INTERNATIONAL DESIGN CONFERENCE – DESIGN 2022
https://doi.org/10.1017/pds.2022.241

A Longitudinal Study of Teamwork Quality in Design Teams

H. Singh [1,✉], N. Horvat [2], S. Škec [2] and N. Becattini [1]

[1] Politecnico di Milano, Italy, [2] University of Zagreb, Croatia

✉ harshika.singh@polimi.it

Abstract

Teamwork quality (TWQ) is often associated with project success. Therefore, understanding TWQ is crucial to have better design project outcomes. Since most of the studies in the past have presented a cross-sectional analysis of TWQ, the current work focuses on capturing TWQ in a longitudinal way for a project-based learning (PBL) course. The results showed that the 6 facets differed significantly during the first half of the course than towards the end. In later phases of the PBL, TWQ and team performance were positively correlated than at the beginning.

Keywords: design education, design teams, collaborative design, teamwork, product development

1. Context and relevant background

Project-based learning (PBL) is popular in engineering design education (Dym et al., 2005). Educational institutions have adopted the PBL approach for the future labour market by giving their current students hands-on experience. Unlike traditional learning, PBL offers students the opportunity to 'learn while doing' on real-world projects (Savery & Duffy, 1995) with tasks that are often complex and ill-structured. PBL is considered to have a positive impact on the students' affective, cognitive and behavioural aspects (Guo et al., 2020). However, the effectiveness of PBL could be impacted by project type, individual capabilities (learning or working under pressure) and team composition (Hsu & Liu, 2005). In fact, in PBL students are also required to work in a team rather than only addressing the project individually. This is also a key point to improve soft skills, like communication and collaboration (Vogler et al., 2018). This approach is suitable to carry out learning-by-doing initiatives in the design domain, as witnessed by many examples of PBL courses structured around design projects or challenges (Kovacevic et al, 2017). Among these, it is worth noticing that some educational initiatives fostered the combination of the PBL approach with e-learning (Becattini et al, 2020).

This kind of approach became extremely relevant from the first months of 2020, as the COVID-19 pandemic required educators to rethink their educational routines and combine both synchronous and asynchronous learning in remote settings. Many PBL educational initiatives had to face the challenge of dealing with design teams that are distributed across different locations, which created additional barriers to collaboration and hindered the communication efficiency that is critical for project success. Despite plenty of work on PBL, most of the studies have focused on PBL course structure, and little is known about team collaboration during such courses. Students, in fact, often have negative perceptions regarding teamwork, and this could affect their performance (Ralph, 2016). For instance, team process and performance are often affected by factors such as team size and task (LePine et al., 2008). Brisco et al. (2019) identified several challenges that might impair collaboration in design courses structured according to the PBL pedagogy, which includes the capability of team members to build trust, the attitude they have during the work as well as previous knowledge and motivation.

Moreover, previous studies showed that technological means might impair the communication in design teams within geographically distributed PBL initiatives (Dym et al., 2005).
Despite it being clear that there are several reasons that might affect the learning and the general experience of students involved in a design course carried out with a PBL structure, the literature does not provide any contribution that explores how the teams evolve from the beginning to the end of the project. Moreover, considering the additional challenges triggered by geographically distributed settings, the understanding of the teamwork dynamics during the project becomes necessary to support designer and ensure a proficient learning experience for students.
Among the many factors affecting PBL teamwork, teamwork quality (TWQ) appears to be a suitable measure of team collaboration as it impacts the success of projects (Hoegl & Gemuenden, 2001). Studies in the past have used similar TWQ measures to explore their impact on the perceived organizational justice (Dayan, 2008) and teams' knowledge integration capability (Gardner et al., 2012). Hoegl and Gemuenden (2001) found that teamwork quality has positive impacts on team performance where it was measured in terms of effectiveness and efficiency. Others found a strong relationship between one of the components of TWQ such as cohesion and performance captured through behaviour and efficiency (Beal & Burke, 2003). Product success and personal satisfaction were also used to measure successful collaboration (Kotlarsky & Oshri, 2005). Scott-Young and Samson (2008) have used project cost, schedule, and operability as elements to measure project outcomes. In these studies, the measure remains constant throughout the activity and may not be suitable for PBL in engineering design that consists of different phases (such as problem clarification, concept generation and selection, prototyping, and documentation). Therefore, having a performance measure that is adequate to the outcome of that particular phase is required. Research in the past has shown that the association between performance ratings and TWQ varies with respect to the evaluator (Hoegl & Gemuenden, 2001). Moreover, respondents' perceptions of personal success and satisfaction that contribute to team performance (Hoegl & Gemuenden, 2001; Kotlarsky & Oshri, 2005) might not be suitable in a PBL setting. In PBL courses, design teams are evaluated by professionals (professors and (or) company experts).
From the above literature, it is clear that researchers should enhance their understanding of behaviour in a globally distributed design team in the PBL engineering design course. The previous studies have mostly focused on a cross-section analysis of design teams. In order to know how these teams collaborate over the entire project, a longitudinal study is necessary. Moreover, the relationship between the team collaboration (measured in the form of TWQ) and the team performance in engineering design teams within a PBL course needs more clarity. Therefore, the paper aims at answering the following research questions:

