

# A Review of Team Effectiveness Models and Possible Instruments for Measuring Design-Team Inputs, Processes, and Outputs\*

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Good teamwork is essential to successfully complete team-based design projects. As such, engineering students are expected to learn how to work collaboratively. While team-project-based design courses have been implemented in almost all engineering and engineering technology disciplines, achieving full contribution by all team members has been a persistent challenge. In this paper, we review instruments for measuring design-team factors (i.e., inputs, processes, and outputs) that may be used for collecting data for forming effective and collaborative design teams. To guide the literature review, we first review existing team-effectiveness models. Next, we propose a new model for student design teams and illustrate possible associations between design-team factors. We then review instruments for measuring these factors using the new model as a literature-review framework.

**Keywords:** design teams; team formation; team effectiveness

## 1. Introduction

In new product development, teams are responsible for designing and developing innovative products. Collaboration and good teamwork are essential to successfully complete design projects [1, 2]. As such, engineering students are expected to learn how to design and work effectively in teams [3]. Team-project-based design courses have been implemented in almost all engineering disciplines [4–8]. However, achieving full contribution by all members has been a persistent challenge in design [9] and other engineering disciplines [10, 11]. Students often have trouble working as part of a team [12] due to issues such as social loafing [13] or free riding [14]. In one survey across multiple disciplines, including engineering, approximately one-third (32%) of the students surveyed experienced poor or very poor group work, and 27% of these students were unsatisfied with their teams and the division of tasks among their team members [12]. Significant numbers of engineering students will have poor experiences in team projects considering that more than 100,000 engineering and engineering technology bachelor's degrees are awarded in U.S. institutions each year [15].

While various individual and team characteristics are considered important in forming effective teams [16], guidelines on how to form effective and collaborative design teams have not yet reached a consensus. Team-forming approaches have been

classified into three categories [17, 18]: instructors randomly assign teams, students form their own teams, and instructors assign teams based on some criteria. Most team-forming approaches have focused on grouping students based on some criteria. These criteria have been used to either diversify, homogenize, or both diversify and homogenize characteristics of students within a team. Criteria to diversify student characteristics include GPAs, grades or knowledge in disciplines [19–23], skills (including computer-aided design software) [20–25], gender [26–28], personality types [22, 29, 30], disciplines [27, 28], cultural heritage [28], students' potential roles in the group [31], left- vs. right-brain thinking [21], and comfort zones [21]. Criteria to homogenize student characteristics include grouping students with the same degree program, gender, or conversational style [32]. Criteria to mix students' characteristics include diversifying GPAs [33] or skills [34] and homogenizing disciplines [33] or student characteristics [34]. In addition to these criteria, the effectiveness of a team may also depend on team or team member characteristics, such as a high need for cognition, task difficulty, group size, team cohesiveness, performance, and clarity of individual contribution [16]. Kolb's learning styles [35, 36] have also been studied. However, guidelines to use learning styles have not yet been proposed, as the sample sizes of the associated studies were relatively small [20] or since most students were biased toward a converging learning

style [27]. If students in a course know one another well, algorithms to match students' preferences about team members may be used [18].

Team effectiveness theory has been recently investigated to improve teamwork in engineering student projects [37–39]. However, this theory has not been fully incorporated into forming design teams. Furthermore, while peer evaluation has been widely used as a feedback mechanism to improve teamwork [40–44], it cannot be used as a mechanism to form teams before a project starts. In this paper, we review instruments for measuring design-team factors (i.e., inputs, processes, and outputs) that may be used for forming effective and collaborative teams. To guide the literature review, we first review team-effectiveness models and propose a new model that illustrates possible associations among design-team factors (i.e., inputs, processes, and outputs). We then review instruments for measuring the factors of the new model. The remainder of this paper is organized as follows. Section 2 reviews team-effectiveness models. Section 3 proposes a new model that outlines possible associations between design-team factors (inputs, processes, and outputs). Section 4 reviews instruments for measuring those factors. Section 5 concludes this paper with a brief discussion for future research.

