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Sensemaking of Block Flow Diagrams in Chemical Engineering

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INTRODUCTION

As engineering educators, we all want our students to make sense of the ideas they encounter in our courses. Sensemaking has been shown to help students build new knowledge and create connections within the knowledge they already have [1]. The process of sensemaking also helps students achieve coherence between a concept and a scenario in the real world [2]. Additionally, sensemaking can positively benefit students' problem-solving, leading to more efficient, insightful, and accurate solutions [3]. In the education literature, most prior research on sensemaking has focused on mathematical sensemaking [3], [4] or building connections between a concept in science and a scenario in the real world [5]. Very few studies have focused on sensemaking in engineering.

In science and engineering, visual diagrams are often used for presenting and engaging with complex scientific concepts. Experimental studies and case studies have reported positive effects of various types of scientific representations [6]. Multiple representations can complement each other because they differ either in the processes each supports or in the information each contains. For example, Tabachneck *et al.* examined the representations that learners created to solve algebra word problems and found that each representation was associated with a different strategy. The use of multiple representations and hence multiple strategies was about twice as effective as any strategy used alone [7]. Using one representation can also constrain the interpretation of a second representation. For example, textual representations are generally less specific than graphical representations. When these two representations are presented together, interpretation of the first (ambiguous) representation may be constrained by the second (specific) representation [8]. Thus, combinations of representations can support students' learning. However, students often struggle to use representations effectively [9]. For example, students have difficulty moving across and connecting representations. Students also tend to focus on the surface features instead of the underlying scientific principles.

In chemical engineering, students are introduced to block flow diagrams (BFDs), a new type of pictorial representation of a chemical process, early in the curriculum. For example, in the sophomore-level material and energy balances, often an initial exercise is to convert a word problem into a simple block flow diagram. The block flow diagram consists of a series of blocks representing different equipment or unit operations that are connected by input and output streams. Important information such as operating temperatures, pressures, and flow rates are included in the diagram. However, the diagram does not include any details of equipment within any of the blocks [10]. In the capstone design course in senior year, students will use block flow diagrams again to draw out the initial design of a chemical process before turning the block flow diagram into a process flow diagram (PFD) that contains much more detailed information (including all the major pieces of equipment and numbered streams). Thus, understanding how to read block flow diagrams is useful for understanding the overall operation of chemical plants and is an essential skill for chemical engineering students to develop.

However, because of the complexity of the information presented in the block flow diagram, it can be quite challenging to fully understand a block flow diagram for students learning about this representation for the first time [11]. Additionally, typical instruction in material and energy balances doesn't have a large focus on the design of the chemical process [11], [12]. Thus, even if students know how to read a BFD, they may not be able to make sense of it to identify possible design flaws or suggest improvements.

To address gaps in the literature on sensemaking in engineering, we chose to investigate student sensemaking with block flow diagrams. We selected block flow diagrams because they are a unique and important representation within engineering, which may be able to provide future information about how students make sense of other engineering representations (e.g., phase diagrams). Our research question is: how do chemical engineering students make sense of block flow diagrams (BFDs)?

THEORY

General features of sensemaking include being active, self-conscious, motivated, and purposeful in the world. There is an abundance of science education research literature that aims to define and characterize scientific sensemaking. When taken as a whole, the literature conceptualizes sensemaking in three different ways: 1) as a stance or frame towards science learning, 2) a cognitive process, and 3) a discourse practice [5], [13].

From a framing perspective, sensemaking is a way in which students approach science learning, which is characterized by trying to "figure something out" using one's prior knowledge. From a cognitive process perspective, sensemaking is a way in which students construct new knowledge by building connections to and within their prior knowledge. From a discourse perspective, sensemaking is a mode of argumentative dialogue in which students articulate and strengthen explanations. Instead of trying to win the argument, the goal of sensemaking is to strengthen claims and improve their explanatory power. Based on a thorough review of the literature, Odden and Russ gave a definition of sensemaking that incorporates the three different ways of viewing sensemaking. This is also the definition of sensemaking we will use in our work. "Sensemaking is a dynamic process of building and revising an explanation in order to figure something out – to ascertain the mechanism underlying a phenomenon in order to resolve a gap or inconsistency in one's understanding [13]."

