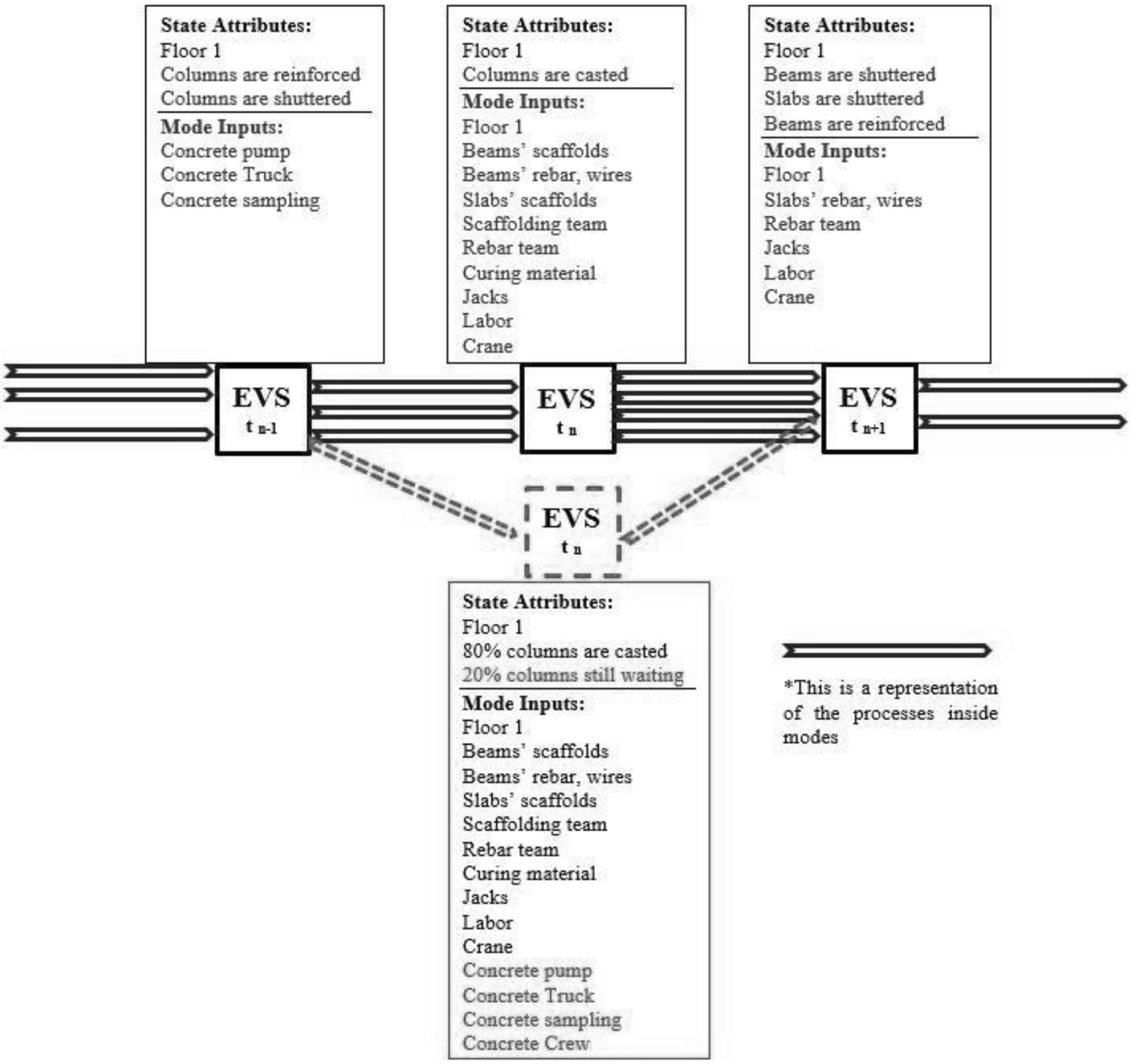

Fig. 2. Example of variation and corrective actions.

Table 1. Adjusted Dimensional Process Design (DPD) protocol

Level	Description
Zero-dimension (Dim-0)-Basic	Only focusing on the activities and materials
One-dimension (Dim-1)-Basic	Estimating the anticipated time for each activity
Two-dimensions (Dim-2)-Basic	Identifying the resources needed for delivering each activity on time
Three-dimensions (Dim-3)-Intermediate	Showing evidence that a student tried to optimize the system over time (nonlinearity) (4D thinking)
Four-dimensions (Dim-4)-Advanced	Spatially allocating the resources (splitting the crew into teams simultaneously working) (5D thinking)
Five-dimensions (Dim-5)-Advanced	Showing evidence that they tried to optimize the system and see potential problems in future

levels starting from the Dim-0 to Dim-5 based on the physical dimensions and time. Each level should be built on the previous level; for instance, Dim-2 should be discussed after Dim-1.

