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Factors Affecting Innovation in Engineering Design Teams: An Empirical Investigation of Student Team Perceptions*

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Innovation is a catalyst for economic growth, competitiveness, and sustainability worldwide. Knowledge has been identified as a key driving force for innovation usually resulting in intellectual property as a reward for creativity. Engineers of today are expected to possess abilities for teamwork, creativity, and innovation in order to meet the challenges and complexities of the 21st century. However, there is insufficient empirical evidence explaining the organizational, social and cognitive processes affecting innovation among engineering student design teams—the engineers of tomorrow. The research addresses the question: What are the factors affecting Innovation in engineering student design teams? The study advances a framework for engineering student team innovation and uses survey data from a representative ABET accredited four-year institution of higher learning involving 709 participants constituting 210 design teams from 40 design sections across nine academic departments at a college of engineering during an academic year. Validity and reliability of the survey instrument were obtained by using pre-existing scales, a pilot test, factor analyses, and scale reliability analysis. Other analyses involved aggregation analysis, ANOVA, correlation, and hierarchical linear modeling. A validated 59-item survey scale was realized. Perceived engineering student team innovation is found to be significantly related to leadership, support for innovation, rewards, team size, communication, task orientation, effort, learning, cohesion, conflict and participative safety at the team level. Most study findings agree with general organization team innovation literature with exceptions of participative safety and support for innovation. Findings from the study have implications for the improvement of engineering design curriculum and provide a framework for endeavors to harness skills for teamwork and innovation among engineering graduates through enhancing or regulating the determinants of innovation. A linear model for assessing team innovation among engineering students is elaborated in the study.

Keywords: innovation; teamwork; engineering design teams; student teams; capstone projects

1. Introduction

Innovation is a catalyst for economic growth, competitiveness, and sustainability worldwide. The United States has been a world leader in Innovation over the last century. Most recently, between 2012 and 2013, the United States accounted for an increase of 5% in global patents filed, second to China, and 13% growth in trademarks registered [1]. The United States along with China, Japan, Korea, and Europe accounted for 81% of all global patents in the same year. Knowledge has been identified as a key driving force for innovation usually resulting in intellectual property as a reward for creativity.

Engineers are at the center of every innovative endeavor [2]. This implies it is of primary concern to institutions of higher learning to assess whether engineering graduates do indeed exhibit skills for teamwork and innovation upon completion of a four-year university program of study. A 2006 report by ABET found 90% of 1622 employers surveyed described engineering graduates as being more adequately prepared for work in the professional arena, but still lacking in abilities and skills for teamwork, communication, learning, growth and adapting to changes in technology and society [3]. The employers reported a noticeable decline in engineering graduates' skills in "understanding of the organizational, cultural and environmental contexts and constraints of their work" compared to graduates prior to the implementation of the Engineering Change 2000 (EC 2000) ABET criteria [3].

Engineering design curricula are fundamental to engineering practice [4] and offer opportunities for creativity, innovation, and teamwork among engineering students. Despite efforts to assess the effectiveness of curricula by practitioners [5] and institutions of higher education as part of their ABET review (or other assessment activities), the authors have not come across a commonly-accepted direct and in-depth method of assessing factors related to the social, cognitive and organizational processes governing teamwork and innovation among engineering students. Innovation, although crucial, is neither directly stated as a learning out-

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come/objective, nor assessed through ABET. Furthermore, although efforts have been made to describe innovative attributes peculiar to engineers [6–8], empirical evidence of hypothesized relationships between pertinent factors and innovation at the team-level is scarce, particularly in the context of engineering student teams engaged in creative design teamwork. This study addresses this knowledge gap by testing a framework for engineering student team innovation developed by [9]. The emphasis on team innovation over individual innovation is motivated by the pervasive use of teams in real workplace organizations today for reasons including the impracticality and near-impossibility of one-person solutions to some of today's complex problems. Previous research has emphasized the viability of teamwork [10, 11] and found the existence of additional variance in innovation at the team-level superseding the sum of constituent individual innovations [12]. Furthermore, social development theories of innovation suggest the need for a social context in order for innovation to occur [13].

The question guiding this research is, "What are the factors affecting innovation in engineering student design teams?" The specific aims of the research are: (1) to design and administer a questionnaire for collecting data on factors affecting innovation in engineering student teams; (2) to assess the validity, reliability and aggregation indices for survey data; and (3) to test hypothesized relationships between innovation and the proposed factors. The study investigates the relationship between team innovation and factors proposed in the Engineering Student Team Innovation (ESTI) framework developed by Asio [9]. The ESTI framework consists of both latent and manifest variables on which data will be gathered. As is typical for survey-type studies, the data was screened and assessed for construct validity and reliability prior to its use for testing hypotheses.

1.1 Proposed Engineering Student Team Innovation (ESTI) framework

This study adopts a definition for innovation provided by West and Farr as, "the intentional introduction and application within a job, work team or organization of ideas, processes, products or procedures which are new to that job, the work team or the organization" [15, p. 9]. Consequently, the ideas may be new to the team and organization adopting them, while they are not necessarily new to others external to the organization. This is the typical case for engineering students who are essentially novices that are learning to design and innovate. West [16] regards creativity as the first stage in the innovation process mostly concerned with the generation of ideas, while innovation is the practical implementation of such ideas. Perry-Smith and Shalley [17] refer to creativity as a concept involving the generation of new ways to perform work through novel procedures or innovative ideas and by remodeling old approaches.

Following a review of literature spanning two decades by Asio, Ekwaro-Osire and Cross [14] it was found there currently exists no consolidated framework for identifying pertinent factors affecting innovation in engineering student design teams. Despite a plethora of research in general organizational innovation literature, there are a limited number of empirical studies describing innovation in relation to engineers in particular [7]. Consequently, a framework for engineering student team innovation was developed by Asio [9] (Fig. 1) based on the classic Input-Process-Output (IPO) systems theory model for team performance [18–20]. In order to address the research question, two general hypotheses are proposed in the study as follows:

H_1: Input factors are related to Innovation at the team-level.
H_2: Process factors are related to Innovation at the team level.

Each hypothesis is further elaborated into sub-hypotheses (H_{1a} to H_{1g} for input factors, and H_{2a} to H_{2h} for process factors) specific to each factor within the proposed innovation framework based on findings from previous research and construct definitions.