## 2. Team effectiveness models

McGrath [45] proposed a framework to study groups, as illustrated in Fig. 1, which showed logical relationships between three inputs, a group process, and three outputs. The three inputs were group composition, group structure, and 'task and environment.' Group composition was described by levels, homogeneity/similarity, or compatibility of members' characteristics such as abilities, attitudes, backgrounds, and personalities. Group structure included members' positions, roles, powers, communications, and friendships or affect patterns. 'Task and environment' consisted of task types, reward conditions, and environmental stresses. Group composition influenced group structure and group structure and 'task and environment' both impacted group process, which described interactions among members.

The three outputs were task performance, group development, and effects on members. Task performance represented quality and quantity of performance as well as the changes of the group's relation to the environment. Group development was comprised of the development of norms and changes in role patterns. Effects on group members consisted of changes in skills and attitudes in addition to the effects on individual adjustment. The input-process-output cycle repeated as shown by the outputs

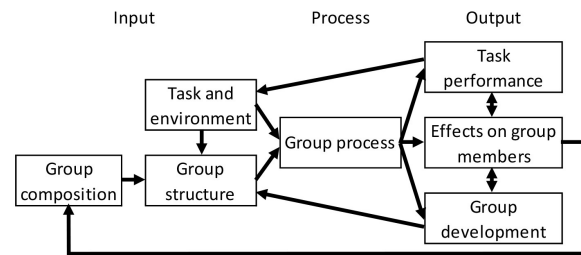
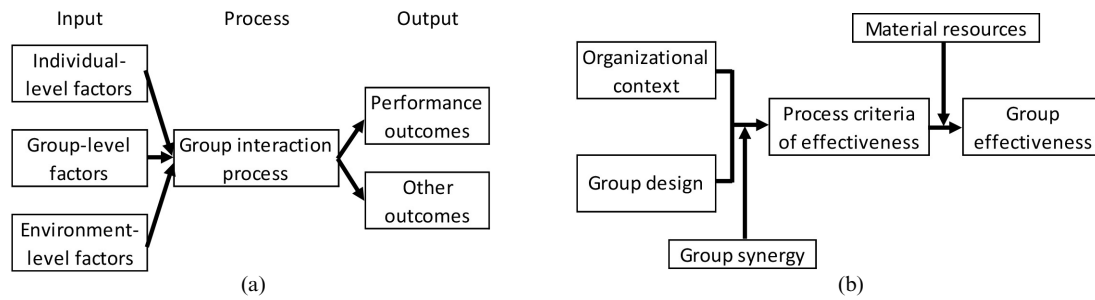


Fig. 1. McGrath's input-process-output framework (adapted from [45]).

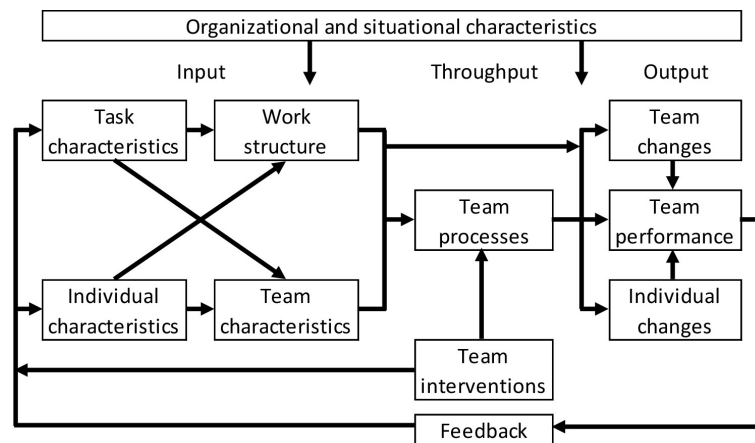
influencing the corresponding inputs in the next cycle.