In Dim-0, students are struggling with defining the activities needed to finish the process. The activities here can be defined similarly to PMI definition of work packages: "The work defined at the lowest level of the work breakdown structure for which cost and duration can be estimated and managed." Students who are looking at the project at Dim-1 level could define some of the activities and some logical sequencing and have some estimations on the duration of the activities they defined. The timing can be achieved when enough resources have been allocated to the task. Students are thinking at Dim-2 level when they consider resources such as human resources or machinery (i.e., technology) to have the task done on time. They express crew sizes and the number of machinery for the specific activities. Here, all activities that have the requirements ready would be started; therefore, different crews are working simultaneously, and activities may overlap.

Dim-3 goes further by looking at the project as a whole and extending the design to other activities as well. In this dimension, designers do not look at activities as linear processes over time. In other words, the resources (crew size, for instance) are changing over time to suit the needs best. Dim-4 needs a higher level of understanding of the project process. In construction projects, some activities can be performed by more than one crew in parallel (called crashing), or crews could be split to perform the job faster. Process designers who reach the Dim-5 level of thinking can see the activities together which increases efficiency and reduces future problems. They shift activities to the time that works best for the project (not the earliest time the activity can be started) and consider some sort of resource leveling. Considering ideas such as agility, lean, and robustness can be seen as evidence of Dim-5 thinking. Dim-4 and Dim-5 need advanced knowledge and a high level of thinking. On the other hand, while Dim-0 to Dim-2 can be seen as basic systems thinking levels, Dim-3 is an intermediate level similar to Satve and Hopper spectrum [28].

The proposed protocol looks at the thinking level, not the level of subject matter knowledge. For example, students may not be able to list all the activities to move from Dim-0 to Dim-1 or above. As soon as they show evidence of considering timing in their deliveries, they jump to Dim-1. Similarly, it is not necessary to estimate all the activity duration precisely to be able to move to Dim-2. Talking about the number of crews and crew size is adequate. In summary, this protocol does not target the design soundness but the design thinking.

2.2 The Context and the Participants

This study was designed as a workshop for students registered in CEM 280, Construction Engineering Professional Development I, in Construction Engineering and Management (CEM) Division, in the College of Engineering, at Purdue University. CEM 280 is a required course for CEM students, and according to the Purdue University course catalog, this course is designed to prepare the students for professional practice in construction engineering and to provide information on careers and issues in construction, history, and culture of the U.S. construction industry, engineering ethics, and leadership. Also, students receive help with their plan of study and become more familiar with the division and the program. CEM 280 is typically offered in the spring semesters, followed by Construction Engineering Professional Development II in the fall semesters. The engineering students at Purdue University are required to pass two first-year engineering courses. Both of these courses have five weeks of engineering design education. Thus, students were exposed to the design process and were expected to be familiar with engineering design concepts.

The CEM 280 class had two sessions per week and met for one hour on Tuesdays and Thursdays. The current study was planned for five sessions. Forty-eight undergraduate students (31 males and 17 females) were enrolled in the course. Students were divided into teams of four for the design practices. The workshop had a number of individual assignments, which are explained in the next section. Forty students attended all sessions. Out of the 12 possible teams, 11 teams formed on time, and two teams had one (or two) members who missed a session. The class attendance rate was higher than average during the workshop. The students were notified that the workshop activities would be graded.

First, students were asked to answer two questions regarding their design and construction design perspectives. Then students were asked to design two similar real-world problems (projects) in teams of four. Before the second design practice, the class had a twenty minutes lecture on the STMs framework. Having a short lecture before the design helped students to practice the material more effectively. Student teams had thirty minutes in the first session and fifty minutes in the second session for the first design. Students submitted their designs after each session on paper to the workshop instructor. They kept their first design and worked on it during the second session. Due to the workshop logistics, the students had only half the time they had for the first design problem for the second design, and then they submitted their designs similarly. In the following session, students peer-evaluated the design of another team. The peer evaluation was double-blind in order to reduce the pressure of criticizing the classmates' work. At the end of the workshop (session five), students were asked to individually compare the two design sessions both as designers and reviewers and report how likely it is to use the framework (STMs model) in the future. Fig. 3 shows the workshop program.