Further categorization of factors identified into the IPO categories was done based on the Cohen and Bailey [21] heuristic team effectiveness framework. On this basis, team inputs are subdivided into *organizational contextual factors, team composition and structure*, and *task design* subcategories. *Organizational contextual factors* refer to the work place setting and support for team innovation activities within the work place. They include:

- *Support for innovation*—support from instructors, graduate assistants, mentors, project sponsors and availability of state-of-the-art facilities that foster innovation (hypothesized to positively affect innovation, H_{1a}).
- *Leadership*—ability of a team facilitator/coordinator to influence a group towards the achievement of goals [22], (positively related to Innovation, H_{1b}).
- *Rewards*—benefits accruing from participation in teamwork and innovation. In the engineering education context, rewards refer grades, prizes, awards, and perceived value of grades to individual students (intrinsic value)–(positively related to innovation, H_{1c}).

Team composition and structure refers to the characteristic components of the team by virtue of its formation. The factors in this input sub-category are:

- *Job relevant diversity*—variety of task-related skills and attributes that team members possess such as education, knowledge, skills or expertise [23], (positively related to innovation, H_{1d}).
- *Background diversity*—non-task-related differences such as age, gender, or ethnicity [24, 25], (negatively related to innovation at the team-level, H_{1e}).
- *Team size*—number of individuals holding membership in a team, (positively related to innovation, H_{1f}).

Task design describes the nature and objective of the project work the team is engaged in, respectively. The variable in this sub-category is:

- *Vision*—common understanding of team objectives and a display of strong commitment to team goals by all members of the team. This factor embodies aspects of goal clarity and role expectations which refer to clear statement of expectations and targets for team members, their importance to the team and assignment of responsibility centers to particular individuals [26], (positively related to innovation, H_{1g}).

Process subcategories include *team process* and *psycho-social traits*. *Team process* refers to the series of actions and activities carried out by the team members collectively in the achievement of their goals. They include:

- *Communication*—this is the process through which team members share information and ideas among themselves. Communication is sub-divided into internal and external communication. The former refers to within team (intra-team) communication and the latter refers to communication with members outside the team (extra-team communication), (positively related to innovation, H_{2a}).
- *Task orientation*—this factor subsumes task reflexivity and intrinsic motivation. Task reflexivity refers to a team's reflective process through which members evaluate each other's work and seek ways to improve team effectiveness and outcomes. Intrinsic motivation describes the extent to which team members are cognitively aligned and driven to invest maximum effort in project activities. Task orientation thus reflects elements of cooperation and coordination of team activities [23], (positively related to innovation, H_{2b}).
- *Conflict*—this is constituted by task conflict and relationship conflict. Task conflict refers to team member disagreements on team tasks. Relationship conflict, on the other hand, refers to social-emotional conflicts stemming from interpersonal disagreements [27]. Conflict is hypothesized to be positively or negatively related to Innovation based on whether constructive or inter-personal conflict dominates across teams, H_{2c}.
- *Effort*—this is conceptually framed as time of commitment, work intensity, and direction in given teamwork [28–30], (positively related to Innovation H_{2d}).

Psycho-social traits are process factors related to the *cognitive* and *social* aspects of teamwork. *Cognitive factors* describe mental and perceptual team processes such as:

- *Learning*—this refers to the process of aligning and developing the capabilities of the team to create desired results. These processes include experiencing, reflecting, thinking and acting, (positively related to Innovation, H_{2e}).
- *Participative safety*—this is sometimes known as psychological safety and refers to the presence of a non-threatening environment in which individuals can freely express their views in a tension-free and less constrained atmosphere, (positively related to Innovation, H_{2f}).

Social factors describe relationships and networks among individual team members. These are:

- *Cohesion*—this is defined as commitment of team members to teamwork and their desire to maintain team membership, and it encompasses aspects of interpersonal attraction, task commitment and group pride [31], (positively related to innovation, H_{2g}).
- *Social network*—this refers to the frequency of formal and informal personal contacts among team members [32]. Individuals with more overlapping third party ties with team mates put forth more effort than those without (positively related to innovation, H_{2h}).

Outputs are classified as *technical system outcomes* which refer to the quality, usefulness and proficiency of the team deliverables. The technical system outcome for the study is team-level innovation

- *Team innovation*—generation of tangible and intangible deliverables (such as ideas, processes, products and procedures) as a result of teamwork that are new to the job, work team or organization [15].

For more details on how ESTI framework (Fig. 1) factors were identified, underlying conceptual and

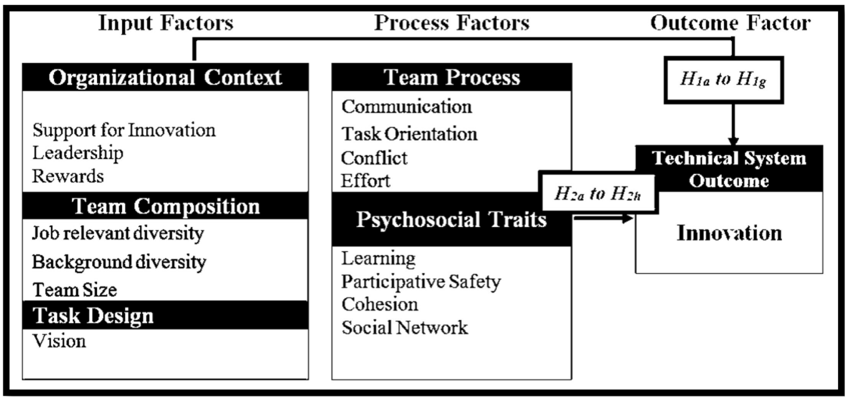

Fig. 1. Preliminary Engineering Student Team Innovation framework. Adapted and modified from Asio [9].

theoretical frameworks and findings from previous studies, readers are referred to Asio [9] and Asio, Ekwaro-Osire and Cross [14]. Three factors from the ESTI framework, namely, competitions, nature of the task, and creative thinking, were omitted from this study as they did not apply to the population surveyed. The ESTI factors investigated in this study were operationalized using carefully selected survey instruments, and appropriate statistical testing methods were applied to validate measures and test hypotheses as described further in the methodology under the presentation section.