METHODS

We adapted a chemical engineering problem-solving assessment our group developed previously [14], [15] to probe student sensemaking. The technical context we chose is the synthesis of tetrachloroethylene, which was widely used as a dry-cleaning fluid and degreasing solvent.

Tetrachloroethylene, $CCl_2{=}CCl_2$, can be synthesized from carbon tetrachloride, CCl_4, by the following consecutive pyrolysis reactions at 800 ºC.

$$2CCl_4 \rightarrow CCl_3{-}CCl_3 + Cl_2$$

$$CCl_3{-}CCl_3 \leftrightarrow CCl_2{=}CCl_2 + Cl_2$$

We situate the participant of the assessment as an engineer responsible for designing a process based on the above chemical reactions and relevant physical properties (melting point, boiling point, solubility in water, and density of the chemicals involved in the reactions). The engineer is tasked to evaluate a block flow diagram of the process drawn by their intern. The block flow diagram is shown in Figure 1 below.

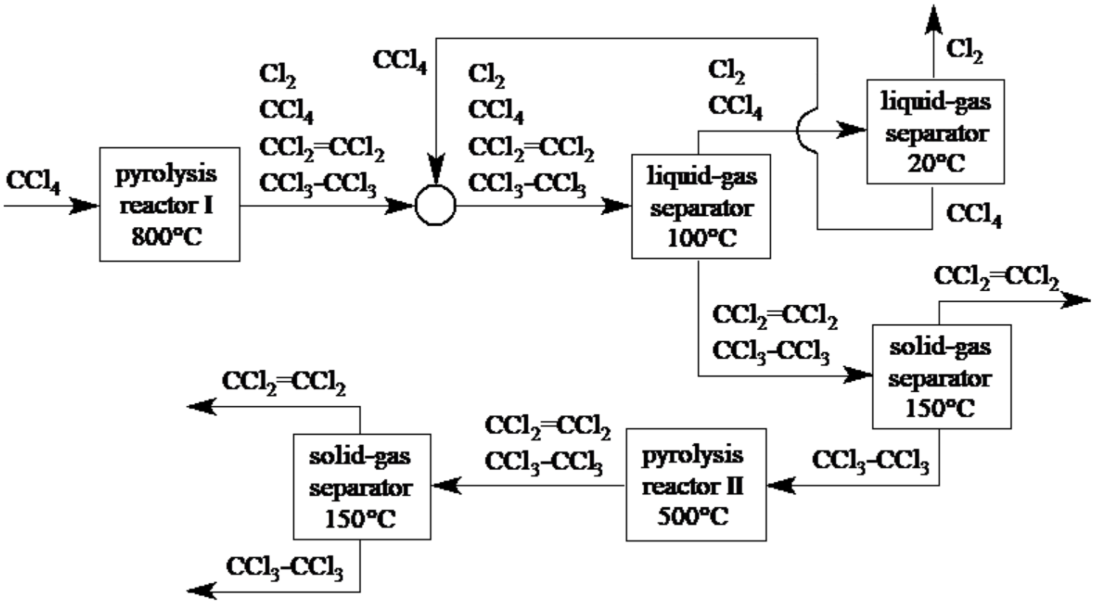

Figure 1: First block flow diagram in the assessment.

In the assessment, we ask the participant what the first thing they notice about the BFD is, what additional information they would request to evaluate the process, and finally ask them to suggest changes or improvements to the BFD. The initial BFD has some errors and inefficiencies, so we then present the participant with a corrected BFD and ask what main differences they notice, what additional information they would request, and if they believe the revised BFD is fully optimized. Finally, we provide the third BFD, which is further optimized compared to the second BFD, and ask the participant what has changed in the diagram and if they agree with the changes their colleague made. The questions were designed to allow many possible lines of reasoning without any obvious right or wrong answer.