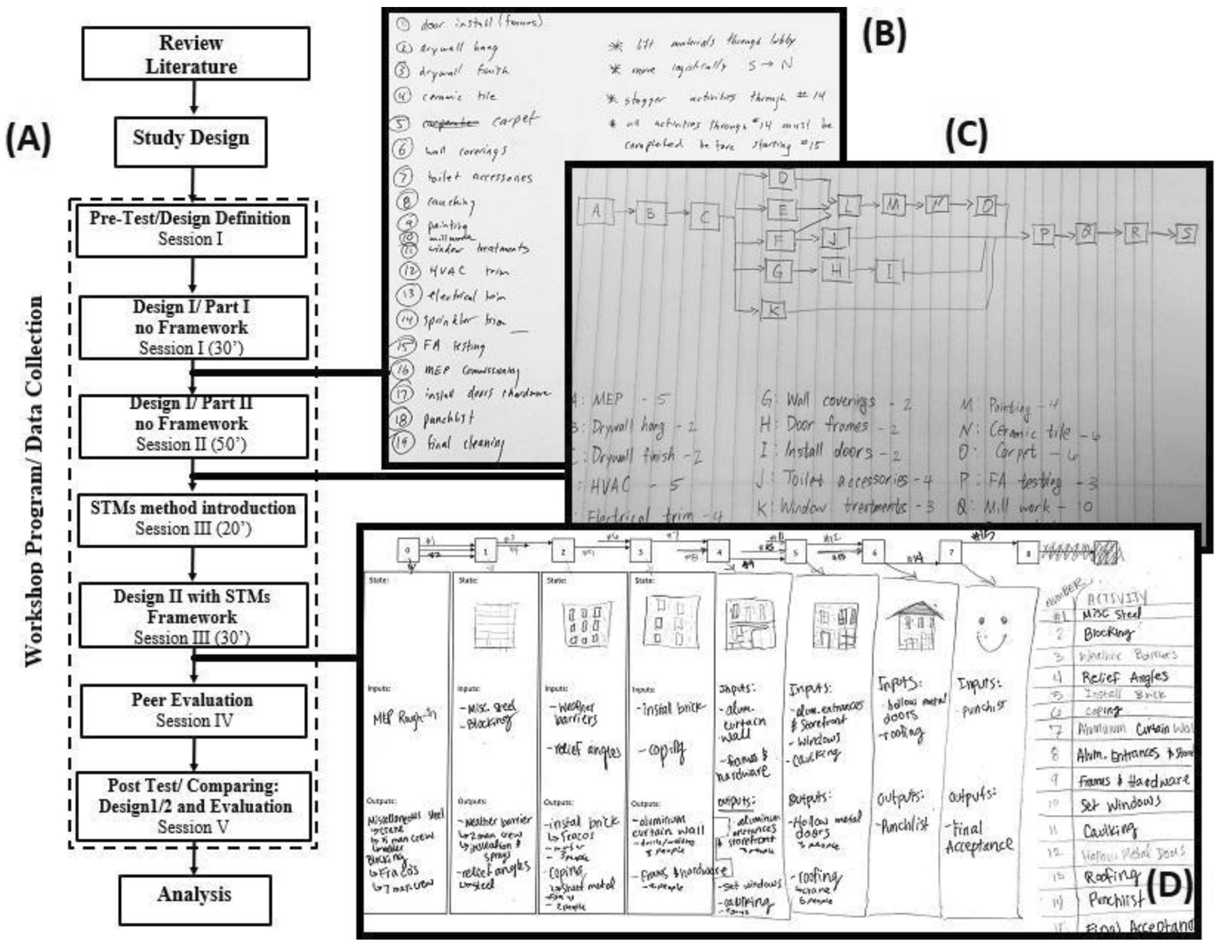

Fig. 3. Workshop program and output examples; (A) workshop program, (B) a sample of the first session design, (C) a sample of the second session design, (D) a sample of the third Session design of the second design problem using STMs framework.

2.3 Design Projects

The project that students worked on was a six-story hotel building. The building included 126 guest rooms, meeting facilities, food preparation, and recreation amenities. The building was a light gauge structural stud panelized building system. The floor-to-floor separation was achieved as a 1-hour fire-rated floor assembly utilizing gypsum cement floor topping over metal deck and gypsum sheathing at ceilings under the joists. The entire building structure was to be raised then the floor slabs poured from the 6th floor down to the 2nd floor for elevated decks. The problems students were challenged with were as follows:

2.3.1 The First Problem: Interior Construction

Develop a finish schedule sequence to complete the second-floor build-out assuming the Mechanical, Electrical, and Plumbing (MEP) rough-in is complete and drywall activities are ready to start. The last activity in this construction process is defined as final acceptance from the owner's representative. Typical schedule activities include the following: punch-list, caulking, painting, ceramic tile, carpet, toilet accessories, drywall hang, drywall finish, window treatments, HVAC trim and devices, electrical trim and devices, sprinkler trim, FA testing, MEP commissioning of systems, final cleaning, install door frames, install doors and hardware, wall coverings, and millwork.

2.3.2 The Second Problem: Façade Construction

Develop an exterior facade finish schedule sequence to complete the exterior of the building. Same as the previous process, the activity is final acceptance from the owner's representative. Typical schedule activities include the following: punch-list, set windows, install brick, weather barrier installation, relief angles, miscellaneous steel, roofing, copings, blocking, caulking, aluminum curtain wall, aluminum entrances and storefront, and hollow metal doors, frames, and hardware.