2. Presentation

2.1 Survey design and administration

Measures for factors in the ESTI framework were operationalized using a questionnaire developed from pre-existing and new survey scales. Scales for *Vision, Support for innovation, Leadership, Rewards, Job relevant diversity, Communication, Participative safety, Conflict, Cohesion, Task orientation, Learning*, and *Social network* were adapted from existing measures in literature. Meanwhile, two variables, namely *Effort* and *Innovation*, had no measurement scales readily available. As a result, survey scales for these factors were developed by the researchers based on factor definitions within the context of the study. The scale items adopted in the survey are summarized in Appendix 1. All scale items were measured using a 6-point Likert-type agreement scale (1 = strong disagree, 2 = disagree, 3 = tend to disagree, 4 = tend to agree, 5 = agree, 6 = strongly agree). In addition to the scale items, the survey also measured *Team size* and *Background diversity* (*Gender* and *Race*) as manifest variables.

The research was designed as a cross-sectional field survey. Study participants consisted of students conducting senior design capstone projects and other (pre-capstone) semester-long group design projects at an ABET accredited institution of higher learning. The final survey was administered to more than 1000 participants belonging to diverse teams from 40 design sections across nine engineering programs in eight academic departments within a college of engineering at a large state university. Student teams were engaged in the improvement of existing products, methods, services, and/or design and development of new products, methods, and services. An initial pilot study was conducted to test the survey instrument prior to full-scale administration, and outstanding issues were clarified before conducting the final study [9].

2.2 Study demographics

Following a one-year data collection period, a total of 869 responses were returned by student participants resulting in 709 useful individual responses and 210 engineering design teams after screening. Study demographics (after screening) are summarized in Fig. 2, and Tables 1, 2, and 3. Demographics

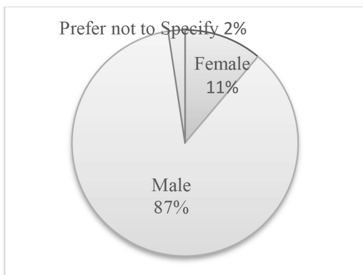

Fig. 2. Study demographics by gender.

Table 1. Study demographics by classification after screening

Classification	No.	% age
Freshman	1	0.14%
Sophomore	3	0.42%
Junior	75	10.58%
Senior	630	88.86%
Total	709	

Table 2. Study demographics by race after screening

Race	No.	% age
American Indian and Alaska Native	4	0.57%
Asian	50	7.08%
Black or African American	35	4.96%
Hispanic or Latin American	106	15.01%
Native Hawaiian and other Pacific Islander	0	0.00%
Other or Prefer not to Specify	42	5.95%
White or Caucasian	469	66.43%
Total	**706**	

Table 3. Study demographics by program after screening

Program	Course Designation	No.	% age
Chemical Eng.	CHE 4555: Chemical Process design and simulation	56	7.90%
Civil Eng.	CE 4330: Design of Engineering Systems	64	9.03%
Computer Eng.	ECE 3331: Project Laboratory I, II, III & Senior Project Laboratory IV & V	22	3.10%
Computer Science	CS 4311: Senior Design Project	25	3.53%
Construction Eng.	CONE 4220: Construction Capstone	24	3.39%
Electrical Eng.	ECE 3331: Project Laboratory I, II, III & Senior Project Laboratory IV & V	204	28.77%
Industrial Eng.	IE 4333: Senior Design Project	27	3.81%
Mechanical Eng.	ME 4370: Engineering Design I & II	281	39.63%
Dual Eng. Degree		6	0.85%
Total		**709**	

of the study respondents are comparable to the state institution's enrollment trends during the study period.

2.3 Assessing scale validity

In the case of the ESTI framework investigated in this study, the survey scale items used were, for the most part, known to measure the underlying factors from previous research studies. As such, there were prior hypothesized relationships among measurement items for each latent construct, and, thus, Confirmatory Factor Analysis (CFA) was used for validating scale items.

CFA was carried out using the maximum likelihood option ("METHOD = ML") in the PROC CALIS procedure in SAS Version 9.3. The main objective of CFA is to identify a measurement model with a covariance matrix equivalent to the implied covariance matrix for a set of variables. Assumptions and considerations for CFA modeling include: *normality*; *absence of multicollinearity; use of at least three indicator variables (items) per latent factor (scale);* and *a maximum of 20 to 30 indicator variables per factor* [33]. Assumptions three and four were inherent in the design of the survey, with the exception of the Leadership scale which only had two items; all other scales in the study had three to seven items. Normality was assessed through graphical analysis of the item distributions, while tests for multicollinearity were evaluated by assessing correlations between indicator items and variance inflation factors (VIF). A correlation ≥ 0.8, an individual VIF ≥ 10, or an average VIF ≥ 3 is indicative of possible multicollinearity [34]. Multicollinearity was absent based on the maximum VIF value of 4, which is less than the threshold of 10.

A diverse set of goodness-of-fit indices were used to assess the fit of survey items for measuring the ESTI factors based on the sample data from the study population. Chi-Square, RMSEA, and SRMR were employed as absolute fit indices, which indicate how well the *a priori* model fits the sample data [35]. Meanwhile, CFI, PNFI, and NNFI were used as incremental fit indices (also known as comparative or relative fit indices), which help to assess fit from one model to another [35]. The thresholds for goodness-of-fit indices were adopted from [36–39] and are summarized in Table 4.

CFA was applied to assess construct validity of survey items for each of the ESTI framework subcategories: *Team Inputs, Team Processes, Psychosocial Traits* and *Outcomes*. As such, the initial CFA measurement model for the ESTI inputs category consists of 15 items. The model for the team process subcategory consists of 16 items while psychosocial traits consists of 19 items from *Cohesion* (5 items), *Social network* (3 items), *Participative safety* (4 items), and *Learning* (7 items). The model for the outcomes category consists of 25 items, with 7 items from *Team Innovation* and 18 items from three other outcomes which are outside the scope of this paper.

The performance of the measurement models on the goodness-of-fit indices is summarized in Table 4.