Hackman [46] summarized McGrath's framework with three inputs and two outputs, as illustrated in Fig. 2(a). The three inputs were individual-level factors such as members' skills, attitudes, and personalities; group-level factors such as structures, levels of cohesiveness, and group size; and environment-level factors such as task characteristics, reward structures, and environmental stresses. The two outputs were performance outcomes, such as performance quality, speed of solution, and the number of errors; and other outcomes, such as members' satisfaction, group cohesiveness, attitude changes, and sociometric structures. Hackman [46] then proposed a normative group-effectiveness model (see Fig. 2(b)) that illustrated the three factors that foster group effectiveness. These three factors were organizational context, such as reward systems, education systems, and information systems; group design, such as task structures, group compositions, and group norms; and group synergy that described supports to reduce process losses and create process gains. The process effectiveness was evaluated based on the level of effort spent on the task, the amount of knowledge and skills used for the task, and the appropriateness of strategies used by the group. This model also highlighted the importance of material resources for successfully performing the task. Even if members were willing to invest significant effort, the team could not perform well if raw materials, tools, equipment, space, funds, and human resources were not provided. Group effectiveness was evaluated by task outputs, members' capabilities to work together in the future, and the degree that members' needs were satisfied.

Tannenbaum, et al. [47] proposed a team-effectiveness model, as illustrated in Fig. 3, which distinguished inputs into task characteristics, work structure, team member individual characteristics, and team characteristics. Task characteristics involved task organizations, task types, and task complexity. Work structure included work assignments, team norms, and communication structures.



**Fig. 2.** Hackman's normative group-effectiveness model (adapted from [46]). (a) Input-process-output framework (b) Normative group-effectiveness model.

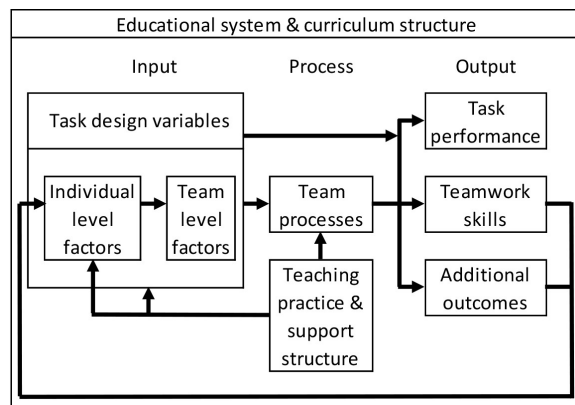


**Fig. 3.** Tannenbaum, et al.'s team-effectiveness model (adapted from [47]).

Individual characteristics consisted of knowledge, skills, and abilities related to the task, general abilities, motivations, attitudes, personalities, and mental models. Team characteristics included power distributions, homogeneity of members, team resources, team climates, and team cohesiveness. Furthermore, Tannenbaum, et al. [47] illustrated that team interventions such as training and team building impacted team processes and eventually team performance. A feedback loop was included to illustrate that team outputs have

long-term effects on processes and performance manifested in future team tasks.

More recently, based on Tannenbaum, et al.'s model [47], Tucker, et al. [38] suggested a framework and 22 factors, as shown in Fig. 4, which described the effectiveness of design teams in the context of teaching teamwork in design education. Task design variables included task structure, task description, team size, and task assessment criteria. Individual-level and team-level factors were similar to those in Tannenbaum, et al. [47]. Individual-level factors included knowledge, skills, learning styles, personalities, attitudes, and motivations. Team-level factors included leadership, roles, team contracts, team climates, team compositions, and team cohesion. Team processes consisted of coordination, communication, idea evaluation, decision-making, and conflict management skills. However, instruments for measuring these factors and associations among them have not yet been investigated [38].