At the end of the workshop (fifth session), students were asked to compare the two design sessions based on their design experience and feedback from other teams. The authors graded the designs and evaluations.

3. Results

3.1 Pre-Test: What is Design from Students' Perspective?

As mentioned before, the workshop started with a pre-test. In the pre-test, students were asked about their perception of construction design. The goal of the pre-test was to answer the study's first question and see if they perceived the construction process as a wicked problem or believed that each construction process has one best way to be executed. Another interest was to explore if the students agree that a procedure can be designed or if the students cannot move from the product (built environment) to the process of construction. To investigate this, before the students were exposed to the workshop materials, they were asked to answer the following questions: (1) What do you mean by "design" as a verb? (2) What does construction design mean to you? Students had 10 minutes to answer these questions. Forty-two student responses were analyzed to understand the CEM students' perception of construction problems.

To analyze the pre-test data, the authors first divided the responses into three main categories. The first group consisted of 32 students who had evidence of design practices in their write-ups (e.g., problem-solving, planning, decision making). The second group consisted of six students who did not mention the construction process. These students only talked about the final built outcomes such as bridges, roads, and buildings as the design problem, and they did not see the construction process itself as a wicked problem that requires design. The third group consisted of four students who had difficulty answering the question; they could not write clearly what they meant, did not try to clarify their answers, or had problems recognizing design as an action.

Not all the 32 members of the first group were consistent in looking at construction design. To one of the students, the construction design was "*a story telling*"; another one defined design as "*creating your own puzzle*". A student saw it as the way that an idea becomes a reality; another one went more into detail and defined it as "*the process of creating a solution to a problem presented by an owner's criteria, specifications, etc. It involves creating a solution that optimize[s] time, cost, manpower, safety, usability and many other factors depending on what is needed of the owner*." To the majority of the participants, construction design is beyond the design of a product, to one specifically "*it is more of a strategy*."

Table 2. Top 5 verbs in students' responses and number of students who used them

Verb	Number of Students
Planning	11
Scheduling	9
Problem-solving	7
Optimizing	7
Integrating	7

Table 2 shows the most frequent verbs in students' responses. The most frequent action verb picked for explaining construction design was planning. Eleven out of the 32 students explicitly included planning in their writings. Scheduling ranked second among the verbs included by the students. Problem-solving and optimization (increase efficiency) were repeated seven times each as the phenomena students considered when they defined design. Although seven students talked explicitly about being as efficient as possible, this does not mean that the rest of the class disagreed. However, it suggests that the students need to be informed about the importance of efficiency in the process design. Integration of different aspects was also pointed out by seven of the students. In other words, seven students saw construction as a set of activities and design as the combining process.

While there are some very interesting definitions among students' responses, there were some missing points in the write-ups. Uncertainty, which is one of the reasons for project complexity [37], was not mentioned even once in the definitions. This means that although students view the construction process as a wicked problem that needs to be designed, they see it as a certain planning problem. This aspect needs to be addressed in the plan of study of similar courses.

3.2 Students' Designing Two Building Construction Problems

After students were asked on their definition of the design and construction process, they started working on the first problem in teams of four. They spent around 30 minutes during the first session on the problem and tried to develop some results, which could be evaluated and graded. Teams then had another class session (50 minutes) to work on their designs and finalize them.

3.2.1 The First Problem – Design without a Framework

As mentioned before, teams were asked to submit their designs at the end of sessions one, two, and three. Fig. 3 shows an example of the first session design. Similar to any other educational activity in class, not all students showed the same level of