Table 4. CFA fit statistics for study measurement models

	Input Model		Team Process Model		Psychosocial Traits Model		Output Model	
Fit Statistic with threshold	**Initial**	**Mod.**	**Initial**	**Mod.**	**Initial**	**Mod.**	**Initial**	**Mod.**
χ^2 p-value > 0.05	<0.0001	<0.0001	<0.0001	<0.0001	<.0001	<.0001	<0.0001	<0.0001
χ^2/df ≤ 5	**4.56**	**3.47**	8.20	**4.85**	5.74	**3.10**	5.22	**4.62**
RMSEA < 0.08	**0.07**	**0.06**	0.10	**0.07**	0.09	**0.06**	0.08	**0.07**
RMSEA 90% Cl, [0, 0.05]	[0.07, 0.08]	[0.05, 0.07]	[0.10, 0.11]	[0.07, 0.08]	[0.09, 0.10]	[0.05, 0.07]	[0.07, 0.08]	[0.07, 0.08]
SRMR < 0.09	**0.05**	**0.04**	**0.06**	**0.04**	**0.07**	**0.05**	**0.05**	**0.03**
CFI > 0.90	**0.92**	**0.95**	**0.89**	**0.95**	**0.86**	**0.95**	**0.92**	**0.94**
PNFI > 0.6	**0.69**	**0.63**	**0.71**	**0.67**	**0.72**	**0.62**	**0.80**	**0.72**
NNFI > 0.96	0.90	0.93	0.86	0.93	0.84	0.93	0.91	0.92

Values in **bold** satisfy suggested reporting thresholds.

In this table, the Initial models contain all original items from the survey (Appendix 1), while the Modified models (Mod.) exclude items that warranted deletion. A total of 16 items were deleted based on suggested modification indices (specifically, Lagrange multipliers from CFA), Cronbach's alpha improvement (when the item is deleted), posthoc Exploratory Factor Analysis (EFA) in some cases, and conceptual considerations by the researchers. The final measurement scales consist of 4 items each for *Communication, Cohesion, Learning*, and *Task orientation*; 3 items each for *Job relevant diversity*, *Support for innovation*, *Vision*, *Conflict* and *Social network*; and 2 items each for *Leadership*, *Rewards*, *Effort* and *Participative safety*; and 6 items for *Team Innovation*. Table 4 shows the modified measurement models for the ESTI inputs, team process, psycho-social traits, and outputs subcategories which satisfy most of the suggested fit index thresholds except χ^2 p-value, RMSEA 90% Cl, and NNFI.

2.4 Assessing scale reliability

Scale reliability was assessed using the Cronbach's alpha measure for internal consistency [40] in SPSS Version 21. The Cronbach's alpha statistic evaluates the extent to which the individual items within a scale are correlated with one another or the whole scale based on scores obtained for each item. An acceptable value of the Cronbach's alpha is generally cited as 0.7 to 0.8 [41]. However, thresholds below 0.7 may be acceptable for psychological constructs [42] and 0.6 is acceptable for newly developed scales [43]. Table 5 shows Cronbach's alpha results for the study survey reliability analysis. The alpha values are clearly acceptable for *Cohesion*, *Communication*, *Conflict*, *Effort*, *Job relevant diversity*, *Leadership*, *Learning*, *Social network*, *Support for innovation*, *Task orientation*, *Innovation*, and *Vision*, as they are greater than 0.7, and marginally acceptable for *Rewards* (Cronbach's α = 0.68) and *Participative safety* (Cronbach's α = 0.5995). To determine whether the reliability of a given scale could be improved by removing one or more items, the Cronbach's alpha "if item is deleted" values were also examined. This analysis along with evaluation of the CFA output resulted in deletion of 16 items in total.

2.5 Tests for data aggregation and nesting

The intended unit of analysis for the study is the team. However, data for the study was collected from individual students belonging to the design project teams. Thus, the data reflects individual perceptions of the team constructs in the ESTI framework. It is therefore necessary to assess whether the data collected can be justifiably aggregated to the team level prior to carrying out hypothesis testing. The intra-class correlation coefficient (1)-(ICC(1)), was used to assess the proportion of variance associated with differences between teams for each ESTI framework factor. ICC(1) values of 0.20 (or at least greater than 0.10) have been suggested as demonstrative of strong group-level association and are considered to support data aggregation [44, 45]. The ICC(1) statistic was further assessed by performing a one-way ANOVA on the ETSI factors with *team* as the main effect. The significance of *team* as the main effect suggests the presence of more variation across groups than within groups. If both of the above criteria are met, the mean scores across individuals within a team can be taken as a reliable measure of the team-level constructs [46].

ICC(1) analyses were carried out using SPSS version 21 "Mixed Models" procedure and SAS version 9.3 PROC MIXED procedure. The ICC(1) results are summarized in Table 5. Values range from 0.1 to 0.5, with an overall mean ICC(1) score of 0.2344, satisfying thresholds. One-way ANOVA tests for nesting effects show that *Team* is a significant grouping variable for the data set at an alpha level of 0.05 for all ETSI factors except for *Gender diversity* (an individual level attribute), which agrees with the results of the ICC(1) analysis (Table 5).

Table 5. Cronbach's alpha, intraclass correlation coefficient (1), and one-way ANOVA test results

			ANOVA Test for Grouping effects					
			Team		Section		Program	
Scale	Cronbach's α	ICC	*F*-value	Sig.	*F*-value	Sig.	*F*-value	Sig.
Cohesion	0.8751*	0.2783	2.2980	**< 0.0001**	2.4510	**< 0.0001**	2.2860	**0.0200**
Communication	0.8057*	0.2387	2.0700	**< 0.0001**	2.3410	**< 0.0001**	4.8340	**< 0.0001**
Conflict	0.7919*	0.1564	1.6280	**< 0.0001**	1.4130	**0.0520**	2.2100	**0.0250**
Effort	0.8602*	0.204	1.8610	**< 0.0001**	2.7410	**< 0.0001**	4.8610	**< 0.0001**
Job relevant diversity	0.7765*	0.2065	1.8910	**< 0.0001**	2.1610	**< 0.0001**	2.9660	**0.0030**
Leadership	0.8065*	0.2159	1.8980	**< 0.0001**	3.2910	**< 0.0001**	3.9590	**< 0.0001**
Learning	0.8246*	0.1475	1.5850	**< 0.0001**	1.8890	**0.0010**	2.7480	**0.0050**
Participative safety	0.5995	0.1109	1.4370	**0.0010**	1.6450	**0.0090**	3.3620	**0.0010**
Rewards	0.6815	0.1833	1.7350	**< 0.0001**	2.7670	**< 0.0001**	6.0870	**< 0.0001**
Social network	0.7051*	0.49	4.3260	**< 0.0001**	6.9870	**< 0.0001**	10.8560	**< 0.0001**
Support for innovation	0.7627*	0.2668	2.2510	**< 0.0001**	5.0360	**< 0.0001**	5.3300	**< 0.0001**
Task orientation	0.8576*	0.2241	1.9910	**< 0.0001**	2.1320	**< 0.0001**	2.6020	**0.0080**
Team Innovation	0.9115*	0.2067	1.8830	**< 0.0001**	1.8710	**0.0010**	3.3510	**0.0010**
Vision	0.8037*	0.1831	1.7520	**< 0.0001**	1.9860	**< 0.0001**	4.6970	**< 0.0001**
Gender diversity	n/a		0.9430	0.6840	1.3260	0.0920	3.9600	**< 0.0001**
Race diversity	n/a		1.2700	0.0180	0.8230	0.7710	1.5560	0.1340
Team size	n/a		1131.7560	**< 0.0001**	55.2290	**< 0.0001**	110.3730	**< 0.0001**

* Cronbach's α values indicating good internal consistency of scale; Value in **bold** indicate sig. of grouping effects for factors at alpha level 0.05.