1. How does TWQ changes in a PBL course?
2. What is the relationship of TWQ with design team performance?

The study could be useful to design education where educators could benefit from these results by better estimating the opportunities and limitations of the PBL courses for geographically distributed design teams. Additionally, it also adds to the literature related to team development and team dynamics by providing insights from a longitudinal study.
The next section provides an overview of the methodology implemented to answer the research questions. The result section presents a detailed analysis of the data, followed by a discussion of these results. The paper concludes by providing a summary of the findings, limitations and future work plans of this research.

2. Method

2.1. Experiment Setup

The data was collected from an international distributed PBL design course called ELPID[1]. The course was organised as a collaboration among four universities (Politecnico di Milano, TU Wien, University

[1] ELPID – E-learning Platform for Innovative Product Development (http://www.elpid.org/)

https://doi.org/10.1017/pds.2022.241 Published online by Cambridge University Press

of Ljubljana and University of Zagreb) in which five virtual student teams work on the design problem introduced by a partner company (Siemens Mobility). The task was given by Siemens Mobility to the teams to design new seats and seating arrangements in metros following the design course phases. The four teams consisted of 8 members (2 from each university) and one team of nine members. There were 41 mechanical engineering students (4 females and 37 males) from both undergraduate and graduate levels that participated in the course. The teams communicated through MS Teams throughout the project. Each team had one or two academic coaches who worked as the teams' facilitators during the course. The team members met organically as they needed among themselves. But they met with their coach at least once a week to seek help and show their progress. The dynamics of teams differed mainly in the extent of the collaborative usage of tools (like CAD, PLM, google docs and many more) as compared to individual use. For example, participants used CAD slightly more individually than collaboratively.

The course started with an initial online workshop (that was to enhance user and market research, brainstorming and to familiarise the students with the problem context) which was followed by four phases (identification of opportunities, conceptual design, embodiment design and final phase). These phases were separated by formal review meetings involving company representatives for which the students prepared a presentation and a report. During the first phase, students conducted user and market research, patent screening, and comparison of existing solutions to propose a few visions on how they would like to proceed. They also developed an initial list of requirements that define the problem space. The second phase consisted of the development of several concepts for a chosen vision. After the conceptual design phase, teams worked on the embodiment design where they selected a concept and worked on building a virtual prototype. After the third phase review, the teams prepared for the final review to present their final design to the company and the academic staff. In this final phase, they further worked on detail design and in their final presentation, the teams incorporated rendered images and a video of their solution.

2.2. Data collection

In a review of PBL literature, it was found that self-reported measures are mostly used to capture affective, cognitive and behavioural outcomes (Guo et al., 2020). Hence, for the current study, teamwork quality (TWQ) was collected in a similar fashion. As mentioned in the introduction, the application of the TWQ measure demonstrated to provide valuable results for the exploration of team dynamics in management and healthcare, and, therefore, its adoption shed light on the collaboration team dynamics in the PBL course appears promising. The study uses the same TWQ construct questionnaire as defined by Hoegl & Gemuenden, (2001). These are communication, coordination, the balance of member contributions, mutual support, effort, and cohesion. To receive more responses, to maintain the integrity of the responses (as the same questionnaire was used multiple times during the course) and to reduce the load on students, the questionnaire was kept short. In other words, the detailed variables of each TWQ facet were not used in the study. Instead, the authors used the constructs along with their detailed explanation as provided by Hoegl & Gemuenden, (2001) (Table 1).

Table 1. Teamwork quality measures

Teamwork quality facet	Description	Scale
Communication	Communication in the team was sufficiently frequent, informal, direct, and open.	Likert scale 1-7 1 = strongly disagree 7 = strongly agree
Coordination,	The individual efforts were well structured and synchronized within the team	
Balance of member contributions	All the team members were able to bring their expertise to their full potential to contribute to the team goal	
Mutual support	The team members helped and supported each other in carrying out their tasks	
Effort	The team members exerted effort to do the team's tasks	
Cohesion	Team members were motivated to maintain the team and there was a team spirit	

https://doi.org/10.1017/pds.2022.241 Published online by Cambridge University Press