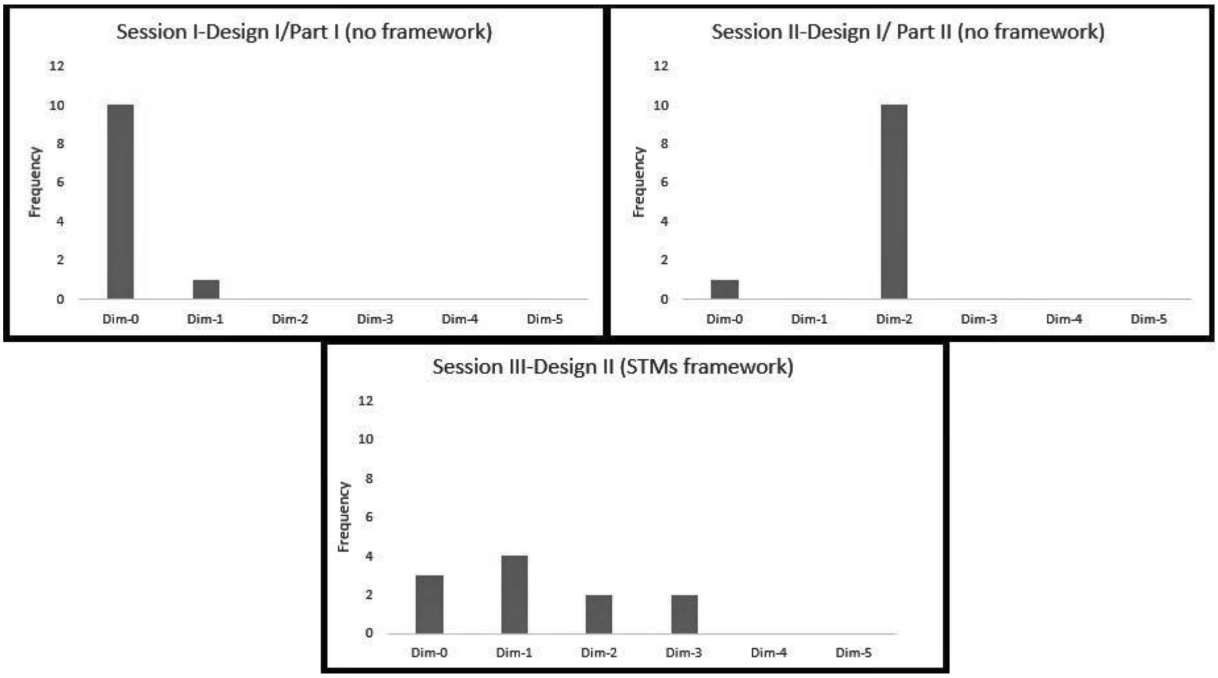

Fig. 4. DPD adjusted protocol results for all three design sessions.

interest. Although all the students had two summer internships, the teams did not have the same approach and outcomes. After the first session ended, 10 out of 11 submitted work just had a list of activities the teams tried to arrange logically. Fig. 3-B shows an example of the arranged activities. The students agreed that a list of activities could not be seen as a final and constructible outcome. The teams then tried to improve their outcomes and develop feasible results that the project could be constructed based on. Fig. 3-C shows one of the submissions at the end of the session. Some teams outperformed others who failed to come up with a plan and had problems in communication and decision-making. In the end, only four teams ended up with a detailed design, which had clear sequencing and trace of some resources such as crew.

3.2.2 The Second Problem – Design using STMs Framework

Fig. 3-D is a submitted work at the end of session 3 using the previously introduced STMs framework. As mentioned before, the second design happened after a 20-minute lecture on the STMs framework. Students received handouts to help them structure their designs; however, they were free to use them or not. All except one team used the handout. Students struggled with understanding the activities during the design mostly because their familiarity with façade construction was less than with interior finishing (the first problem). This unfamiliarity, as well as the framework requirements, brought up several questions during the design session.

3.2.3 Comparing Students' Designs using DPD Protocol

The three student design sessions were analyzed and compared using the introduced DPD protocol (Fig. 4). During the first design session, only one team reached Dim-1; all other teams were at Dim-0. At the end of the second design session and after 80 minutes of working on the problem, most teams reached Dim-2 level of thinking. In contrast, in the third session, in which students were working on the 2nd design problem utilizing the STMs framework, in only 30 minutes teams were distributed between Dim-0 to Dim-3. Considering that the students were less familiar with the façade construction process, they performed much better than in the first session. Lack of familiarity with the problem caused three teams to struggle with problem definition for more than 25 minutes and they stayed at Dim-0. Even for these teams, traces of timing can be seen but not enough to be classified as Dim-1 thinking. Based on the observations, all teams failed to assign crews to different locations simultaneously. However, some teams did look at crew size as a variable they could change. In other words, they changed the crew size in order to optimize the project process (Dim-3 level of thinking).

After 30 minutes, two teams could not list all the activities. However, compared to the design one in the first session, the number of details the teams considered was more. They provided some graphi-