2.6 Hypothesis testing using Hierarchical Linear Modeling (HLM)

The data structure for this study was nested, such that a *respondent* (engineering student) is nested within a *team*, which is nested within a *design section* nested within an *engineering program of study*. Consequently, study hypotheses were tested by using a Hierarchical Linear Modeling (HLM) approach, which models the linear relationships between team input and process factors (*predictors*) and innovation based on responses from individuals (level 1) nested within teams (level 2) belonging to different design sections (level 3) and engineering programs of study (level 4). HLM was used over the traditional Ordinary Least Squares (OLS) because OLS assumes random independent errors, normally distributed data and constant variance, and results in misestimation of standard errors in multilevel/nested data in which there is dependence among individual responses within the same group. HLM, on the other hand, accommodates non-independent data, heterogeneity of variance, missing data (only at level 1), and small sample sizes [47, 48]. HLM was carried out in SAS 9.3 using the PROC MIXED procedure. Equations 1, 2 and 3 show mathematical representations of hierarchical linear relationships modeled in this study.

$$Y_{ijkl} = \mu_j + \alpha_j + r_{ijkl} \quad (1)$$

$$Y_{ijkl} = [\beta_{00} + \beta_{0j}\mathbf{X}_{ijkl}] + [\mu_{0j} + r_{ijkl}] \quad (2)$$

$$Y_{ijkl} = [\beta_{00} + \beta_{0j}X_{ijkl} + \beta_{10}\,(\mathbf{Z}_{ijkl})] + [\mu_{0j} + \mu_{1j}\,(\mathbf{Z}_{ijkl}) + r_{ijkl}] \quad (3)$$

Equation 1 shows the baseline model against which more complex models can be compared. Y_{ijkl} is the outcome –innovation – for individual *i* nested in team *j*, nested in design section *k*, nested in engineering program of study *l*; μ is the grand mean for team-level innovation; α_j is a series of deviations from the grand mean μ; and $\alpha_j \sim iid\ N(0, \tau_{00})$; r_{ijkl} is the random error associated with the i^{th} individual response, in the j^{th} team, in the k^{th} design section, in the l^{th} engineering program of study, and $r_{ijkl} \sim iid\ N(0, \sigma^2)$. The unconditional means model has one fixed effect, μ, and two variance components – one representing variation between team means (τ_{00}) and the other representing variation among students within teams (σ^2). The unconditional means model tests the null hypothesis that the variance components are zero.

Equation 2 shows the HLM conditional means model with team-level factors. $\mathbf{X}_{ijkl}$ is a vector of team factors/predictors from the ESTI framework; β_{00} is the intercept; β_{01} represents the coefficient for each team-level predictor of innovation; μ_{0j} represents variation in intercepts between teams, and $\mu_{0j} \sim N(0, \tau_{00})$; r_{ijkl} represents variation within teams and $r_{ijkl} \sim N(0, \sigma^2)$. The conditional means model has two parts—a fixed part and random part: γ_{00} and γ_{01} represent the fixed part of the model while μ_{0j} and r_{ijkl} represent the random part of the model and are estimated based on their respective variance components, τ_{00} and σ^2. The conditional means model tests the null hypothesis that there is no linear relationship between innovation and team-level predictor variables (team input and process factors). Finally, Equation 3 shows the conditional model including both team level and individual level predictors (also called the intercepts and slopes as outcomes model), where $\boldsymbol{Z}_{ijkl}$ is a vector of individual-level predictors for team innovation in the TI model, β_{10} is the slope (intercept) for individual level predictors of team innovation, and μ_{1j} is the random effect for the slope. The next section describes the study results.

3. Discussion

3.1 Hypothesis test results

The baseline/null (unconditional means) model shows the grand average for *innovation* across all teams, μ, is 4.76, with a standard error of 0.07 (Table 6); the team-level variance, τ, is 0.02 and the individual/student-level variance in innovation, σ^2, is 0.29 (Table 7). The model fit statistics for the null model are AIC = 1155, BIC = 1178, and Chi-Square = –1145 which serve as a baseline against which the other models are compared for assessing model fit (Table 7).

The conditional means model shows there is a statistically significant positive relationship between *Innovation* and *Team size*, *Learning*, *Rewards*, *Task orientation*, *Cohesion*, *Leadership*, *Communication*, and *Effort* at an alpha level of 0.05 (Table 6). There is a statistically significant negative relationship between *Innovation* and *Support for innovation*, *Conflict*, and *Participative safety*. Consequently, we reject the null hypothesis that there is no linear relationship between innovation and these predictor variables. On the other hand, *Social network*, *Job relevant diversity*, and *Vision* have positive but statistically insignificant relationships with *innovation* (Team 6). Thus, we fail to reject the null hypothesis in these cases. The conditional variance components – conditioned on team-level predictors, are: the residual, $\sigma^2 = 0.072$, which is less than that for the null/unconditional model of 0.29; and the variation in teams, τ = 0.0061, which has reduced from 0.02 in the unconditional means model case (Table 7). The reduction in the tau variance component is computed as (0.0222 - 0.0062)/0.0222 which yields 0.7207 or approximately 72% [35]. The model fit statistics for the conditional means model are AIC = 274, BIC = 360 and Chi-Square, χ^2 = –236 (Table 7), which yields a 76%, 69% and 79% reduction compared to the fit statistics for the unconditional means model.