After developing the assessment, we recruited 7 students (3 sophomores, 2 juniors, 1 senior, and 1 PhD candidate) to participate in our study. All of the students are in the chemical engineering department at a large public research university in the southeastern US. The sophomores were taking a material and energy balances class in which BFDs were taught at the time of participating in our study. The other students had already taken the material and energy balances class. Each participant was asked to participate in a one-hour think-aloud interview [16] with the second author. The participants were given a link to the Qualtrics survey for the assessment and were asked to complete the assessment and talk about their thought process during the interview. The responses in Qualtrics, interview audio files, and interview video files were used during the data analysis.

ANALYSIS

We transcribed the interviews using the audio files and broke the transcript into 15-second blocks. The first two authors chose one interview transcript to code independently using an open-coding approach [17]. Once the researchers had independent codes, they increased the reliability of the coding by comparing and resolving differences until a consensus was reached and a single set of consistent codes was accepted. The second author then used the same coding approach to code the rest of the interview transcripts. After the transcripts were coded, we added color coding for common behaviors that emerged (e.g., reading questions, requesting relevant information, actions to make diagrams easier to interpret) and used the codes and color coding to identify four general stages of the sensemaking process. While reading short sections of the interview transcripts, the stages appear to be linearly connected. However, when reading the interview transcript of each student as a whole, we realized that a cyclic structure is more suitable for describing the sensemaking process, as we will discuss below.

RESULTS

Our analysis revealed a four-stage cyclic structure that students followed when carrying out the sensemaking of all three diagrams. Because our research is phenomenographic, the specific actions and behaviors we observed within each stage varied widely from student to student, but the structure we provide aims to highlight how students made sense of the block flow diagrams and reached their conclusions. Figure 2 provides a summary of the sensemaking cycle.

I. Forming a Surface-level Understanding of the Diagram

Most students began their analysis of each diagram by creating a basic understanding of the block flow diagram and the process that the diagram aimed to display. This would serve as a foundation or a framework upon which they would build by forming connections between the diagram, given information, and outside knowledge. Some of the many actions which characterize this stage are tracing streams, identifying chemical species that enter and exit, noting process units and temperatures, and studying the chemical reactions. For example, some students began their analysis by examining the given chemical reactions:

> “So, it (reactions 1 and 2) says that CCl_4, which looks like the carbon tetrachloride converts to CCl_3–CCl_3 plus chlorine. And then CCl_3 as a further reaction into CCl_2=CCl_2”

This was usually followed by a transition into tracing through the diagram and determining input and output streams:

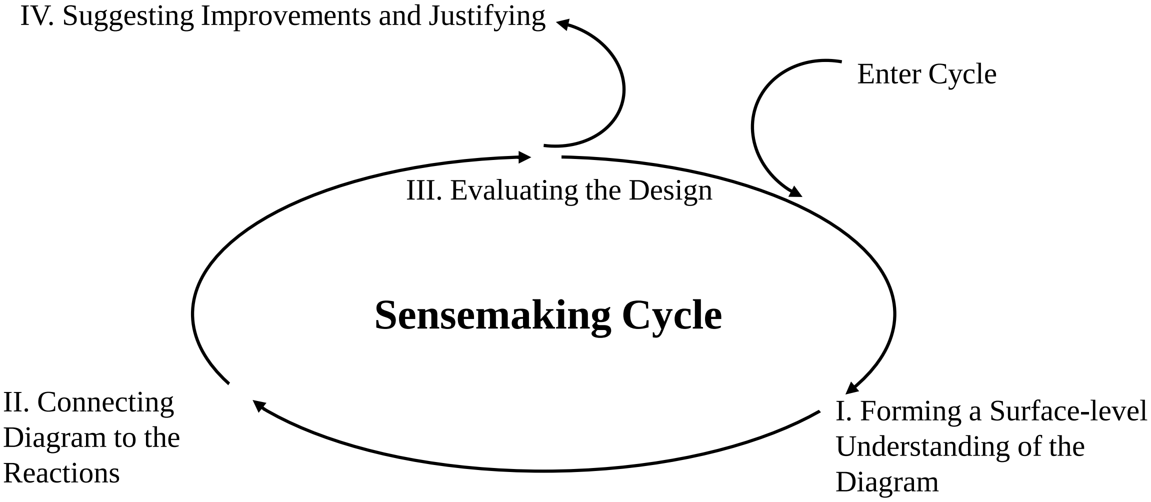

Figure 2: A diagram displaying the relation between and progression through each stage.