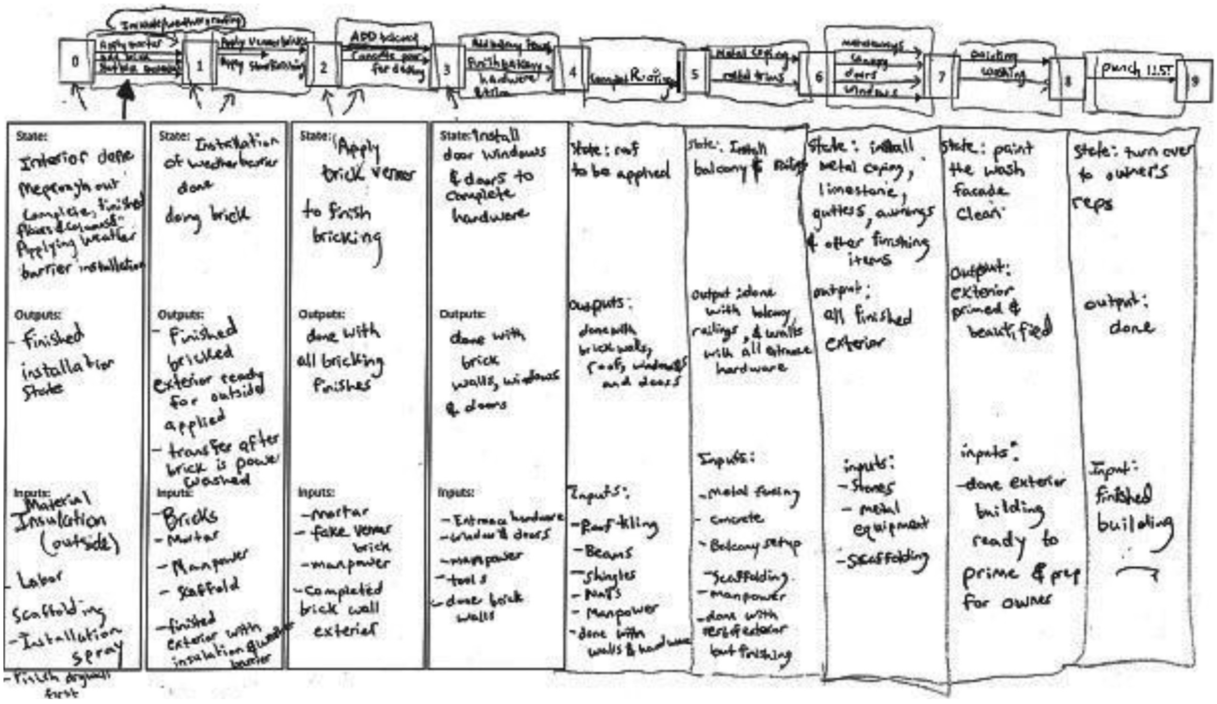

Fig. 5. An example of the second design activity during the third session by using the STMs framework.

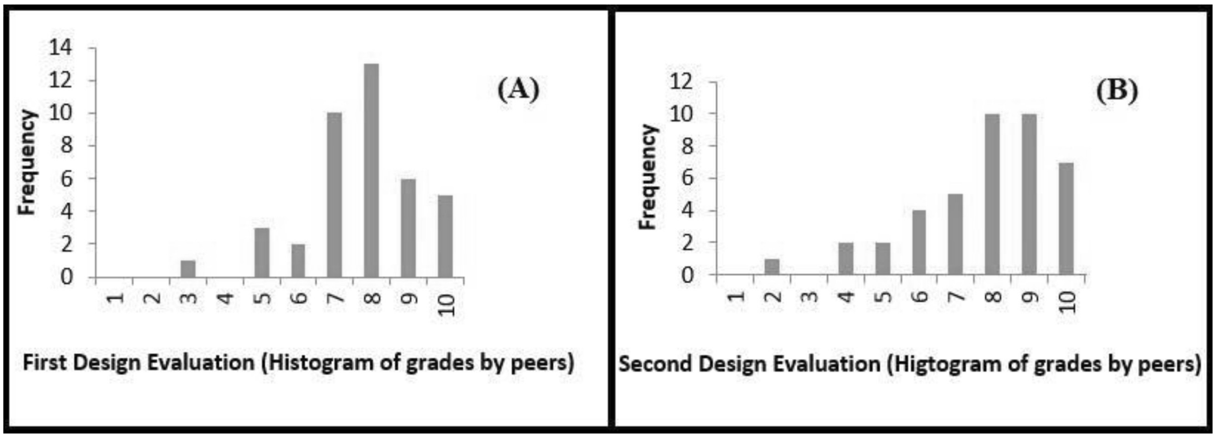

Fig. 6. Adaptation of the framework by the students. (A) peer-grades histogram for the first design; (B) peer-grades histogram for the second design.

cal representation for the design (Fig. 5). Two teams reached Dim-3 (4D outlook). One of the teams was able to provide more detail in the second design. They had input to the states, which were the resources needed for the next week, and had a clear sequence of activities.

3.3 Peer Evaluation and Post Test Survey

During session four, students individually peer-reviewed and graded (Fig. 6) another team design. STMs not only reduced the problem complexity due to its systematic nature, it also reduced the cognitive loads for both designers and assessors due to the scaffolding it provided [33, 34]. Students graded the first design higher compared to the workshop instructor, similar to what was pointed out in the literature for the face-to-face classes [38]. Second design grades had higher reliability and were closer to the instructor's grades. Literature supports the role of scaffolding in increasing the quality of peer assessment and grading [39–42].