The questionnaires were used to collect data from seven sampling periods (SPs) distributed across the course (seen in Figure 1) using Microsoft Forms. The sampling started the course week 3 because the first two course weeks were reserved for the initial workshop that differed in its structure from the rest of the course. For that reason, the data was not collected for this initial period. Each phase lasted approximately 4 weeks and the team coaches distributed the electronic questionnaire to their teams every two weeks. This sampling enabled analysis of the TWQ within a course phase as well as the comparison between phases. The coaches also reminded their teams to fill the questionnaire if they have forgotten after a few days of the SP. In total, 248 responses were collected for seven sampling periods, distributed as follows: SP1 - 41 responses, SP2 - 34 responses, SP3 - 37 responses, SP4 - 35 responses, SP5 - 37 responses, SP6 - 39 responses, SP7 - 25 responses. The distribution of the responses within each sampling period and their position mapped to course weeks and phases could be seen in Figure 1.

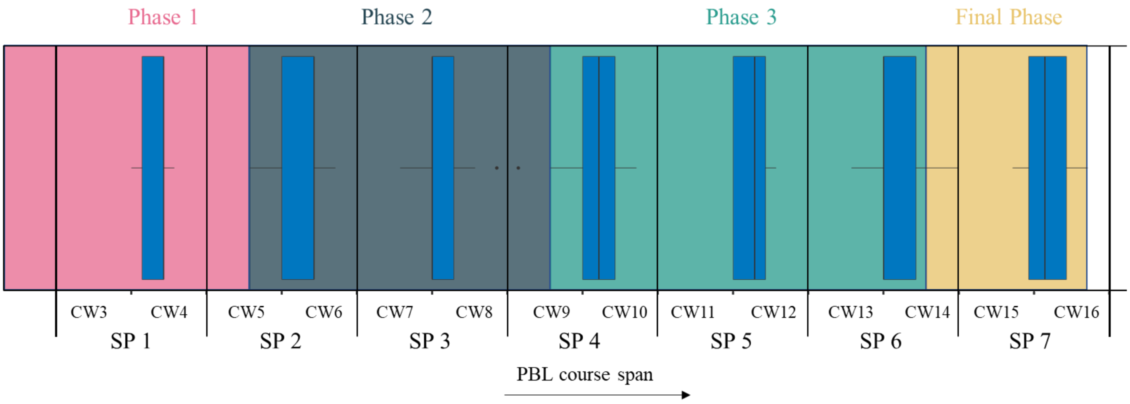

Figure 1. Data distribution across sampling periods (SPs), course weeks (CWs) and course phases

Table 2. Team performance measures

Phase	Measure	Scale
1 Identification of opportunities	-User and market research -Comparison of existing solutions -Formulation of visions and functional requirements	Likert scale 1-7 1 = very poor 7= exceptional
2 Conceptual design	-Quality of formulating requirements -Quality of problem clarification -Variety of proposed partial solutions -Quality of proposed concepts -Quality of concept evaluation	
3 Embodiment design	-Novelty of the solution -Feasibility of the solution -Quality of supporting analysis	
4 Final presentation preparation	-Methodology, approach and implementation of requirements definition -Innovation/creativity of all ideas -Level of detail (technical focus) -Attractiveness for the passenger	

As pointed out in the above section, the team performance measure for a PBL engineering design course should evaluate the outcome of a particular phase. Keeping this in mind, the phase-wise team evaluation metrics could be seen in Table 2. The organisers of the ELPID who are also the university professors of engineering design courses knew the expected outcomes of each phase of the course, hence, the evaluation metrics for each phase were developed by them. The ratio of company

https://doi.org/10.1017/pds.2022.241 Published online by Cambridge University Press

professionals to university professors were always around 1:1 except in the last phase where there were more company professionals present.

2.3. Data processing

Although the data related to the TWQ was collected bi-weekly, this does not mean that all the students filled the questionnaire at the same time. Therefore, data received over a span of days after the questionnaire was distributed corresponds to one sampling period. A sampling period was introduced and defined as a 14-day period with a mean date corresponding to the sampling point. Each period started seven days before the sampling period and lasted for seven days after the sampling period.
Secondly, a data cleaning procedure was developed to deal with the multiple answers of a team member within one sampling period, thus preventing skewing the results. Duplicate answers for each participant within each sampling period were identified and then averaged. Lastly, to compare the relationship between TWQ and team performance scores, the data of SPs lying in a phase were aggregated. For example (Figure 1), for phase 2, TWQ in SP2 and SP3 were aggregated. The TWQ was calculated as the sum of its 6 constructs while the team evaluation was the mean of all scores given by the evaluators for the different measures defined in Table 2 (as the number of evaluators differed in each phase). In the section below, analysis is conducted for each SPs, team level and phase level. Statistical differences and significance levels were computed using ANOVA and in case the data for an SPx were not distributed normally, the analysis was done using the Kruskal-Wallis test.