The conditional means models with both individual and team level factors (intercepts and slopes as outcomes model) show there is no significant relationships between *Innovatio*n and *Background diversity* (*Racial diversity* and *Gender diversity*), which are individual-level attributes. The fit statistics are AIC = 296, BIC = 396 and Chi-Square, χ^2 –252, yielding an 8%, 10% and 7% increase, respectively, in comparison to the fit statistics for the conditional means model (Table 7). This implies the model fit is slightly worse when individual level variables related to students' backgrounds are added into the model. The observed variance components are a random individual level effect (residual), σ^2 = 0.0725, and a random effect for variance across teams, τ = 0.0062 (Table 7). This suggests a reduction in the tau variance component of 0.72 or approximately 72% over the null (unconditional means) model, computed as (0.0222–0.0062)/0.0222), a decrease of 0% in comparison to the conditional means model. Thus, the conditional

Table 6. HLM results for null, conditional means, and intercepts and slopes as outcomes (ISO) models

Model	Fixed Effect	Coefficient, βp	Std. Error	t-value	p-value
Null	Average Team Innovation	4.7597	0.0713		<0.0001**
Team Level (Conditional Means)	Intercept, β_{00}	4.5415	0.0660	68.863	<0.0001**
	Learning	0.2659	0.0371	7.1614	<0.0001**
	Rewards	0.1254	0.0243	5.1594	<0.0001**
	Task orientation	0.2641	0.0488	5.4127	<0.0001**
	Team size	0.0533	0.0134	3.9848	0.0001**
	Cohesion	0.1367	0.0373	3.6636	0.0003**
	Support for innovation	–0.0757	0.0221	–3.431	0.0006**
	Leadership	0.0516	0.0194	2.6603	0.0080**
	Conflict	–0.0416	0.0191	–2.178	0.0298*
	Communication	0.0872	0.0410	2.1283	0.0337*
	Effort	0.0535	0.0263	2.0353	0.0422*
	Participative safety	–0.0346	0.0179	–1.9330	0.0537‡
	Social network	0.0400	0.0915	0.4373	0.6621
	Job relevant diversity	0.0082	0.0266	0.3082	0.7580
	Vision	0.0043	0.0283	0.1521	0.8792
Ind. Level (ISO)	Race diversity	0.0107	0.0091	1.1694	0.2427
	Gender diversity	0.0006	0.0299	0.0198	0.9842

** sig. at an alpha level <0.01; *sig. at an alpha level <0.05; ‡ marginal sig. at an alpha level <0.10.

Table 7. HLM variance components and model fit results

	Null Model	Conditional Means Model	Intercepts and Slopes as Outcomes Model
Random Effect/Variance Component			
Team Level-2 effect, τ	0.0222	0.0062	0.0062
Individual Level-1 effect, σ^2	0.2898	0.0724	0.0725
Model Fit Statistics			
Chi-Square, χ^2	–1145.4984	–235.6826	–252.0628
AIC	1155.498	273.6827	296.0628
BIC	1178.275	359.8523	395.7421

means model is adopted as the final model with the best fit for the study population.

3.2 Examination of findings

Statistically significant relationships in the hypothesized directions in section 1.1 were observed between *Innovation* and *Leadership*, *Rewards*, *Team size*, *Communication*, *Task orientation*, *Conflict*, *Effort*, *Learning*, and *Cohesion* in engineering student teams. However, significant relationships in the opposite directions of the hypothesized relationships were observed for *Support for innovation* and *Participative safety*. Meanwhile, no significant relationships were observed for *Job relevant diversity*, *Background diversity*, *Vision*, and *Social network*. Further discussion of these unexpected results is provided below.

Although supportive environments are reported to encourage risk taking and attempts to innovate [38], the findings of this study show the opposite. This indicates *Support for innovation* may be different in the workplace in comparison to the classroom setting. One plausible explanation is there may exist a student—instructor dynamic that is detrimental to innovation in the classroom setting. For example, instructors may be too involved in the design process as they lead and guide student design teams, which inadvertently hinders students' ability to innovate. In addition, some design courses may be overly restrictive in assignment guidelines, not allowing leeway for students to be creative. For example, students may be given detailed procedures to follow in carrying out and reporting on experiments and simulations in a Chemical Engineering design course, and Civil Engineering students are required to adhere to a strict code of building and construction.

Findings for *Participative safety* are also contradictory to previous research as they indicate the less safe individuals feel to communicate their ideas and opinions, the more innovation occurs. This is the most counter-intuitive finding of the study and warrants further research to see if it can be replicated in additional studies, and, if so, to understand the mechanisms underlying this relationship. One potential explanation is *Participative safety* may be highly correlated with *Background diversity* at the team-level. While *Racial diversity* and *Gender diversity* were only considered at the individual level in this research (and did not have significant effects), when considered at the team-level (e.g., using a diversity index) they might be linked to both lower *Participative safety* and higher innovation. That is, the positive effects of team-level *Background diversity* might outweigh the negative effects of reduced *Participative safety*.

The negative and statistically significant effect observed for *Conflict* and innovation suggests interpersonal *Relationship conflicts* are more prevalent than task-related conflicts in engineering student design teams. Furthermore, considering engineering student design teams consist of novices, and Vygotsky's [49] social development theory specifies cognitive development is limited to a certain range at a given age, it is also possible the students may not yet possess the capability necessary to cultivate benefits from *Task conflict*

The non-significance of *Job relevant diversity* as a predictor of innovation, despite previous findings that diversity exposes the team to a variety of different perspectives and approaches, which stimulate creativity-related cognitive processes [50], implies engineering student teams may not be as diverse as required for this factor to have an impact. In fact, the teams investigated in this study consisted of individuals in teams from the same discipline, with little work experience (on average); thus, the levels of functional or *Job relevant diversity* across teams are low. Similarly, gender and racial backgrounds (elements of *Background diversity*) had no significant effects on *innovation*. Only a weak positive correlation was observed between innovation and *Race* and *Gender*. Moreover, the overall HLM model fit worsens when individual-level attributes are added to the HLM model; that is, no additional variation in team innovation was explained by adding individual *Background diversity* measures in the model with team-level variables. This suggests *Background diversity*, which is a non-task related form of diversity, either did not evoke cognitive resource diversity among the novices in this study [51] or acts only at the team-level as previously discussed.