The final data set collected from the class was the comparison document. In this document, the students were asked to compare their experiences in both design problems. One of the questions that the students answered was about the possibility of using the new method in the future. Fig. 7-A shows the histogram of the student responses. In summary, students preferred a structured design. The systematic nature of the STMs framework

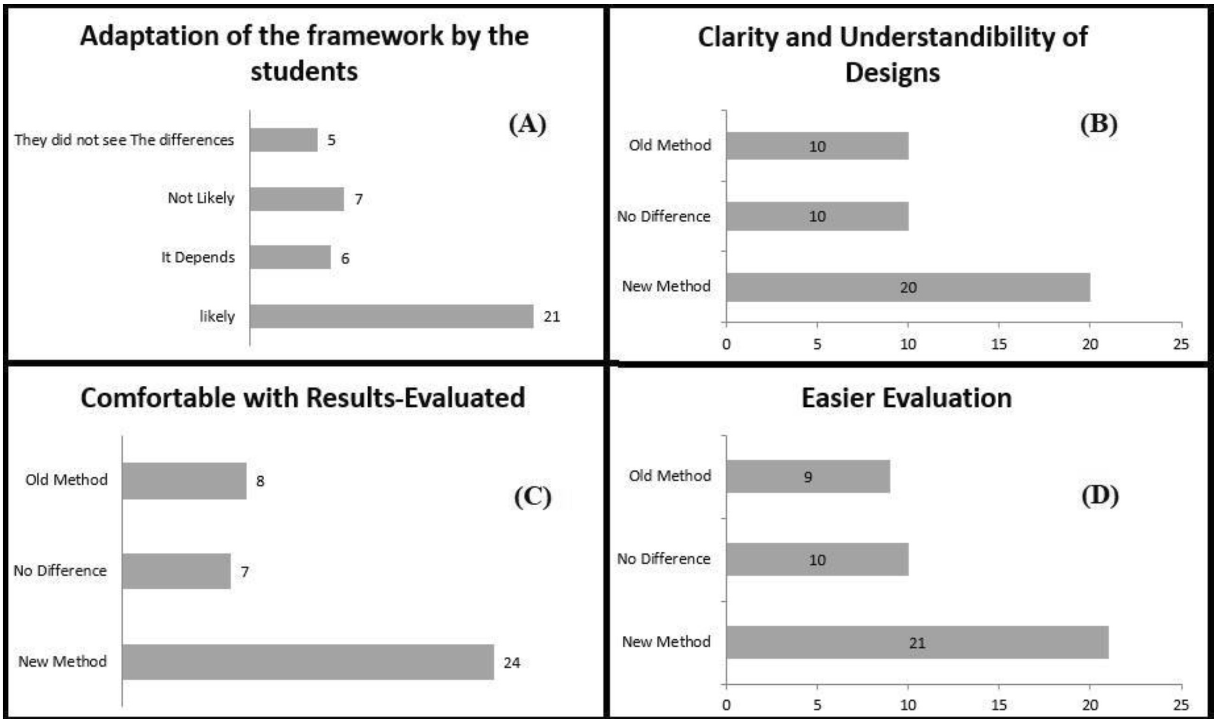

Fig. 7. Post-test survey results. (A) adaptation of the framework by the students in future designs; (B) clarity and understandability of the peer designs; (C) in which peer-evaluation the students were more comfortable with their evaluations; (D) which design was easier to evaluate.

persuaded some students to utilize some systems thinking terminology in their evaluations and post-test writings. More importantly, it also enhanced the quality of the design communication, which is particularly crucial in construction engineering. Students agreed that the other team's second design is clearer and more understandable than the first design (Fig. 7-B) and easier to evaluate (Fig. 7-D). In addition, the students were more comfortable with their evaluations (Fig. 7-C).

4. Discussion

As discussed in the introduction section, designing a construction process can be very complex as it should accommodate many different constraints. Students as novice designers struggle with understanding the underlying structure and effectively communicating the problems as well as the solutions. Increasing the students' skills that require a higher level of thinking would be helpful in facing such a complex problem. This paper utilizes a system-based framework, State Transition Modes (STMs), to enhance the construction engineering students' competency in design.

To do so, first, the student's perspective on construction design was investigated. It is clear that the majority of the students differentiate between construction as a complex process from what is being built. They use verbs such as integrating, planning, and problem-solving to describe the construction design actions. Therefore, they believe that they face a wicked problem during design practice and acknowledge the need for higher-level thinking to identify the system parts, classify them, and find solutions [28]. On the other hand, approximately 15% of the students had problems in this recognition. These students need support to recognize the need for higher-level thinking skills prior to being exposed to construction design problems.