> “Right here we’ve got CCl_4 and then we have Cl_2 coming out and then excess CCl_4. We have some of this (CCl_3-CCl_3) here (products of reactor I), and then that gets this (CCl_2=CCl_2).”

Students also made note of the basic layout of the process units as well as the temperatures at each as in this example:

> “So, there is a sequence of separators and pyrolysis reactors … also as we progress downstream, we can see the temperatures decrease. So, the first pyrolysis reactor is operated at 800 ℃, and the second reactor is operated at 500 ℃, while the liquid gas separator… initially it is 100 ℃ and then it’s increasing to 150 ℃.”

These prior examples were all taken from students’ analysis of the first diagram. This stage was present in student engagement with all three diagrams but most heavily in diagram one since students are still forming a framework with which to interpret the diagram. In the following diagrams in which changes were incorporated, students built upon this framework. When presented with the second and third diagrams, students still initially engaged in a surface-level understanding of the process:

> “I’m noticing the CCl_4 that they’re moving back into the feed, they’re not moving into the second stream out of pyrolysis reactor one.”

It is important to note that this stage does not involve further analysis of the changes such as their implications rather only the identification of the structural change of the diagram.

II. Connecting Diagram to the Reactions

This next stage of sensemaking involved unit-specific analysis. After the first stage, students understood the flow of chemicals through the diagram and their next step was determining what was occurring at each step of the process. This involved the creation of connections between their stage one understanding of the diagrams and the given reaction information. How the connections were made varies among the students. Again, here most of the time spent in stage two was during students' analysis of diagram one. But stage two was also present in the analysis of all three diagrams. One of the more common ways in which students made connections to the reactions was by realizing that both reactions occurred in both pyrolysis reactors.

> "Okay, carbon tetrachloride first [tracing the stream into pyrolysis reactor one], yeah the first reaction, and some of the second."

This designation of which reaction occurred within each reactor was demonstrated by most students and illustrates a higher level of sensemaking. Students exhibited the ability to take the input and out species labels for each reactor and connect them to the given reactions to determine the reactions which were taking place. Similarly, students also used the stated separator temperatures in tandem with the given chemical data table to determine the states of the separated species. Although this aspect was not the target of any follow-up question, it nevertheless indicated the same ability and level of sensemaking as connecting reactions and thermodynamic information to unit operations.

Additionally, students made note of the role of each species–which species were reactants, intermediates, and products–and grouped the species together accordingly. This behavior was observed to aid students in their determination of improvements when done correctly, but when species were classified or grouped incorrectly the opposite effect was observed. An example of a student correctly classifying a species can be seen in this quote:

> "There is also one intermediate compound produced, which has a carbon-carbon single bond, and three chlorine atoms covalently bonded to the carbon, and also the byproduct produced is chlorine."

As described earlier, detecting a change on the surface level, e.g., "this stream was moved from here to here," is a stage one behavior. A stage two behavior that builds upon this stage one behavior was stating what this change does in the scope of the process and connecting that back to the reaction information. For example, in diagram two a student stated:

> "So, it's (CCl_4 recycle stream) going to the initial feed stream from where they have separated the carbon tetrachloride and they are recycling it here as well so that there is more CCl_4 that can be used."

The student forming an understanding that the relocation of the recycle stream sends the recycled reactant is an example of a possible stage two behavior.

This stage of our sensemaking cycle seems to be the most beneficial when done thoroughly and correctly but also the most detrimental when done incorrectly and incompletely. The connections between the given diagram and the reaction information are what the students use to evaluate the design in the next stage. Students who engaged more time in the breakdown of the process into its individual units and how they relate to the reaction information had a greater understanding of the interplay between process units and the role of each species and were able to suggest more improvements and notice more errors.

III. Evaluating the Design

In stage two, students made connections between the given information (e.g., the block flow diagram and the reactions). In the third stage, students had to make decisions based on outside information or outside knowledge and how it related to their understanding of the process which they developed in the prior two stages. This aspect of connecting to outside information or knowledge demonstrates a higher level of sensemaking than in the prior two stages. Unlike stages one and two, this stage was equally present during students' analysis of all three diagrams but proceeded much differently in each. The behaviors that characterize this stage are rationalizing changes between diagrams, requesting more information, and deciding if improvements can be made to the current diagram.