3. Results

The different components that construct TWQ were correlated to each other, as seen from Figure 2 (Kendall's correlation with p-values <0.05). These results align with the work presented by Hoegl & Gemuenden (2001), where they showed that communication, coordination, the balance of member contributions, mutual support, effort and cohesion could capture the quality of the collaboration in teams. A strong positive correlation among these TWQ components was found. This also supports the short survey format used in this study, where definitions from Hoegl & Gemuenden (2001) were used to collect information regarding TWQ instead of the original format where each component had several variables (Hoegl & Gemuenden, 2001).

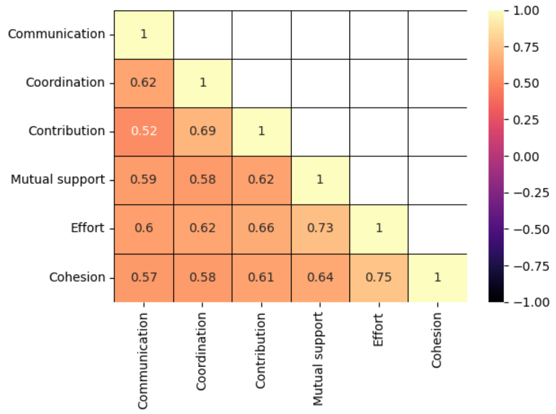

Figure 2. Correlation matrix of 6 facets of TWQ

3.1. TWQ over the course period

Figure 3 shows the variation in the TWQ components over the course length (i.e., SPs). Figure 3(left) shows that, overall, the 6 facets of TWQ differed significantly during the first phases of the course (i.e., SP1: H=21.1, p<0.001; SP2: H=10, p=0.08; SP3: F= 2.5, p=0.03 and SP4: H=9.7, p=0.08) than towards the end of the course (i.e., for SP5-SP7 p-values were insignificant).
The detailed analysis of each TWQ component could be seen in Figure 3 (right). This figure shows how a component value differs for all the teams in a given SP. Figure 3 (right) heatmap shows the

https://doi.org/10.1017/pds.2022.241 Published online by Cambridge University Press

significant p-values in darker hues and insignificant in lighter. It could be seen that all the design teams differed significantly from each other in mostly all SPs for cohesion and effort unlike for TWQ components such as communication, coordination, balanced contribution and mutual support.
Another interesting thing to notice in Figure 3 (right) is that the teams' TWQ components differ significantly towards the end of the course which further supports the findings related to Figure 3 (left).

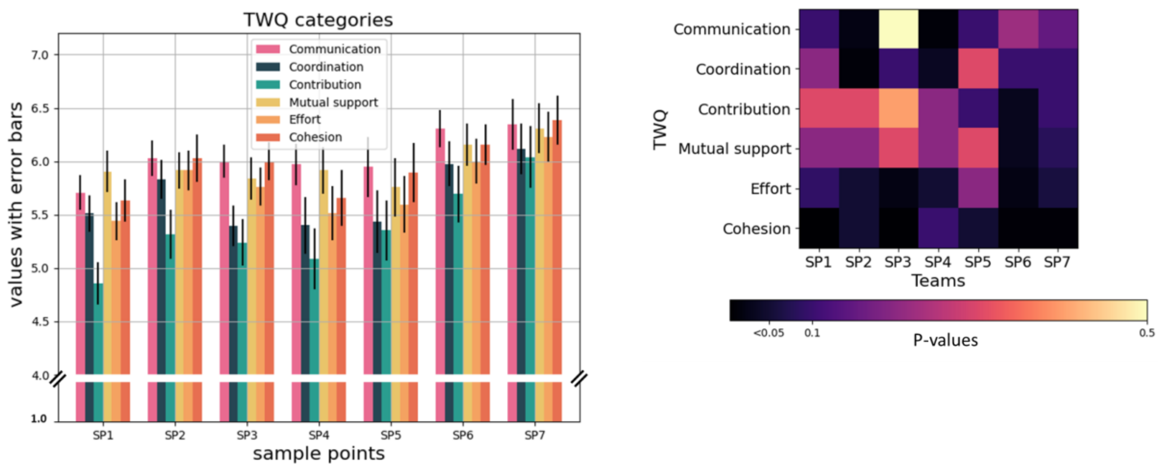

Figure 3. The 6 components of TWQ for all the SPs during the course (left); Comparison of the difference for all the teams for each of the TWQ components for a given SP (right)

3.2. TWQ in teams

Figure 4 shows the variation in the TWQ components for different teams. It could be seen from Figure 4 (left) that the 6 components of TWQ differed significantly for teams B (F=2.5, p=0.03), C (H=14, p=0.02), and D (H=50, p<0.001) during the course (i.e., for all SPs). While other teams like A (F=1.4, p=0.2) and E (H=6.9, p=0.2) did not differ in their TWQ components throughout the course.

