Characterizing Teamwork Dynamics and Computational Model-Based Reasoning in Biomedical Engineering Projects

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Abstract—:

Background: In STEM professions, teamwork is a fundamental aspect of the job. As a result, it becomes imperative for STEM graduates to possess a comprehensive set of professional skills such as communication, teamwork, leadership, and creative thinking to name a few. In this study, the focus is investigating teamwork dynamics within interdisciplinary Biomedical Engineering teams to understand and characterize the role the teamwork process plays in students' model-based reasoning activities.

Purpose: In this study, preliminary contributions are made to understanding how biomedical engineering students engage their computational model-based reasoning and team-based skills through effective collaboration and social interaction over a semester-long project in a graduate course. The research question guiding the study is: "How do biomedical engineering students engage their model-based reasoning, interdisciplinary learning, and teamwork dynamics skills when enacting computational modeling and simulation practices?"

Methods: The conceptual frameworks for this study are rooted in the cognitive-constructivist and social-constructivist theoretical perspectives. The research design adopts a mixed-method case study design approach where qualitative data is transformed and analyzed quantitatively to address the research question. The case study approach focused on the participants within a chosen team and involved a single case analysis across three modeling and simulation sessions.

Results: The qualitative findings reveal four team dynamics dependent variables and four independent modeling and simulation stages inherent in the 3-hour 180-minute-long teamwork interactions between three graduate students. The quantitative visualizations showed that the students engaged in knowledge-sharing and interdisciplinary learning events seventeen times in all three project meeting sessions.

Implications: The insights derived from this research can prove valuable in implementing effective team-based course intervention strategies that pertain to project-based modeling and simulation instruction. Students and practitioners are furnished with evidence-based outcomes endorsing the need to fully integrate comprehensive team-focused problem-solving methods in tackling complex STEM-based modeling and simulation challenges.

1. Introduction and Background

Computational modeling and simulation (CMS) involve the application of computational science principles to solve real-world problems using state-of-the-art computer tools, resulting in more accurate numerical approximations of experimental or empirical data[1], [2]. As a result, CMS has become a core engineering skill for engineering practitioners across various STEM disciplines bringing with it a heightened need for competencies such as computational thinking, model-based reasoning, computer programming, and professional skills like teamwork. CMS often requires expertise from different disciplines and teamwork enables the integration of this expertise during CMS practices where team members can take on specific aspects of the modeling process, from the data collection, coding, analysis, and model result visualization.

Although there are not many studies connecting students' computational modeling practices with teamwork dynamics, teamwork skills have been a recent focus of Engineering Education researchers and found to be most utilized by students when implemented in cooperative learning pedagogies [3]-[5]. Some of the teamwork skills observed in students include setting goals, assigning roles, implementing coordination processes, and developing interpersonal relationships[6]. Research on the advancements in teamwork behaviors and effectiveness is primarily conducted in corporate organizational settings, including sectors such as healthcare and sports [7]-[13]. However, there is already an increasing progressive recognition of the need for effective team-based learning experiences that support interdisciplinary learning and teamwork, especially for STEM-based pedagogies[3]-[5]. The study conducted by [5], examined students' teamwork skills in a cooperative and project-based learning environment where the researchers investigated the relationship between students' team collective orientation and academic performance in a semester-long information technology project. Their results align with previous studies that demonstrated the effectiveness of cooperative and project-based learning pedagogies in helping students develop teamwork skills such as setting goals, assigning roles, implementing coordination processes, and developing interpersonal relationships. Similarly, in [14] the researcher examined how activities in an introductory engineering course for first-year students influence the cultivation of teamwork skills. According to the survey results, 94% of the participants found team projects with other in-class collaborative activities to be the most beneficial in developing teamwork skills and a significant number of students attributed their team success to how effectively they distributed the tasks among team members.

Therefore, this study aims to contribute to the broader research on teamwork assessments by providing an understanding of team dynamics and interdisciplinary learning in the context of team-based computational modeling projects. The study explores how Biomedical Engineering graduate students utilize their model-based reasoning skills through effective collaboration and social interaction. The guiding research question of this study is: "How do biomedical engineering graduate students engage their model-based reasoning, interdisciplinary learning, and teamwork dynamics skills when enacting computational modeling and simulation practices?"It is anticipated that the findings from this study in the context of graduate-level modeling and simulation projects, will inform instructors about the need to provide students with the necessary curriculum and teaching adjustments to aid students in honing their professional teamwork skills, such as effective communication, interactive problem-solving, project management, leadership commitment, critical and creative thinking, and evidence-based decision-making skills, thereby adding to the depth of interdisciplinary approaches, experience, and expertise students would share with teammates during class projects.