Students were prompted to request information to further analyze the given diagram. In order to do this, the students must already have a firm understanding of the diagram at hand and the relevant reaction information. Students who did not engage thoroughly in stage two when prompted to request information asked for irrelevant data that would not aid them in any aspect of evaluating the diagram. Some examples of these data are enthalpies of mixing, enthalpies of reaction, enthalpies of formation, operating pressure, and catalysts for the reactions. While this information is relevant to chemical engineering more broadly, it served no purpose here. Conversely, students who spent a large portion of time within stage two were able to determine data that would benefit them in assessing the design further. For example, in their analysis of diagram 2, a student states:

> "But I'm really worried about reactor two because this seems to be what really determines the efficiency of our entire process. Because this is determining what percentage is ending up leaving and waste and what percentage ends up leaving basically as, you know, our desired product. So, I would probably request a single pass efficiency of pyrolysis reactor II with the intermediate reactant fed outputting our desired products."

Here the student utilized their understanding formed in stage two that $CCl_2{=}CCl_2$ is the desired product and that $CCl_3{-}CCl_3$ is the intermediate. They realized first that the intermediate can be reacted further into the product, but also that under the current conditions the amount of intermediate wasted is determined by the efficiency of the second reactor, and requested that information accordingly. Their determination of reactor efficiency as relevant data is an example of a stage three behavior.

When prompted to decide whether or not they agreed with the changes made in diagram two, students similarly used their understanding of the changes from stage two and their outside knowledge of the effect of the recycle stream on process efficiency to decide whether to agree or not. Almost all students agreed, but for the ones that did not agree, it was due to a lack of knowledge and misinterpretation of the diagram. The action of agreeing or disagreeing and the corresponding reasoning is another example of a stage three behavior. Students used the same process in their determination of whether or not improvement was needed. If a student decided improvement was not needed, they proceeded to the next diagram and engaged in stage one of the cycle again.

IV. Suggesting Improvements and Justifying

Suggesting improvements and justifying is outside the cycle and is the highest level of sensemaking and understanding observed. To suggest an improvement requires the student to have a thorough understanding of a given diagram and how both the given reaction information and outside information connect to the diagrams and use this to correctly identify where the diagram could be improved. The student has to form a new idea based on their decision that there is room for improvement, which they made in stage three of the sensemaking cycle. This creation of a new idea and forming the reasoning behind it is the stage four behavior. An example of a student taking an aspect of the diagram through the entire sensemaking cycle can be seen in the following quotes from a student's analysis of diagram one:

Stage I

> "So, we have two streams of that ($CCl_2{=}CCl_2$) going out, and then as well as we have one $CCl_3{-}CCl_3$ and then chlorine going out as well."

The student was tracing flows and seeing how species, in particular $CCl_3{-}CCl_3$, are moving throughout the diagram.

Stage 2

> "That (CCl_4) is going into is some $CCl_2{=}CCl_2$ and some $CCl_3{-}CCl_3$ which is our intermediate reactant."

The student assigned hexachloroethane the role of intermediate reactant.

Stage III

> "And that bottom product– that bottom flow ($CCl_3{-}CCl_3$) is that's all waste."

Here the student combined their understanding of how the species flows through the diagram with their knowledge of the role of the species in the process and determined that the process is wasting the intermediate reactant.

Stage IV

> "Then I would say just recycling the CCl_3-CCl_3 to the pyrolysis reactor II and basically, that would just, I guess increase the efficiency of the system."

The student has completed the cycle by taking his understanding from stage three and creating something new, an improvement to the process. The student goes on to justify his reasoning with outside knowledge.

Following stage four, students would reenter the cycle upon moving to the following diagram. Additionally, during stage four students would revisit the other stages to bring information to the front of their minds. An important note is the first three stages occurred iteratively; students were observed to repeatedly move through the cycle when assessing different aspects of the design.