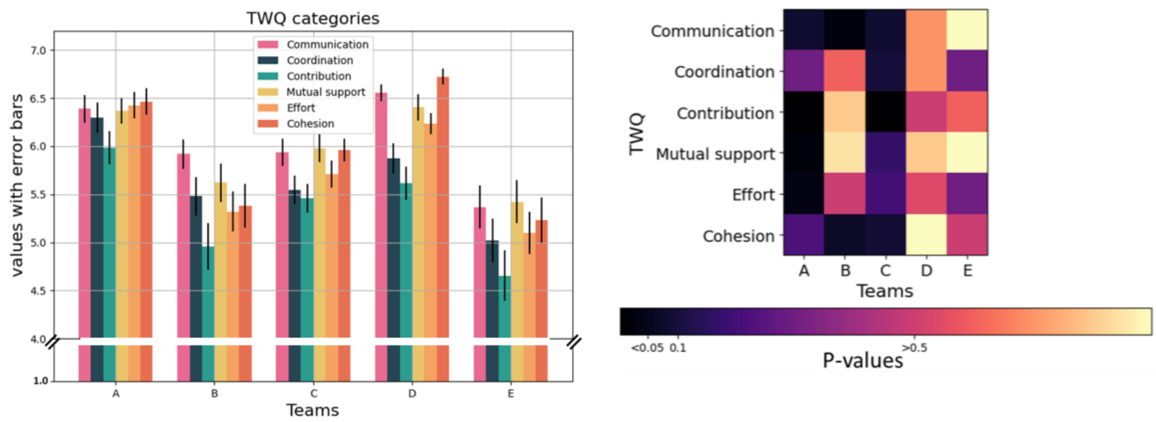

Figure 4. The 6 components of TWQ for all the teams (left); Comparison of the difference for all the SPs for each of the TWQ components for a given team (right)

The detailed analysis of how each team's TWQ component differed during the course periods (i.e., SPs) could be seen from Figure 4 (right). Similar to Figure 3 (right), Figure 4 (right) also shows a heatmap of significant p-values in darker hues and insignificant in lighter. This figure shows how a component value differs for all the SPs in a given team. The detailed analysis of each component revealed that team A's TWQ components like communication, the balance of member contributions, mutual support and effort differed significantly for all the SPs. Similarly, team C's TWQ components like communication, coordination, the balance of member contributions and cohesion differed

https://doi.org/10.1017/pds.2022.241 Published online by Cambridge University Press

significantly for all the SPs. The individual components of TWQ for teams, D and E did not differ for the entire course period.
It could also be seen that the difference in communication and cohesion was more significant for most teams during the course.

3.3. TWQ and performance

As stated in the Method section, the teams were evaluated 4 times for 4 different phases of the course by the company experts and the university professors. It could be seen from Figure 5 that both TWQ and the scores obtained by the teams increased towards the end of the course (independent samples t-test was used when both the samples were normally distributed). In Figure 5 (left) it could be seen that total TWQ (i.e., the sum of the 6 TWQ components) by all the teams in the final phase increased significantly from the first phase (T= 2.59, p=0.01). Additionally, final phase TWQ had a tendency to be higher than phase 2 (T= 1.8, p=0.08) and phase 3 (T= 1.5, p=0.1).
The scores for each phase significantly differed from each other (H=37.5, p<0.001) as seen in Figure 5 (right). However, this difference was mainly due to the high scores received in the final phase. The scores received by the teams at the end of the course were significantly higher than phase 1 (T= 6.5, p<0.001), phase 2 (T= 4.8, p<0.001) and phase 3 (H= 29.6, p<0.001).

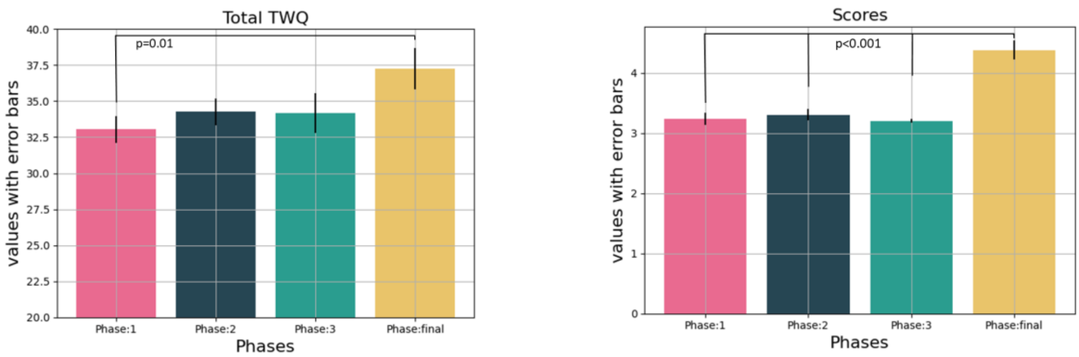

Figure 5. TWQ (left) and scores (right) with respect to the different phases of the course