2. Conceptual Framework

The conceptual framework of this study is rooted in the cognitive-constructivist and social-constructivist theoretical perspectives. The social-constructivist perspective directs attention to the impact of interaction, culture, and peer circles on student learning experiences[15], [16]. In contrast, cognitive-constructivist perspectives underscore the significance of learners linking prior knowledge with new information, employing a learner-centered approach [15]-[18]. The cognitive-constructivist and social-constructivist theoretical perspectives also help to shed light on the significance of the research question selected in the study. The Computational Model-Based Reasoning (CMBR) and Team Dynamics (TD) conceptual frameworks hinge on the cognitive-constructivist and social-constructivist theoretical perspectives respectively and provide broad lenses through which this study is grounded. The ideas and knowledge shared by team members in this study are computational model-based and therefore the combination of frameworks to capture the connections between team dynamics and modeling and simulation activities is required [19]. CMBR is a form of thinking necessary for making sense of physical phenomena or systems via the use or creation of external representations [20]-[22]. According to [3], TD is characterized as patterns of interactions, communication and coordination processes among team members involved in a semester-long software development project.

3. Methods

This study employs a mixed-method case study (MMCS) research design approach, where the data is analyzed with qualitative and quantitative techniques to uncover trends[23]. The MMCS approach is a methodology that combines both qualitative and quantitative research methods within a case study framework to gain a comprehensive understanding of a research problem [24], [25]. In qualitative research, a single case study typically focuses on understanding the internal dynamics or processes occurring within the selected case of event or instance [26]-[28]. The MMCS approach is useful for this study because it allows the researchers to explore the strengths of both approaches in analyzing the qualitative data and interpreting the findings qualitatively and quantitatively firstly for the individual learners and secondly for the learners as a team [25]. MMCS approach was implemented in this study using the four-step sequence as presented in Figure 1. The MMCS approach is implemented on a single dataset (Team 2) as part of an initial pilot study towards a much broader study involving up to twenty teams.

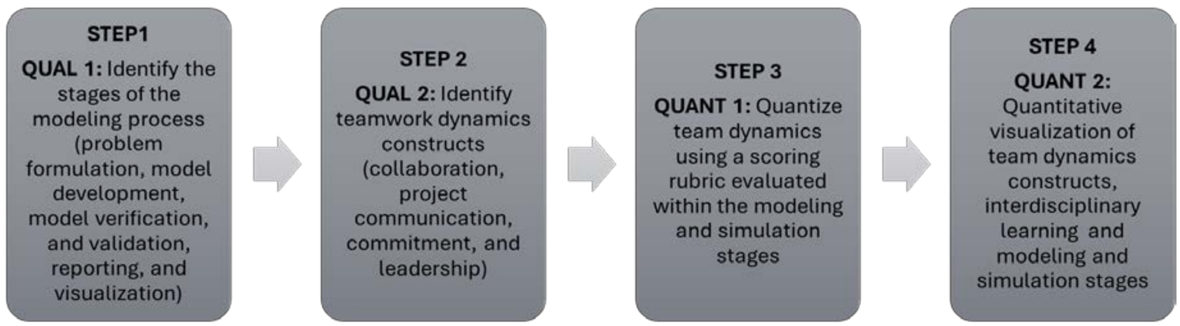

Figure. 1 Mixed-method implementation flow design

The implementation strategy is well suitable for addressing the chosen research question where the first and second steps involved using qualitative methods to identify the modeling and simulation processes and team dynamics constructs deployed by the students. The third step involved using the "quantization" technique to score the students' team dynamics behavior, and modeling and simulation activities. The fourth step involved quantitatively tracking and visualizing interdisciplinary learning scenarios. The quantization technique is the process of quantizing qualitative data using a framework, like a scoring rubric, to transform the qualitative data into quantifiable numerical labels [29], [30]. The process of quantizing qualitative data is adopted to transform the team dynamics qualitative interactions into numerical summations used to measure team dynamics variables for every modeling and simulation process. The main reason the researchers chose to quantize the qualitative data was to achieve data visualizations like those in Figures 4 – 6, which capture trends not possible through qualitative methods alone as demonstrated in the study by [30].