**Fig. 4.** Tucker, et al.'s framework of effectiveness in student design teams (adapted from [38]).

### 3. A design team effectiveness model

Building on the model proposed by Tannenbaum, et al. [47], we propose the design-team-effectiveness model in Fig. 5 and use it as a framework to review instruments for measuring design-team inputs, pro-

cesses, and outputs. The proposed model illustrates possible associations between inputs, processes, and outputs. In particular, design-team processes are modeled as a composition of team member collaboration and design process. In brief, the model shows that given characteristics of an individual and a design problem that defines task characteristics, forming design teams will impact work structure and team characteristics. In turn, the work structure and team characteristics will impact team member collaboration and design process. Finally, team member collaboration and design process will impact team performance. Note that there may be both direct and indirect effects of work structure and team characteristics on team performance. Associations between inputs, processes, and outputs are shown by nine arrows ①–⑨ in Fig. 5.

*Work structure and team member collaboration, arrow ①:* Work structures, such as communication or assigning fixed roles to members, influence how work is performed [47]. Forming a team with members who have similar preferences on the work structure is expected to improve team member collaboration.

*Team characteristics and team member collaboration, arrow ②:* Team characteristics are composed from individual characteristics. Team members must be similar enough to work collaboratively. Thus, teams with homogenized or improved individual characteristics are expected to improve team member collaboration.

*Team characteristics and design process, arrow ③:* Design outcomes depend on ideation of design solutions [48, 49], prototyping of design ideas [50, 51], and the semantic coherence of members' design documents [52]. One of the goals of the ideation process is to generate as many ideas as possible without evaluating their quality [53]. The number of concept sketches has been shown to have a positive association with design outcomes [54, 55]. Empirically, it is argued that the more prototypes the design team generates, the more successful the

final products are [50, 51]. While similar team members are expected to work collaboratively and improve the design process, a team also must have diverse characteristics to improve design outcomes. For example, Wilde [30] proposed that assembling design teams with members who have different strengths in their cognitive modes improves the creativity of the team and leads to better design outcomes. Similarly, members need diverse expertise in order to complete the required tasks [46]. Thus, a team may require an optimum balance between homogeneous and heterogeneous team characteristics; i.e., design process outputs may improve if a set of individual characteristics is homogenized or improved within a team and if another set is diversified within a team.

*Intermediate evaluation and team member collaboration, arrow ④:* Team intervention improves member collaboration and reduces process loss, e.g., social loafing [46, 47]. Providing intermediate evaluations, e.g., mid-project grades and peer evaluations, is expected to improve team member collaboration.

*Team member collaboration and design process, arrow ⑤:* Collaboration among members and good teamwork are essential to successfully complete design projects [1, 2]. Thus, improving member collaboration will most likely improve the design process.

The remaining arrows ⑥–⑨ in Fig. 5 indicate associations between design-team inputs and outputs or between processes and outputs.

Team member collaboration, arrow ⑥, *design process, arrow ⑦, or work structure, arrow ⑧, and team performance:* Improved team member collaboration, improved design process, or assembling a team with members who have similar preferences on work structure is expected to improve team performance (outputs).

*Team characteristics and team performance, arrow ⑨:* Each team may need to have an optimum balance of homogeneity and diversity [46]. Thus, for

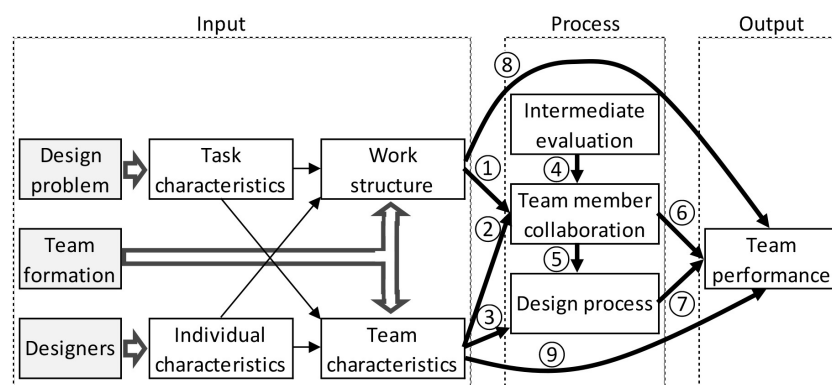


Fig. 5. Design-team-effectiveness model.

achieving higher performance, there may be a set of individual characteristics that need to be homogenized or improved within a team and another set that need to be diversified.