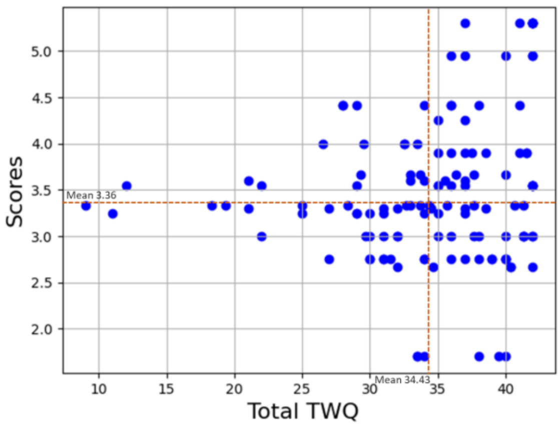

Figure 6. Total TWQ vs performance scores

As seen before (Section 3.3 beginning), both TWQ and performance scores were higher at the end of the course than at the beginning. Further analysis between the phases (length of the course) and the TWQ, and scores showed a slight positive correlation between them (Kendall τ = 0.24, p<0.001). Similarly, performance scores also tended to increase with the phases (Kendall τ = 0.32, p<0.001).
To further TWQ and performance scores, a Chi-squared test was conducted by counting the number of data points that occurred in the 4 quadrants (which could be seen in Figure 6). The means were chosen as the threshold to count data points in each quadrant. A relationship was found between the TWQ and

https://doi.org/10.1017/pds.2022.241 Published online by Cambridge University Press

scores with $\chi2 = 4.99$ and p= 0.026. The phase-wise correlation between TWQ and team performance was stronger towards the end of the project than at the beginning. For phases 1 and 2, no correlation was found, while for phase 3 (Kendall $\tau = 0.3$, p=0.06) and the final phase (Kendall $\tau = 0.4$, p=0.02), a significant positive correlation between TWQ and team performance scores was observed.

4. Discussion

In general, studies in face-to-face settings had attributes like support, team members' involvement and communication that significantly impacted team performance (Hoegl et al., 2004). Similarly, in the current study done for an e-learning platform of product development, attributes like communication, contribution, collaboration and mutual support also contributed to TWQ. It was seen that the 6 facets of the TWQ differed more at the beginning of the PBL than towards the end. One explanation of these results could be the creation of teams' social structures (Singh et al., 2021a) like familiarity, cohesion, trust-building, social influence and so on. In the initial part of the project, the team members get familiar with each other's habits, behaviour and working style that affects their trust-building and social influence, while towards the end, they already know their peers, hence less variation the TWQ components. The detailed analysis showed that cohesion and effort differed for almost all the SPs, while other components differed only for specific SPs. Thus, implying that the team member efforts were not uniformly distributed during the course. For instance, some members were experts in the rendering of the CAD model more than generating innovative solutions. Hence, these members who could have had put less effort at the beginning of the project worked more towards the end.

It was found that the values of the 6 facets of the TWQ differed for most of the teams throughout the project. In other words, the values for the 6 facets were perceived differently throughout the course by most of the teams except teams A and E. Interestingly, these two teams behaved completely different from each other in their TWQ as team A members were higher in the perceived TWQ and team E was significantly lower. Team A's individual component values for TWQ also differed throughout the course. However, exploring the factors that might have caused the difference in the variation in the TWQ component values might be an area of future research.

Additionally, certain components like communication and cohesion varied more among the team members for all the teams than other components. This could be due to the mode of collaboration (which in this case was completely remote) that might have affected the communication (Eris et al., 2014) and cohesion components more than the others (Singh et al., 2021(b); Marlow et al., 2018). Secondly, the PBL design course includes some phases (mainly the initial ones that consisted of problem framing, concept generation and selection) that required more collaboration than the later phases, where the teams divided the work and members worked individually (for example: while some worked on the CAD model, others did documentation).

A slight correlation between the TWQ and the length of the PBL course was found. As stated at the beginning of the discussion, an increase in familiarity among the team members could have had affected teams' social variables like influence, trust agreeability and so on, coherently with the findings of Singh et al. (2021a). An increase in team performance scores was also observed towards the end of the course. The reason could be the nature of PBL that enables the individuals and teams to improve themselves due to frequent feedback from the experts (Powers & de Waters, 2004). The team performance scores in the final phase increased significantly from the initial phase as the teams had a complete picture of their design solution or due to additional evaluators (company executives) for the final phase who saw the project outcomes for the first time.