3.1. Context and participants

The study was conducted in a 600-level Multi-Scale Modeling biomedical engineering course offered at a large Land Grant Public Mid-Western University in the USA. A total of twenty graduate students enrolled for the course where seven teams were formed, each comprising a minimum of two to three students who were all committed to the team contracts. The researchers purposefully targeted the selected biomedical engineering class population based on the research goals. The selection of the student participants in the teams was based on convenience sampling [31], [32]. In this study, the focus of the investigation is on (n = 3) students in Team 2 only. The students bring to the team interdisciplinary strengths from biology, agricultural engineering, and biomedical engineering undergraduate backgrounds.

3.2. Learning Design

The course is a 3-credit load designed for graduate students interested in advanced computational modeling of complex multi-scale biology or biomedical systems. The goal is for students to recognize and describe multi-scale phenomena in biomedical systems and to develop or modify existing models for implementing, validating, or verifying an integrated multi-scale model using computational methods. It is expected that students enrolling in this course have a prior understanding of traditional computational modeling techniques.

The course adopted a project-based approach to enhance learning through the implementation of a multi-scale approach. Students were required to propose and develop a multi-scale model for a biomedical problem that involves multiple scales. They had the option to work on a model related to their thesis or choose any suitable multi-scale problem. The project spanned the entire semester, and students were expected to present three milestones.

3.3. Data Collection

Data collection involved capturing video recordings of student collaboration sessions on the Microsoft Teams platform which showed audio-visual interactions as students worked on completing the project milestones. Recordings were obtained for three meeting sessions held by Team 2 members. Each session lasted for more than an hour. Session 1’s duration was 86 minutes, Session 2 lasted for 78 minutes, and Session 3 lasted for 74 minutes. A total of 238 minutes (3 hours 180 minutes) worth of qualitative data was obtained.

3.4. Data Analysis

The qualitative data was prepared, cleaned, and subjected to the MMCS analytical approach starting with the thematical analysis [33]. The thematic analysis involved open coding, allowing for the initial identification and labeling of significant concepts within the data [34], [35], [36]. Subsequently, the generated codes were organized into meaningful categories, laying the foundation for the development of coherent themes that encapsulate the essence of the data. Next was to develop the teamwork or team dynamics assessment rubric used to systematically transform the qualitative data for each 2-minute interval of the students' interaction. The decision to split the transcripts at regular 2-minute intervals was motivated by the scoring process adopted in [3]. The interval ensures granularity in the coding process to maintain an appropriate level of rigor and detail in the coding process [37]. The scoring process led to the successful transformation of the qualitative data to quantitative numerical weights or scores known as the teamwork evaluation scores.

3.4.1 Thematic Analysis

The first step of the thematic analysis aimed at retrieving the data from the recorded video transcripts. The second step involved organizing the data by importing the transcripts into an Excel spreadsheet and preparing them for thematic analysis. The thematic analysis involved open coding, axial coding, and selective coding where central themes are created to capture the meanings of the codes conveyed in the students' interactions [38]. The last step of the thematic process involved organizing the codes, categories, and themes that emerged from the inductive process. The thematic analysis process generated core TD themes and CMBR stages that form the performance variables used in the rubric construction. Details of the generated themes are discussed in the results section.

3.4.2 Team Dynamics Assessment Rubric

The first step in the TD assessment rubric construction was deciding on the type of rubric in terms of the scale. A 4-point scale type of rubric was chosen with the highest score of 4 and the lowest score of negative 1. The researchers selected the 4-point scale rubric by convenience to capture a wide range of teamwork behaviors within the selected TD constructs including a negative 1 score to capture negatively impactful or destructive TD actions [39]. The TD assessment rubric for this study compares favourably in quality with the rubric used in the Comprehensive Assessment of Team Member Effectiveness (CATME) system. CATME uses a 5-point rating scale rubric for peer evaluation of teamwork contributions[40]. The rubric, however, fails to cover at least two TD constructs identified in the thematic analysis and is not structured in a way that accommodates the categorization of the teamwork behaviors considered in this study.