DISCUSSION

The ability to determine a viable correct answer and the exact process to get there was unique for each student, but the overall sensemaking cycle aimed to broadly describe the general process that was observed in each participant. We also compared the sensemaking cycle with stages of sensemaking identified in related studies. In particular, in the sensemaking epistemic game paper, Odden and Russ identified four stages for the sensemaking process for students working in pairs on an electric circuit, which involves 1) assembling a knowledge framework, 2) noticing an inconsistency or gap in knowledge, 3) generating an explanation to reconcile it, 4) and resolution [5]. Stages one and two form an iterative process, with students identifying new inconsistency in their new explanations. Although the context for sensemaking is different between this paper and our study (electric circuit and block flow diagram), similar stages are identified and both processes involve iterations.

In our study, all students except one failed to suggest an improvement when analyzing diagram one (Fig. 1), it was only after seeing the change made in diagram two that they were able to suggest an improvement of their own. This could point to the fact that block flow diagrams contain a large amount of information making it hard for students to dissect them initially. Students also did not suggest the same improvements at the same frequency. The most commonly suggested improvement to diagram two was the addition of a CCl_3–CCl_3 recycle stream similar to the example discussed above for stage IV. Interestingly, two students suggested different solutions, one suggesting the reactors react consecutively followed by separation and appropriate recycling, and the other suggesting the removal of reactor two and subsequent separators and recycling everything back into reactor one. Each of these students had unique approaches to the task, with the former focusing on trying to reduce the total number of separators, and the latter looking to combine separators. Both students had chemical engineering internship experience, and these results may be a product of their time in the field.

As mentioned in Stage IV in the results section, several students justified the changes in the diagram that they observed or justified the changes that they suggested. These justifications strike us as particularly strong instances of engineering sensemaking because the students sought coherence between at least three representations: one or two block flow diagrams, the chemical reactions, and conceptual knowledge about chemical engineering processes (e.g., benefits of using a recycle stream). In the work on student sensemaking about equipotential graphs, the authors also observed students justifying their claims [18].

Throughout the sensemaking process of the BFDs, students created a “story” that followed the flow of the diagram which they would use in tandem with the diagram. For example, when the students first saw the BFD, they would trace the streams to explain to themselves the purpose of each unit. In chemical engineering education, most problems are word problems and students are taught to make diagrams to model the problems. For problems involving BFDs, the focus is shifted to diagrams and students tend to use verbal descriptions (i.e., a ”story”) to help them understand the diagram. Additionally, in stage two, students connected the BFDs to the given information about the chemical reactions. Both of these are evidence of students creating links between different types of scientific representations (written or verbal descriptions and diagrams). This is consistent with the cognitive process perspective of sensemaking: when making sense of a new science concept, students construct new knowledge by building connections to and within their prior knowledge and these connections may be facilitated when students create links between different types of scientific representations for that concept [5].

Although students were able to suggest some improvements to the diagrams after seeing the changes that were made in diagrams 2 and 3 compared to diagram 1, and were able to request some relevant information, most of them failed to identify any flaws in diagram 1 before they saw diagram 2. Also, none of the students were able to identify all the flaws in the diagrams or suggest all the needed improvements. We hypothesize that this is partially due to the lack of design experience in the material and energy balances course in which students learned BFDs and partially due to the large amount of information that's contained in the BFD. This calls for a need of effective instructional practices that can better support students' sensemaking of BFDs. For example, students should be given more opportunities to troubleshoot flawed BFDs and make design improvements. It would also be helpful for students to work in pairs and critique each others' solutions.

LIMITATIONS AND FUTURE WORK

Although the one-on-one think aloud interviews revealed general stages of the sensemaking cycle for BFDs, we were not able to capture the sensemaking process of students working in pairs on the assessment. As suggested by the discourse practice perspective of sensemaking, whether it is being done collaboratively or individually, sensemaking always involves the dialogue between construction and critique [5]. A single person may use different mental "voices" for construction and critique [19]. It will be useful to conduct interviews with students when they are working on the BFDs in pairs and check if the same sensemaking stages emerge. Additional future directions include developing instructional practices that support sensemaking of BFDs and using our sensemaking assessment in classrooms as a pre-test and post-test to evaluate the effectiveness of the instructional practices.

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