The TWQ results (rated by the team members) and team performance scores (given by the university professors and company professionals) showed a slight association. Although Hoegl & Gemuenden (2001) found a strong association between TWQ and team performance, they also stated that the magnitude of the relationship between TWQ and team performance differs with the performance evaluator. In other words, the university professors and company professionals may have a different understanding of the constructs used in the team evaluation questionnaire (for example, the feasibility of the solution might be different for the two sets of evaluators). Unlike the team performance defined by Hoegl & Gemuenden, (2001) (in terms of effectiveness and efficiency), the constructs used in the current study to evaluate team performance differed for every design phase to capture the specific

https://doi.org/10.1017/pds.2022.241 Published online by Cambridge University Press

outcome of the corresponding phase. Moreover, this study differs in a methodological measure of team performance. While most of the previous studies used self-reported measures, this study utilises an independent evaluator measurement. This type of measurement enabled independence from the developed solutions and better relative comparison amongst teams, thus being more objective than self-reported measures of team performance. This resulted in fewer samples for team performance, which might have contributed to the weak association between the TWQ and team performance.

Even though both TWQ and team performance scores increase at the end of the project, it is not necessary that having high TWQ will result in high-performance scores as no overall correlation could be found (Kendall $\tau = 0.1$, $p=0.16$). Studies in the past have shown that high collaboration in teams does not mean high productivity (Paulus & Dzindolet, 1993). This may be due to social factors such as social loafing (Robert, 2020), team conflicts (Hinds, 2003) or more influence from dominating individuals that results in less variety in the solutions (Lau et al., 2012; Singh et al., 2021c). However, the phase-wise analysis showed that a TWQ and team performance were more positively correlated towards the later phases than at the beginning. Without the data during the initial workshop, this finding does not support the hypothesis stated by Hoegl et al. (2004) that early phase TWQ has more impact on team performance than the later phases. It aligns with the explanations given above that initial project phases are used to build social construct among the team members, and once they are established, TWQ starts to impact team performance. However, future studies are necessary to explore these suggestions.

5. Conclusion

The aim of the work was to answer the research questions, *How does TWQ changes in a PBL course? and what is the relationship of TWQ with design team performance?* The work showed how the facets of TWQ behave over time, with more variation observed at the beginning of a PBL course. Components like effort and cohesion varied throughout the PBL course. The teams varied in some of the TWQ components like communication and cohesion at more periods throughout the course than the others. Lastly, it was revealed that both TWQ and team performance increased with time. TWQ and team performance were positively correlated in the later phases of the PBL course.

Though the study shows some interesting results, it is important to understand the underlying limitations of the work. Firstly, the work deals with TWQ that was collected in the form of self-reported questionnaires. The collection of the TWQ data was bi-weekly, while the team evaluation was done phase-wise. Hence, the data of the bi-weekly SPs were aggregated to phase level in order to compare it with the team performance. In order to have more granularity in TWQ constructs, future studies would focus on the detailed constructs of the 6 TWQ facets. Furthermore, the team performance evaluators were both from academia and the company, which might have resulted in different views while evaluating the teams. Each phase had a different number of evaluations (phase 1 had 5 evaluators, phase 2 had 4, phase 3 had 2 and the final phase had more than 5 evaluators). Finally, the authors believe that team size and the different nature of the teams (homogenous background while heterogeneous culture) could have affected TWQ. In this aspect, further studies should be done considering various individual (such as novices or experts), team (such as team size) and project (like the nature of the task complexity) characteristics to explore how TWQ varies with them. This would help in comprehending the hidden variables that mediate TWQ and team performance.

Acknowledgement

This paper reports on work funded by the Erasmus+ project 2018-1-HR01-KA203-047486: ELPID – E-learning Platform for Innovative Product Development (http://www.elpid.org/).

References

Beal, D. C. R. & Burke, M. M. C., 2003. Cohesion and performance in groups: a meta-analytic clarification of construct relations. *Journal of applied psychology*, 88(6), p. 989–1004.

Becattini, N., Škec, S., Pavković, N. and Cascini, G., 2020, May. E-Learning Infrastructure Prototype For Geographically Distributed Project-Based Learning. *In Proceedings of the Design Society: DESIGN Conference* (Vol. 1, pp. 1667-1676). Cambridge University Press.