In the scoring process outlined in Figures 3 and 4, the points gained for each rubric TD construct (performance indicators) represent the individual TD competencies of the students when conducting modeling and simulation activities as a team. The rubric’s performance indicators were structured to be measured as follows: 0 points for no TD skill contribution, 1 point for basic or limited level TD skill contribution, 2 points for competent TD skill contribution, 3 points for proficient TD skill contribution, and 4 points for an exceptional TD skill contribution. The TD constructs used are Collaboration, Communication, Project Commitment and Leadership. The researchers designed the scoring criteria for all TD competencies suitable for each CMS stage. For example, exceptional collaboration is characterized by a team member's active engagement in all team activities, being an excellent team player the member supports and encourages team members. This member makes significant contributions to the team’s project progress and offers comprehensive guidance or instruction that facilitates learning through various tools to better convey ideas to teammates. Similarly, exceptional communication is demonstrated by a team member whose interactions are consistently clear and task-related. This member listens attentively, responds thoughtfully, freely shares information and ideas, and uses relatable items, terms, or concrete examples to communicate concepts. Exceptional project commitment occurs when a team member reliably completes tasks on time, takes responsibility for individual contributions, defines the project scope, objectives, and deliverables, and assists in establishing clear roles and responsibilities within the team. They may also create a project timeline featuring milestones and deadlines. Lastly, exceptional leadership is shown when a team member assumes leadership roles as needed, effectively delegates tasks, sometimes provides guidance and direction, and motivates and inspires team members with examples or personal relatable achievements.

In Figures 3 and 4, the various color codes highlight participants' scores as they collaborate, communicate, coordinate, tackle modeling and simulation technical challenges, and take on leadership roles. The red color-coded cells with the arrowheads and the orange color-coded cells with the arrow tails help the researchers to identify the various times students share prior scientific knowledge and learn from the interdisciplinary backgrounds of their peers. The cell with the arrow tail shows which student engaged in sharing prior scientific knowledge while the cell with the arrowhead shows which student learned from the more knowledgeable peer.

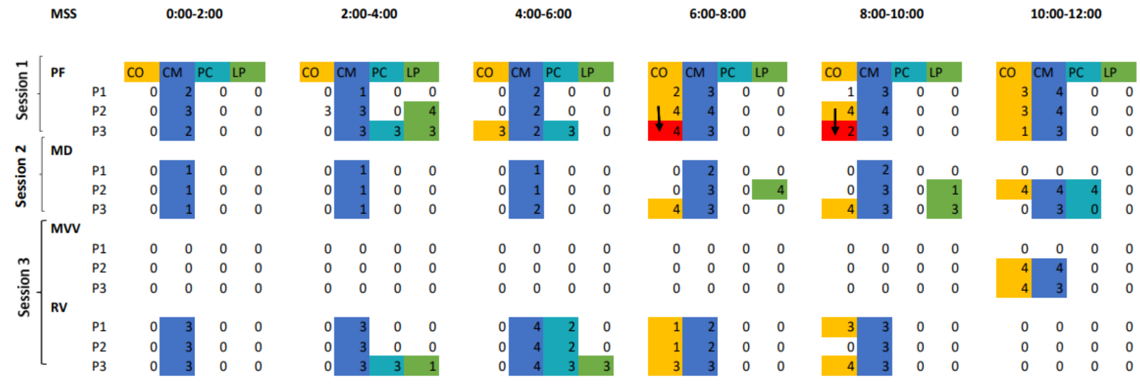

Figure 3. Scoring process for teamwork interaction[1]