#### 4. Instruments for measuring design-team inputs, processes, and outputs

The following subsection reviews instruments and methodologies that may be used when we measure the design-team factors in Fig. 5.

##### 4.1 Task characteristics

Task characteristics include type and complexity of design tasks.

*Type:* The type of design task may be described by the innovativeness of design projects. While there are no physical products at the beginning, the level of innovativeness may be assessed from the project description by using 15 items of the Creativity Product Semantic Scale (CPSS) for novelty evaluation [56] or the 10-item *Technology Instrument* [57]. Each CPSS item consists of a 7-point scale. The first set of five items are used to calculate the Original subscale; the second five items are used to calculate the Surprising subscale, and the last five items are used to calculate the Germinal subscale of the CPSS Novelty dimension [56]. The *Technology Instrument* consists of two subscales. Five items of the Exceptions subscale are used for evaluating uniqueness of a task and five items of the Analyzability subscale are used for evaluating a lack of routine procedure for analyzing the task [57].

*Complexity:* The complexity of a design task may be assessed by (1) the complexity of the design requirements using the five items in the Complexity subscale of the CPSS Elaboration and Synthesis dimension [56] or (2) the number of disciplines, such as mechanical, electrical, and software engineering, required in the design project.

##### 4.2 Individual characteristics

Individual members may have a different preference for work structure that includes task assignments, behavioral norms, and communication structure [47]. As examples, for task assignment, some members may prefer to divide work, assign each part to one member, and then compile it together; whereas others may prefer that everyone work each part together. For norms, some members may prefer assigning roles such as leader or scribe, and then keep the same roles throughout the project; whereas others may prefer rotating the roles. For communication, some members may prefer face-to-face meetings; whereas others may prefer email communication. In addition to the preference for work structure, individual characteristics include knowl-

edge, skills, abilities, motivation, attitudes, personalities, and mental models of the members [47]. Any activities outside the design project may limit the time that each member spends on the project and impact team member collaboration and performance [58].

*Knowledge, skills, and abilities:* Teams with higher knowledge, skills, and abilities are expected to perform better [47]. Knowledge may be measured by the number of design-relevant courses taken and course grades. Skills may be measured by self-reported proficiency in discipline-related skills, such as fabrication machines, tools, computer-aided design software, and programming codes. Abilities may be measured using the *Wonderlic Personnel Test* [59], *Multiple Intelligence Profiling Questionnaire III* (MIPQ III) [60], or *Sternberg Triarchic Abilities Test* (STAT) [61].

*Motivation:* Motivation in a design project may be measured by adapting the *Academic Motivation Scale* [62], *Achievement Motivation Inventory* (AMI) [63], or *Work Engagement Profile* [64] to the context of design courses.

*Attitude:* Team members' attitudes towards group work impact collaboration and eventually team performance. Attitudes towards group work may be measured by seven items relevant to preference for group work as stated in Shaw et al. [65].

*Personality:* Personalities of members' impact both outputs [66, 67] and creativity [30, 68–71]. The big five personality traits (extraversion, emotional stability, agreeableness, conscientiousness, and openness to experience) have been shown to relate to team outputs [66, 67]. Increasing the variety of strong cognitive modes among members has been claimed to improve the creativity of the design team [30, 68–71]. Personality traits may be measured using the *International Personality Item Pool* [72], *Myers-Briggs Type Indicator (MBTI)* [73], or *Jackson Personality Inventory-Revised (JPI-R)* [74]. Cognitive modes are calculated by using the survey proposed by Wilde [30].