As shown in section 1.3, a system-based framework was introduced to the class in order to scaffold the students' systems understanding during the design activity. To be able to evaluate the effectiveness of the introduced framework, a measurement tool was needed. Therefore, the DPD protocol was developed. This protocol is introduced in the methods section and consists of six consecutive levels, starting from the Dim-0 to Dim-5 based on the physical dimensions and time. There are other proposed codifications for systems thinking levels that are referred to by other scholars, such as Stave and Hopper [28] and Plate and Monroe [43], among others. Despite the fact that the Stave and Hopper spectrum came from the systems dynamics domain, the DPD protocol shows a good congruence with Stave and Hopper [28] classification. The level of thinking spectrum proposed by Stave and Hopper [28] starts with recognizing the interconnections

(Dim-0 to Dim-2), understanding dynamic behavior (Dim-3), using conceptual models, creating simulation models (Dim-4 and Dim-5), and testing policy. Based on the Stave and Hopper [28] thinking spectrum, the skill of using a conceptual model is higher than recognizing elements and interconnections and dynamic behavior skills. The result of this study also shows evidence that by using the STMs, as a system-based conceptual model, some students could reach higher-level thinking in less time. This shows that the DPD-protocol helps with measuring systems thinking in the process design and has convergent validity. The DPD protocol measures interconnectedness with more details, although it is not able to measure systems dynamics aspects, such as feedback loops and stock and flows.

Although the students' lack of construction knowledge increased the time needed for defining and framing the problems, by extending time and providing brief feedback, the majority of the class were able to reach a higher level of thinking based on the adjusted DPD protocol. The STMs framework helped the learners' capacity to connect more aspects of the process, which is what Scott [44] pointed out as an educational need in construction education. The presented framework (STMs) showed potential to speed up the transformation process from novice to expert designers [45]. It helped the students better understand the relationship among the materials, systems, structures, and processes in the procedure of construction, which is the second most important competency for construction management students [46] after the construction cost accounting competency.

Perhaps, one of the most supported outcomes of this study is the impact the framework had on the quality of communication in terms of design clarity to their peers. The majority of the class found it less difficult to evaluate the second design outcomes, and they were more comfortable with their evaluations. The grading pattern also supports the influence of the system-based scaffolding framework (STMs) on communication quality. After the framework implementation, students graded the peers' designs closer to the instructor's grades. This can have two aspects. Students' designs were easier to evaluate and the students used the scaffold constructively as a measure for their evaluations. These findings align with prior studies. Design communication has three layers: the design process, the interaction between participants, and the representation of design information. Systematic approaches, like STMs, can improve all these aspects [47, 48]. On the other hand, STMs helps to reduce the task complexity for the designers. For novice designers who are dealing with problems similar to the workshop problems, the complexity is relatively high, and communicating such complex problems is challenging. Studies show that the quality of peer assessments is lower for complex tasks [49]. This creates difficulties for the students to share the information effectively and reach a mutual understanding [50]. In the second design, the trace of systems thinking could help both designers and reviewers get engaged in mutual adjustments [51].

Finally, this study failed to lead the students into advanced level systems thinking. This can be because of the fact that students did not have enough knowledge to understand and recognize the activities; consequently, it is not very likely that they will be able to see the possible variations and changes during the execution. Expecting changes in the construction process along the road may cause students to think of coordination systems and monitoring systems as well as contingencies [52]. Heinbokel and Potash [53] blamed the lack of foundation and knowledge for the poor performance of students in systems thinking in their experiment. However, other factors such as the length of the students' exposure to the new method as well as the limited time they had for the second design might have exacerbated the problem. Future research may test the impact of allocating a longer time for introducing the new method and design on the results. This study only used sophomore students as the participants, so a future step of this research can be using the expert designers to test the framework's effectiveness and compare the novice and expert designers.

5. Conclusion

In this study, a system-based framework, State Transition Modes (STMs), and Dimensional Process Design (DPD) protocol were utilized to help novice designers in their process design. This protocol takes into account critical aspects that novices can address in their solutions. The framework consists of six consecutive levels; each level should be built on the previous levels. Both of these tools may help novice designers see the process design as a set of small design problems. Also, since the focus is on designing a set of snapshots (outputs) rather than procedures (processes), it is easier for them to connect with the problem.

This study shows that students, as novice designers, look at construction problems as design problems and see the construction process as a system. The majority of the students differentiate the construction process system from the product system (i.e., what is being built such as buildings, roads, etc.). Students most commonly defined construction design using the verb "planning". To other students, construction design was the process of creating an optimal solution to a problem shaped by the owner's needs and restrictions and planning for combining different systems to make it happen.

The results of this study highlight that the framework reduced the time for most students as novice designers to reach a higher level of thinking. In addition, students were more successful in connecting different aspects of the project process by using the framework. Thus, it is expected that using the framework helps the novice designer to understand better the relationship among materials, systems, structures, and processes.

The results also demonstrated that students believed the framework is useful and showed interest to use it in the future. The interest of more than half of the participants in using the framework in their future practices further confirms the benefits of the framework for novice designers. Finally, the results of this study suggest incorporating such experiences into the programs' curriculum, in which students have to learn procedure or process design, are beneficial for the students.

In summary, this framework shows the potential to speed up the transformation process from novice to expert designers for construction students. Construction programs can incorporate such a workshop into their programs as an educational tool that students can benefit from.

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