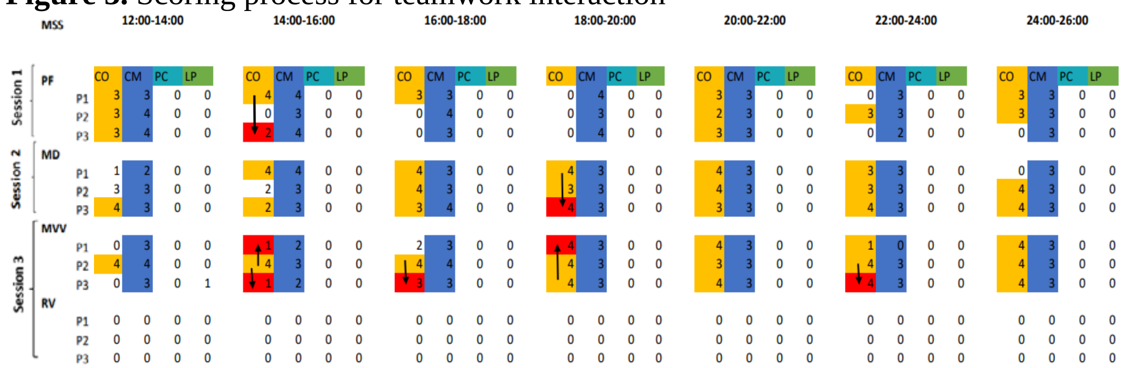

Figure 4. Scoring process for teamwork interaction (Contd...)

4. Positionality Statement

The thematic analysis, research, learning design, and data analysis were significantly shaped by the personal backgrounds, experiences, beliefs, and individual and collective biases of the researchers' experiences and backgrounds. The team of researchers involves one graduate student with expertise in computational modeling and engineering education and two faculty members, one with expertise in computational biomedical engineering and another one with expertise in discipline-based education research. The research design was conceived by the faculty in discipline-based education research and implemented together with the faculty in computational biomedical engineering. The data analysis was conducted by a graduate student with expertise in both fields, who was in constant communication and discussion with the faculty members throughout the data analysis process.

This study received IRB approval from the institution's review board. The participants' privacy and confidentiality were ensured by de-identifying the data and instead referring to the students as P1, P2, and P3. The trustworthiness of the coding process is upheld using code-recode and intra-rater reliability (IRR) strategies an agreement rate exceeding 80% was reached in this study, indicating a high level of consistency between the sets of codes generated at various rounds of coding.

[1] Problem formulation (PF), Model development (MD), Model verification and validation (MVV), Results reporting and visualization (RV), Modeling and Simulation Stages (MSS).

5. Results

This section presents the mixed method findings of Team 2's model-based reasoning, teamwork skills, and interdisciplinary learning. The preliminary results address the research question RQ1: "How do biomedical engineering graduate students engage their model-based reasoning, interdisciplinary learning, and teamwork dynamics skills when enacting computational modeling and simulation practices?" The conducted qualitative analysis, which used quotes from the 238-minute-long video sessions of Team 2's interaction, generated a total of 100 unique codes. The generated codes from the above documented thematic process entailed axially coding quotes into sub-categories and selectively coding the axial codes into nine distinct categories. The codes associated with nine categories were regrouped into four TD themes and four modeling and simulation stages. The TD themes are Collaboration, Communication, Project Commitment, and Leadership. The overall CMBR activities were categorized into four modeling and simulation stages, namely Problem formulation, Model development, Model verification and validation, and Results reporting and visualization.

An example of the thematically analyzed quotes used in this study is presented for a selected 2-minute time frame 1:16:00-1:18:00 for Team 2, in Session 1. In this two-minute interaction, the conversation revolves around the concept of using flow dynamics to predict cardiovascular complications. Student P1 exhibits Leadership in focusing the team on determining which cardiovascular diseases can be predicted based on flow characteristics. Student P2 acknowledges the connection between flow and cardiovascular complications. Student P3 brings up the development of models that use flow to indicate the mechanical stress experienced by tissues. The discussion is summarized and coded as " Flow dynamics and cardiovascular disease" a sub-category of the Model development efforts. All sub-categories from each 2-minute interaction are combined into various TD and CMBR categories or themes.