In addition to personality traits and cognitive modes, Table 1 lists other personalities that may impact design-team outputs [75, 76] and instruments for measuring these personalities [30, 36, 72–74, 77–107]. For example, teams that consist of members who have high empathy to others tend to perform better [108]. Other interpersonal skills such as emotional intelligence, interpersonal value, and propensity to connect with others may also impact collaboration and design outcomes. Empathy may be measured by the *Reading the Mind in the Eyes* test [77]. Emotional intelligence is about understanding one's own feelings and those of others [78] and may be measured using the *Work Profile Questionnaire-Emotional Intelligence* (WPQei) [78]. Interpersonal

value describes one's relationships with others [79]. It may be measured using the *Survey of Interpersonal Value* [79]. Propensity to connect with others may be measured using the *Propensity to Connect with Others* (PCO) scale [80].

Team member collaboration and performance may also depend on members' risk of and reaction to social loafing. A member may *a priori* decide not to contribute to the team project and cause social loafing [13] or free riding [14]. Then, if one member does not contribute to the team project, others who initially contribute may *posteriori* decide to stop contributing to the project which is called the sucker effect [109, 110] or decide to continue contributing to the project which is termed social compensation [111]. The tendency to cause social loafing may be measured by items proposed by Schippers [81] adapted from George [112]. The sucker effect may be measured by an instrumental factor, ethical factor, and equity factor as discussed in Abele and Diehl [82]; these three factors are constructed using items in the *Protestant Work Ethic Scale* [113] and the *Australian Work Ethic Scale* [114]. Social compensation may be measured by conscientiousness and agreeableness [81] using the *International Personality Item Pool* [72], or the *Interpersonal Trust Scale* [83].

Teams with high levels of creativity, entrepreneurship, and innovativeness may create innovative design projects. Creativity may be measured using various approaches which include word-based instruments such as the *Remote Associates Test* (RAT) [84] and *Thinking Creatively with Words* (Verbal TTCT) [85] or drawing-based instruments such as the *Creative Engineering Design Assessment* (CEDA) [86], the *Test for Creative Thinking—Drawing Production* (TCT-DP) [87], or *Thinking Creatively with Pictures* (Figural TTCT) [85]. Entrepreneurship may be measured with the *Entrepreneurial Behavior Inventory* [88], *Entrepreneurial Self-efficacy* (ESE) [89], *Individual Entrepreneurial Orientation* (IEO) [90], *General Enterprising Tendency* [91], or *Entrepreneurial Orientation* (EO) [92]. Innovativeness is typically measured using the *Kirton Adaption-Innovation Inventory* (KAI) [93].

Leadership and proactiveness of members may lead to a higher chance of project success. These characteristics may be measured using the *Multi-factor Leadership Questionnaire* (MLQ) [94] and *Proactive Personality Scales* [95].

Critical thinking and the need for cognition may relate to a team member's ability to comprehend tasks. This may increase the chance of delivering successful design projects. Critical thinking may be measured using the *California Critical Thinking Disposition Inventory* (CCTDI) [96] or the *California Measure of Mental Motivation* (CM3) [97]. The

need for cognition is the tendency to engage in cognitive effort, which may represent the ability to perform difficult tasks [115]. The need for cognition may be measured using the *Need for Cognition Scale* [98].

Design is an open-ended process that lacks guaranteed steps to achieve goals and involves a large degree of uncertainty about outcomes. Thus, a team member's need for clarity, tolerance for ambiguity, and tolerance for uncertainty may impact design outcomes. The need for clarity is the need for clear instructions to do a task [99, 116]. It may be measured using the *Need for Clarity Index* [99]. The tolerance for ambiguity may be measured using the *Scale of Tolerance-Intolerance of Ambiguity* [100] and the tolerance for uncertainty may be measured using the *Intolerance of Uncertainty Scale* [101].