The non-significance of *Vision*, despite reports it enhances chances of innovation as it contributes to self-motivation and focus of team efforts [52–54], may suggest engineering student design teams do not value setting explicit goals for project outcomes in the same way work teams do, or such goal setting is inherently less important for student projects. Similarly, *Social network* was not significantly related to innovation based on the results of the HLM analysis, although a moderate correlation was observed for the pairwise relationship between *Social network* and innovation (ρ = 0.154, p-value <0.0001). These results may suggest weaker social ties are more beneficial for innovation than stronger social ties, as proposed by the social network theory [17].

The final ESTI framework indicating significant predictors of team innovation in engineering student design teams along with their respective coefficients based on the study population is shown in Fig. 3. The linear relationship between these predictors and innovation may generally hold for similar populations, although further research is needed to confirm this.

3.3 Implications

Based on the study findings, a number of propositions are offered. Firstly, design courses and project teamwork should be encouraged as there is empirical evidence showing they provide a platform for effective *learning* that nurtures innovation. A combination of active, experiential, and cooperative learning approaches through coursework, design education, integrative learning, seminars, and interdisciplinary studies as suggested in previous educational research may be used to enhance learning [14]. *Task orientation* allows student design teams to be self-motivated and focus their efforts in one direction with a shared sense of purpose and responsibility for their project outcome. Engaging students in engineering analysis, problem-solving, detailed evaluation, and analysis of design concepts, alternatives assessment, prototyping, progress tracking, reflection, and journaling are ways of increasing cooperation.

Use of team recruiting strategies that allow students to choose their own team members may promote team *cohesiveness*, leading to greater enjoyment in working together, as well as trust, and willingness to share ideas. Instilling expectation of appropriate job placement as a *reward* for design work among engineering students, and the inclusion of motivational speaker series/sessions as part of the curriculum, may also provide opportunities to inspire students and in turn spur innovation. *Leadership* from both peers and advisors is essential for team progress towards desired outcomes. A lack of experience by peer leaders is compensated through leadership from sponsors, partners, and more experienced industry experts and business leaders. Sufficiently large *team sizes* foster innovation through the generation of more ideas, which increases chances of generating novel solutions. The average team size for this study was 4.5 students per team, while previous educational literature reports team sizes of 2 to 25 [14].

The interaction between an individual's ideas and a social context (through the medium of *communication*) is necessary in order to ascertain the novelty and usefulness of the ideas. To facilitate this process, we recommend encouraging students to: use electronic communications; conduct oral and video presentations; and participate in regular project meetings, multi-disciplinary courses, professional societies, student design competitions, speaker series, and university-wide events that enhance *internal* and *external communication*. Setting up course policies stipulating a minimum amount of *effort* (in the form of grade standards and time requirements) in team design work is suggested as a way to help to optimize the amount of time and commitment from student team members. Instructors should seek to identify instances of

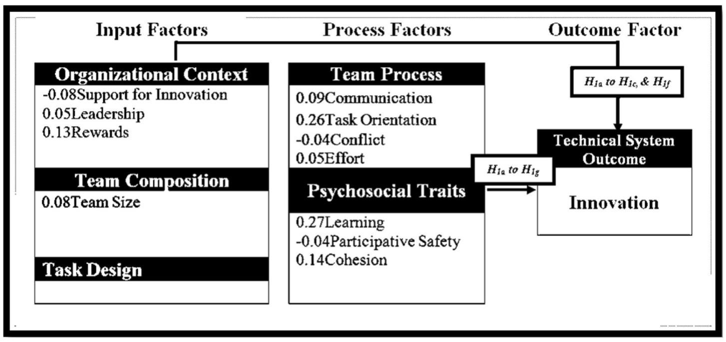

Fig. 3. Refined Engineering Student Team Innovation framework.

interpersonal *conflict(s)* within teams and implement appropriate remedial action such as reassigning members to different teams or adopting other appropriate conflict resolution approaches. A topic on how to deal with conflict can be presented to students prior to commencing teamwork in order to reduce negative effects of relationship conflicts.

To encourage *psychological safety* among student design teams, which is critical for ideation and brainstorming, instructors can engage students in team building exercises and other activities that foster an atmosphere where students feel empowered to express their views. Instructors, advisors, industry partners, and sponsors should support ideas generated by students, and serve as advisors and facilitators of the students' own creative design process, with as few restrictions as possible (endeavoring to shift away from recipe-type design guidelines that may stifle creativity). *Support for innovation* also includes providing state of the art facilities and engaging students in entrepreneurial activities such as company formation.

Study findings have implications for focused improvements on engineering design and innovation curricula or introduction of more content in engineering degree programs so as to strategically harness skills for teamwork and innovation among graduating engineers. The study suggests that graduating engineers may have limited exposure to certain skills and attributes that support teamwork and innovation, such as *Social networking* and *Job relevant diversity*. In addition, organizations can develop training for new hires in these areas as part of their recruiting and training programs for new engineering graduates. On the other hand, findings from this study also suggest many of the skills that promote innovation in organizational work teams are already instilled in engineering student teams.

Finally, the ESTI survey and framework developed in this research could be useful to other educators and researchers for measuring engineering student teamwork and innovation abilities. The authors used factor analysis, reliability analysis, and tests for aggregation to validate the ESTI survey.

4. Conclusions

This research was designed as a cross-sectional field survey in order to empirically test factors proposed in the engineering student team innovation framework and identify key determinants of innovation. Measures for factors were operationalized using a 75-item questionnaire developed from pre-existing and new survey scales. Study respondents belonged to 210 design teams across nine engineering programs within a college of engineering at an ABET accredited four-year institution. Strong internal consistency and reliability of the survey scales based on 709 responses was observed. In addition, aggregation indices for individual responses were acceptable suggesting sufficiently homogeneous unique teams, implying that survey responses appropriately captured team constructs evaluated in the study. A final validated survey scale consisting of 59-items was then used to test the study hypotheses. Based on the hypothesis test results, we reject the null hypotheses and conclude that leadership, support for innovation, rewards, team size, communication, task orientation, effort, learning, cohesion, conflict and participative safety are key determinants of innovation at the team level. These team inputs and processes can be enhanced (for positive predictors) or regulated (for negative predictors) through focused improvements on engineering design and innovation curricula so as to strategically harness skills for teamwork and innovation among engineering graduates. The tools, methods and survey instruments developed in this study are useful to researchers, educators, and practitioners. Study findings also have implications for organizations for recruitment and training of new engineering hires.