> *P1: "Our goal is to find what kind of cardiovascular-related disease is gonna be the output based on how flow is."*
> *P2: "You can link flow to cardiovascular complications."*
> *P3: "People are trying to develop models where flow is then informing the mechanical stresses that the tissue is experiencing."*
> *P3: "Even flow itself, like how intense the flow is or how big your ejection fraction is, can predict."*
> *P2: "Is there still a way to get to the population level with this model?"*
> *P3: "Would you guys prefer to do it a different way?"*

5.1 Interdisciplinary Learning Assessment

Quantitative visualizations are presented in Figures 4-6 to show the TD evaluations of three individual students in Team 2, during meeting session 3 only. However, the analysis was conducted for Team 2's three meeting sessions and the results are discussed in this paper. Based on the TD assessment rubric developed for this study, interdisciplinary learning is evaluated based on students' collaboration through active participation with peers, collaborative problem-solving activities, and sharing prior and interdisciplinary knowledge simultaneously. The conversations below are quotes from the time frame 15:54:00-18:45:00

for Team 2, in Session 3. This conversation can be visualized quantitatively using Figures 4-6. Utilizing these quotes, the researchers were able to investigate how interdisciplinary learning happens when the students enact computational modeling and simulation practices.

P2; " Ohh wait, no, this will work. I think this will actually make kind of sense becausewe're going from one pressure value to an estimated pressure wave. "
P1; " Wow"
P2; " And then from there we can technically make those PV loops we were talking aboutif we were feeling fancy. But we don't have to do that either. Like I'm totally open to not doing that,"
P3; " Yeah"
P1: "That'll be part of the preliminary work, I guess"
P2: "Does that make sense what I've written there?" P3: "Think so, yeah"
P2: "So we're going from just one individual systolic pressure value to a time-basedpressure value and then from that, we can evaluate the[…] ohh!. OK. So, I think we should actually do those pressure-volume loops now that I think about it. Yeah, if wehave time, if there's time next week, we can do that. But if not[…]
P3: "This might be a silly question. How are we then going to connect this back to the gutmicrobiome? Like, I know these blood pressure values are related to the gut microbiome,but in terms of presenting the information?"
P2: "I think we're only going up. I don't think we're going back down"P1: "Yeah"
P2: "Because I'm not smart enough to get from Windkessel model back to[…]
P3: "No, sorry, I'm not. I don't mean like putting it back into a gut microbiome model. I mean, like, after we have all of the results, we wanna be able to state something about therelationship of the gut microbiome in the heart, right? "
P1: "Oh yeah, good point"
P2: "OK. So that's why I think we do need to do those PV loops because then we can evaluate the efficiency of the heart as a pump based on[…] So we have flow and we just,we just integrate that. So just like traps or something.
P3: "But I think we just need to be able to make some type of statement of either like ohhthe FB ratio does or does not affect blood pressure"
P2: "I think we showed that it doesn't affect blood pressure"P3: "Okay"

The quotes provide evidence of how P2 played a more active role in sharing interdisciplinary knowledge with P1 and P3. First by discussing the technical option of moving from one pressure value to an estimated pressure wave. P1 then expresses some amazement toward the idea and confirms understanding at some point. P2 then sought feedback from P3 to check if they gained some understanding which P3 affirms. P3 sought some clarifications, raising questions to which P2 responded by suggesting that they should consider the potential of creating PV loops to evaluate the efficiency of the heart as a pump.

In Figures 4-6, point 1 in green is placed to represent the times when students share prior scientific knowledge or information with peers, and point 2 in red shows the times when the students learn new knowledge from peers. Both points are tracked and visualized on the collaboration profile curves for the participants concerned.