Conation and locus of control may relate to how designers react to their own feelings and surroundings. Conation describes how people act on their thoughts and feelings [102]. Conation may be measured using the *Kolbe Conative Index* [102]. Locus of control describes how people perceive outcomes of events as either something over which they have control (internal control) or something due to external forces in which they do not have control (external control) [103]. The locus of control may be measured using the *Internal-External Scale* (I-E scale) [103].

Curiosity and high self-esteem may improve involvement of members in projects. Curiosity may be measured using the *German Work-Related Curiosity Scale* [104] and self-esteem may be measured using the *Self-Esteem Scale* [105].

Teams that consist of members with diverse thinking and learning styles may perform better. Thinking styles describe preferred ways of using one's abilities and may be measured using the *Thinking Style Inventory* [106]. Learning styles describe preferred means for processing information [35]. Learning styles may be evaluated using the *Kolb Learning Style Inventory* [36] or *Index of Learning Styles* [107].

*Mental models:* Mental model describes how knowledge is stored and structured in meaningful patterns [117–120]. Task-based mental models (equipment and task mental models) and team-based mental models (team-interaction and team mental models) have been discussed as factors that may impact team performance [121–123]. For example, similarity and accuracy of task mental models and team mental models have been shown to have significant positive associations with team performance [121, 122, 124]. Equipment mental models describe, for example, the functioning of equipment. Task mental models describe, for exam-

**Table 1.** Personalities and instruments

Personality	Instruments
Personality traits	International Personality Item Pool [72] Myers-Briggs Type Indicator (MBTI) [73] Jackson Personality Inventory-Revised (JPI-R) [74]
Cognitive modes	Wilde's survey [30]
Empathy	Reading the Mind in the Eyes test [77]
Emotional intelligence	Work Profile Questionnaire-Emotional Intelligence (WPQei) [78]
Interpersonal value	Survey of Interpersonal Value [79]
Propensity to connect with others	Propensity to Connect with Others (PCO) [80]
Social-loafing tendency	Schippers [81]
Sucker effect	Abele and Diehl [82]
Social compensation	International Personality Item Pool [72] Interpersonal Trust Scale [83]
Creativity	Remote Associates Test (RAT) [84] Thinking Creatively with Words (Verbal TTCT) [85] Creative Engineering Design Assessment (CEDA) [86] Test for Creative Thinking - Drawing Production (TCT-DP) [87] Thinking Creatively with Pictures (Figural TTCT) [85]
Entrepreneurship	Entrepreneurial Behavior Inventory [88] Entrepreneurial Self-efficacy (ESE) [89] Individual Entrepreneurial Orientation (IEO) [90] General Enterprising Tendency [91] Entrepreneurial Orientation (EO) [92]
Innovativeness	Kirton Adaption-Innovation Inventory (KAI) [93]
Leadership	Multifactor Leadership Questionnaire (MLQ) [94]
Proactiveness	Proactive Personality Scales [95]
Critical thinking	California Critical Thinking Disposition Inventory (CCTDI) [96] California Measure of Mental Motivation (CM3) [97]
Need for cognition	Need for Cognition Scale [98]
Need for clarity	Need for Clarity Index [99]
Tolerance for ambiguity	Scale of Tolerance-Intolerance of Ambiguity [100]
Tolerance for uncertainty	Intolerance of Uncertainty Scale [101]
Conation	Kolbe Conative Index [102]
Locus of control	Internal-External Scale (I-E scale) [103]
Curiosity	German Work-Related Curiosity Scale [104]
Self esteem	Self-Esteem Scale [105]
Thinking style	Thinking Style Inventory [106]
Learning style	Kolb Learning Style Inventory [36] Index of Learning Styles [107]