The limitations of this study are those common to survey research, such as the potential for response bias and difficulty in proving causality. To the best of our ability, these were addressed through data screening and support from literature, respectively. Another limitation is several individual-level attributes that might influence team-level innovation, such as individual learning styles and personality traits, were not investigated within the scope of this study due to the focus on team-level determinants. Future research should further validate the ESTI survey and framework in additional study populations, take a closer look at factors with unexpected findings in this study, further translate findings into practical enhancements for engineering design curricula, and investigate the role of individual-level attributes in promoting individual and team-level innovation.

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Appendix 1

ESTI Survey Items and Sources of Measures

Factor	Initial Item measures	Scale / Source of measures
Support for Innovation (SI)	SI1: "Our instructor and/or mentors valued the contributions of our team to our project." SI2: "Our instructor/mentor offered ideas for improving our project." SI3: "Our instructor was readily available for consultation during our project." SI4: "Our team had access to state-of-the art facilities and equipment during our project."	Item 1 was adapted from the top management support and recognition scale by Scott [55]. Items 2 and 4 were developed by the researcher based on the definitions of the construct. Item 3 was adapted from measures for team leader coaching by Edmondson [56].
Leadership (LD)	LD1: "Our team leader kept an eye on how our project was progressing." LD2: "Our team leader consulted with other members of our team for ideas and advice for our project."	Adapted from measures for team leader coaching by Edmondson [56].
Rewards (RW)	RW1: "Our team expected to benefit a lot if our project was successful." RW2: "It was clear how our team's performance would be evaluated." RW3: "Our team expected to gain other opportunities after the project work."	Item 1 was adapted from the rewards measure developed by Susman & Ray [57]. Items 2 & 3 were adapted from the rewards scale by Liu [58], who developed these items based on Barczak & Wilemon [59].
Vision (VS)	VS1: "Our team had clearly defined goals." VS2: "Our team goals clearly defined what was expected of our team." VS3: "It was clear as to what was expected of each team member."	Based on the scale for goal clarity by Wilson, Van Aken & Frazier [60].
Job relevant diversity (JD)	JD1: "Each of our team members had knowledge relevant to our project." JD2: "Each of our team members made unique contributions to our project." JD3: "No one on our team lacked the special skills needed for good team work."	Items 1 and 2 are based on the transactive memory system scale developed by Akgun, Byrne, Keskin, Lynn, & Imamoglu [61]. Item 3 was adapted from Edmondson [56] measures for team composition.

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Communication – internal and external (CI & CE)	CI1: "Our team members conducted formal communications through team meetings." CI2: "Project-relevant information was shared openly by all team members." CI3: "Our team members were satisfied with the timeliness in which they received information from other team members." CI4: "Our team members were satisfied with the quality of the information received from other team members." CE1: "Our team interacted with people from outside our team when generating ideas for our project?'	Items 1 to 4 are based on Hoegl & Gemuenden [62] measures for internal communication. Item 5 was adapted from Andrews & Smith [63] measures for interaction with others.
Task orientation (TO)	TO1: "Our team members helped each other as best as they could." TO2: "If conflicts came up, they were quickly resolved." TO3: "Team discussions were conducted constructively." TO4: "Our team was able to reach consensus regarding important issues."	Based on Hoegl & Gemuenden [62] measures for mutual support.
Conflict—Task conflict (TC) and Relationship conflict (RC)	TC1: "Our team had problems coordinating our efforts." TC2: "There were conflicts within our team regarding subtasks." RC1: "In our team, there were conflicts regarding the information flow between team members."	Item 1 is based on the scale of inter-team coordination developed by Mott [64]. Item 2 is based on the cooperation scale developed by Hoegl and Gemuenden [62]. Item 3 is based on the communication scale developed by Hoegl and Gemuenden [62].
Effort (EF)	EF1: "Our team put a lot of effort into the project." EF2: "Our team put a lot of time into the project." EF3: "Every team member fulfilled their commitments to our project." EF4: "Every team member made the project a high enough priority."	Items 1, 2, 3 were adapted from Hoegl & Gemuenden [62] measures for effort. Item 4 was adapted from Edmondson [56] measures for team efficacy.
Learning (LN)	LN1: "We regularly took time to figure out ways to improve our team's work processes." LN2: "In our team, someone always made sure that we stopped to reflect on the team's work process." LN3: "Suggestions and contributions of team members were discussed and further developed." LN4: "Our team members were challenged by the work which we did on our project." LN5: "Our team members acquired new knowledge from our project." LN6: "Our team members developed new skills from our project." LN7: "Our team members will be able to do a better job on future projects because of our project"	Items 1 to 3 were adapted from Edmondson [56] measures for team learning behavior. Items 4 to 7 were adapted from Liu [58] measures for team learning.
Participative safety (PS)	PS1: "If one made a mistake on our team, it was held against him/her" (R). PS2: "In our team, no one was afraid to bring up problems and tough issues." PS3: "People on our team sometimes rejected others for being different." (R). PS4: "On our team no one deliberately acted in a way that undermined other member's team efforts."	Based on Edmondson [56] measures for team psychological safety

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Cohesion (CH)	CH1: "It was important to the members of our team to be part of this project." CH2: "Our team members were strongly attached to this project." CH3: "Each of our team members enjoyed interacting with other members of our team." CH4: "Our team was a close group." CH5: "The members of our team felt proud to be part of the team."	Based on Hoegl & Gemuenden [62] measures for cohesion.
Social network (SN)	SN1: "Not including yourself, how many of your team members did you know before starting your project?" SN2: "If you knew any of your teammates previously, how many would you have considered a friend before your project started?" SN3: "How often did you get together for non-academic purposes with any of your teammates?"	Based on measures for team social network analysis by Williams [65].
Innovation (IN)—Team level	IN1: "Our teammates generated creative ideas during our project." IN2: "Our teammates promoted new ideas to others." IN3: "Our teammates sought out new technologies, processes, techniques, and/or product ideas." IN4: "Our teammates came up with an innovative product design or process design." IN5: "Our teammates developed adequate plans and schedules for the implementation of new ideas." IN6: "Our skills and abilities to innovate increased as a result of our teamwork." IN7: "Our team was innovative."	Items 1, 2, 3, 5, 7 were adapted from Scott & Bruce [66] supervisor rating for innovative behavior based on Kanter [67]. Item 4 was adapted from Axtell et al., [68] and Borrill et al., [69] measure of suggestions and implementations for a peer review instrument. Item 6 was developed by the researcher based on the definitions of the construct.

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