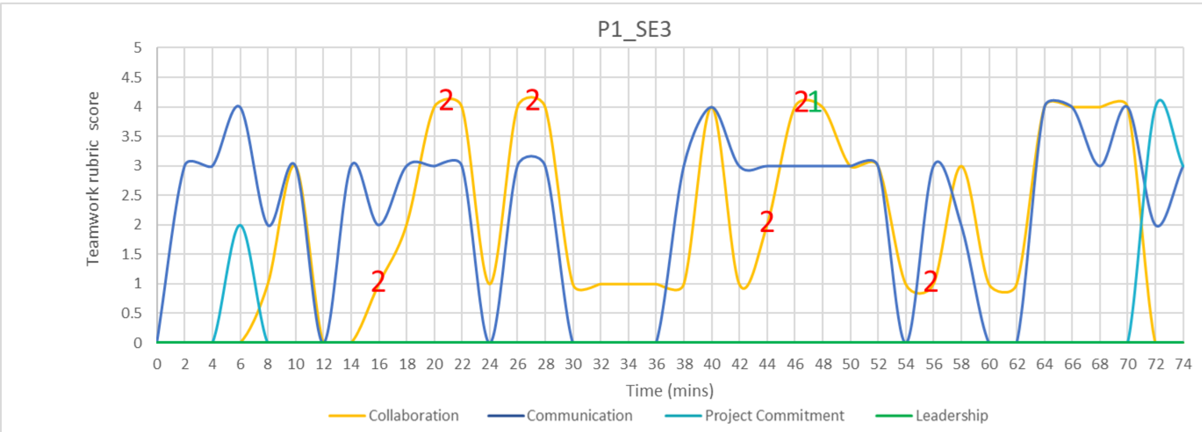

Figure. 4 Time-Series Profile for P1; Model verification and validation stage [Session 3 - Team 2][2]

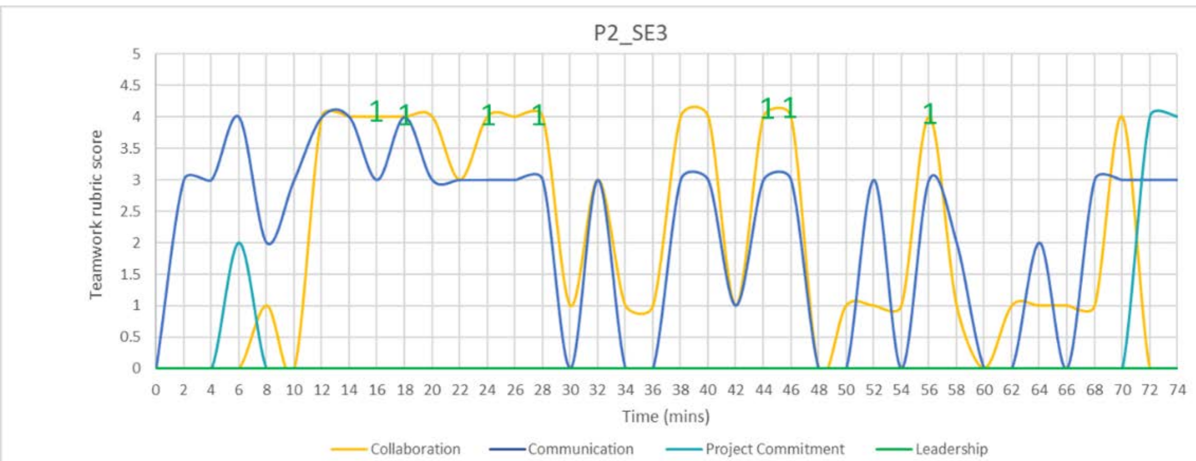

Figure. 5 Time-Series Profile for P2; Model verification and validation stage [Session 3 - Team 2][3]

[2]Point **1** denotes P1 sharing prior knowledge with peers; Point **2** denotes P1 Learning from peers

[3]Point **1** denotes P1 sharing prior knowledge with peers

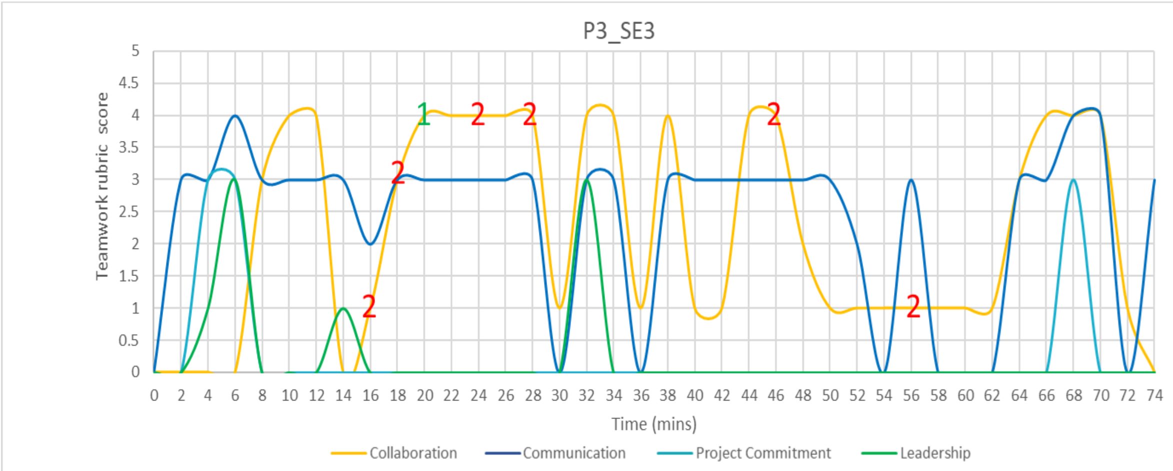

Figure. 6 Time-Series Profile for P3; Model verification and validation stage [Session 3 - Team 2][4]