Brisco, R., Whitfield, R.I., Grierson, H. and Bohemia, E., 2019. Overcoming the challenges of global collaboration through design education. *In DS 95: Proceedings of the 21st International Conference on Engineering and Product Design Education (E&PDE 2019)*, University of Strathclyde, Glasgow. 12th-13th September 2019.
Dayan, M. D. B. A., 2008. Procedural and interactional justice perceptions and teamwork quality. *Journal of Business & Industrial Marketing*, 23(8), pp. 566-576.
Dym, C., Agogino, A., Eris, O. & Frey, D. L. L., 2005. Engineering design thinking, teaching, and learning. *Journal of engineering education*, 94(1), pp. 103-120.
Eris, O., Martelaro, N. and Badke-Schaub, P., 2014. A comparative analysis of multimodal communication during design sketching in co-located and distributed environments. *Design Studies*, 35(6), pp.559-592.
Gardner, H., Gino, F. & Staats, B., 2012. Dynamically integrating knowledge in teams: Transforming resources into performance. *Academy of Management Journal*, 55(4), pp. 998-1022.
Guo, P., Saab, N., Post, L. & Admiraal, W., 2020. A review of project-based learning in higher education: Student outcomes and measures. *International Journal of Educational Research*, Volume 102, p. 101586.
Hinds, P. B. D., 2003. Out of sight, out of sync: Understanding conflict in distributed teams. *Organization science*, 14(6), pp. 615-632.
Hoegl, M. & Gemuenden, H., 2001. Teamwork quality and the success of innovative projects: A theoretical concept and empirical evidence. *Organization science*, 12(4), pp. 435-449.
Hoegl, M., Weinkauf, K. & Gemuenden, H., 2004. Interteam coordination, project commitment, and teamwork in multiteam R&D projects: A longitudinal study. *Organization science*, 15(1), pp. 38-55.
Hsu, R. & Liu, W., 2005. Project based learning as a pedagogical tool for embedded system education. s.l., IEEE, pp. 362-366.
Kotlarsky, J. & Oshri, I., 2005. Social ties, knowledge sharing and successful collaboration in globally distributed system development projects. *European Journal of Information Systems*, 14(1), pp. 37-48.
Kovacevic, A., Vukasinovic, N., Pavkovic, N. and Horak, P., 2017. Evaluation of “Codeve” methodology for teaching npd to virtual design teams. *In DS 88: Proceedings of the 19th International Conference on Engineering and Product Design Education (E&PDE17), Building Community: Design Education for a Sustainable Future*, Oslo, Norway, 7 & 8 September 2017 (pp. 555-560).
Lau, K., Beckman, S. & Agogino, A., 2012. Diversity in design teams: An investigation of learning styles and their impact on team performance and innovation. *International Journal of Engineering Education*, 28(2), pp. 1-15.
LePine, J. et al., 2008. A meta-analysis of teamwork processes: tests of a multidimensional model and relationships with team effectiveness criteria. *Personnel psychology*, 61(2), pp. 273-307.
Marlow, S., Lacerenza, C. & Paoletti, J. B. C. S. E., 2018. Does team communication represent a one-size-fits-all approach?: A meta-analysis of team communication and performance. *Organizational Behavior and Human Decision Processes*, Volume 144, pp. 145-170.
Paulus, P. & Dzindolet, M., 1993. Social influence processes in group brainstorming. *Journal of personality and social psychology*, 64(4), pp. 575-586.
Powers, S. & de Waters, J., 2004. Creating project-based learning experiences for university-K-12 partnerships.. s.l., IEEE.
Ralph, R., 2016. Post secondary project-based learning in science, technology, engineering and mathematics. *Journal of Technology and Science Education*, 6(1), pp. 26-35.
Robert, L., 2020. Behavior–Output Control Theory, Trust and Social Loafing in Virtual Teams. *Multimodal Technologies and Interaction*, 4(39), pp. 1-21.
Savery, J. & Duffy, T., 1995. Problem based learning: An instructional model and its constructivist framework. *Educational technology*, 35(5), pp. 31-38.
Scott-Young, C. & Samson, D., 2008. Project success and project team management: Evidence from capital projects in the process industries. *Journal of Operations Management*, 26(6), pp. 749-766.
Singh, H., Becattini, N., Cascini, G. & Škec, S., 2021(a). *How Familiarity Impacts Influence in Collaborative Teams?*. Gothenburg, Sweden, s.n.
Singh, H., Cascini, G. & Christopher, M., 2021(b). *Comparing virtual and face-to-face team collaboration: insights from an agent-based simulation.* s.l., ASME 2021 Virtual International Design Engineering Technical Conferences & Computers and Information in Engineering Conference.
Singh, H., Cascini, G. & McComb, C., 2021(c). Influencers in design teams: A computational framework to study their impact on idea generation. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, pp. 1-21.
Vogler, J. et al., 2018. The hard work of soft skills: augmenting the project-based learning experience with interdisciplinary teamwork. *Instructional Science*, 46(3), pp. 457-488.

https://doi.org/10.1017/pds.2022.241 Published online by Cambridge University Press