When examining the plots in Figures 4-6, P2 shared scientific information with P1 and P3 in the 16th minute during active participation and collaborative problem-solving moments with team members. P2 shared scientific information again with P3 in the 18th minute and P3 shared scientific knowledge with P1 in the 20th minute.

The tracking process for interdisciplinary learning continued on the collaboration curves until the 74th-minute end of session 3. In the end, P1 and P3 have learned from peers a total of 6 times respectively. The students' interdisciplinary learning activities captured occurred during the Model verification and validation stage of session 3 and the learning assessment presents P2 as the most experienced and knowledgeable candidate of the 3 students. Overall, the interdisciplinary learning assessment shows that for Team 2, students engaged in knowledge-sharing and interdisciplinary learning events 17 times in all three sessions. That is 4 times during the Problem formulation stage (Session 1), 1 time during the Model development stage (Session 2), none during the Result reporting and visualization stage (Session 3), and 12 times during the Model verification and validation stage (Session 3).

6 Discussion and Implications

This study presents preliminary evidence of how biomedical engineering students use their social and professional TD skills and learn from peers while completing CMBR activities. Firstly, during the qualitative analysis phase, it was discovered that some "non-distinct" codes did not fit neatly into any specific sub-category and therefore lacked a focused theme. In this case, the researchers observed the usefulness of quantifying the qualitative data such that the student activities associated with these "non-distinct" codes were documented and analyzed during the quantization and quantitative visualization processes. This finding provides a significant contribution to the qualitative research community about the relevance of quantizing qualitative data.

The results from the thematic analysis reveal a significant relationship between students' problem formulation, model development and model verification and validation skills. This implied that providing students with useful prompts in their projects will allow the team members to

[4]Point **1** denotes P1 sharing prior knowledge with peers; Point **2** denotes P1 Learning from peers

synergize more through communication and collaboration which will significantly improve their Problem formulation, Model development and Validation skills. Similarly, students with strong prior interdisciplinary knowledge and modeling and simulation competencies will interact far better with their peers and build their communication and collaboration skills based on those guiding prompts. The qualitative results showed that the students tended to engage their model development and result reporting and visualization skills more independently than as a team because of the disciplinary technicalities and team members' prior knowledge.

Overall, the insights derived from this study can prove valuable in the planning and implementation of effective team-based course intervention strategies that pertain to project-based modeling and simulation instruction. Students and practitioners are furnished with evidence-based outcomes from this study as a way of endorsing the need to fully integrate comprehensive team-focused problem-solving methods in tackling complex STEM-based modeling and simulation challenges.

7 Conclusion, Limitations, and Future Work

In this research, the qualitative evaluations confirmed the thematic significance of the generated codes, categories, and themes related to team dynamics constructs and computational model-based reasoning activities that were prevalent among the members of Team 2. However, the thermatic coding and scoring processes involved only one research that utilized the code–recode and intra-rater reliability strategies respectively. Although 80% consistency in the validity was achieved in the different rounds of coding and scoring, having more researchers involved in the IRR processes will produce a different validation of the coding methods and scoring rubric.

The researchers further noticed that it was difficult to determine precisely what a student was working on at certain times when there was noverbal communication or visible body movements during the technical collaborations. Therefore, it is recommended that for future studies, participants of the study should be encouraged to capture and share audio-visual recordings of their computer screens throughout all phases of modeling and simulation stages.

Based on the gains of quantitative visualizations of the qualitative data especially in tracking students' team-based learning behaviors, the authors recommend to the Engineering Education research community the use of quantization technique to quantize audio or audio-visual transcripts. Future extensions of this work should involve characterizing and measuring CMBR as students engage TD skills on the team's performance in each milestone of the semester-long project. A multivariate analysis using ANOVA may be required to handle multiple relationships including the student's milestone performance.

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