ple, task procedures. Team-interaction mental models describe, for example, member roles, responsibilities, and communication modes. Team mental models describe, for example, members' knowledge, skills, abilities, and preferences [123]. Team-based mental models may be used for improving team formation because they may be measured before the design projects start. In contrast, task-based mental models may only be measured once a project starts; thus, they may not be used for team formation. Team-based mental models may be constructed by asking each member to rate relationships between attributes of team-based mental models (leadership, assertiveness, decision making, adaptability, situation awareness, and communication) [121], dimensions

of teamwork (amount of information, quality of information, coordination of action, roles, liking, team spirit, and cooperation) [122], or 14 statements describing team interaction processes and member characteristics [124]. The ratings will range between -4 (negatively related) to +4 (positively related) [121, 122] or between 1 (unrelated) to 7 (highly related) [124]. The pairwise rating of attributes is summarized in a matrix. The column and row of the matrix is a list of attributes, dimensions, or statements. Each cell of the matrix is a rating about the relationship of each pair of attributes, dimensions, or statements in the corresponding row and column. This matrix represents each student's team-based mental model if rating is performed by students.

*Resource:* Resource or time constraints on a

project may deter members from fully contributing to the team project. Members may decide not to fully contribute to the team project when they have individual projects (or individual-based courses such as physics) in addition to the team project (in a team-based course such as design) [58, 125, 126]. Surveys may be used to identify resources and time constraints; for example, the number and types of courses a student is enrolled in, whether the student is part-time or full-time, and the time the student can spend on the design course.

#### 4.3 Work structure

A homogeneous work structure enabled by assembling team members who have similar preferences on work structure is expected to improve collaboration among members. Homogeneous work structure may be measured using surveys. For example, an individual member's preferences on work structure can be gathered using a survey with a five-point scale (1: not important, 5: very important). Based on the individual's preferences, the homogeneity of the work structure among the members may be quantified by the total dissimilarity or the variance of the dissimilarity between their preferences. Dissimilarity between two members may be quantified by the pairwise Euclidean distance of their preferences. Suppose that the preference of two members on task assignments, norms, and communication structures are (5, 4, 3) and (1, 2, 5). Then the Euclidean distance between the two individuals is:

$$d = \sqrt{(5-1)^2 + (4-2)^2 + (3-5)^2} = 4.9.$$

Smaller distances indicate that two individuals have similar preferences. If there are four team members, there are six possible pairs and corresponding distances. Then, the similarity or homogeneity can be measured by a smaller total distance or a smaller variance of these six distances. A smaller sum or variance indicates that all team members have similar preferences.

#### 4.4 Team characteristics

Team characteristics may be quantified by an aggregation of individual characteristics. To work effectively, a team needs to have a good composition of team characteristics (a good balance of homogeneity and heterogeneity), cohesion, and a relatively small team size. A more homogeneous team may work well together but may lack enough diversity such that members overlap one another in many areas. In contrast, a more heterogeneous team may have enough knowledge and skills to achieve the project goals but may be too diverse and cannot acknowledge each other's varied perspectives,

which may hinder their ability to achieve their collective outcome [46]. Risk of social loafing reduces as a team is more cohesive and the team size is relatively small [16]. Team cohesion may be measured by shared mental models.

*Composition of team characteristics:* Two approaches may be used to quantify team characteristics: (1) average, maximum, minimum, and variance of members' individual characteristics [66] and (2) the number of cognitive modes [30]. The mean is most suitable for additive tasks that require the effort of all members to be successful as a team. The maximum is most suitable for disjunctive tasks that require only one member to perform well. The minimum is most suitable for conjunctive tasks that require all the members to perform beyond the lowest acceptable level. And the variance is most suitable for compensatory tasks that require diverse inputs from members [66]. In Wilde's method [30], eight cognitive modes are described as the combinations of two orientations of cognitive energy (extroversion and introversion) and two information collection functions (sensing and intuition), or two orientations of cognitive energy and two decision-making functions (thinking and feeling) [30]. Responses to 20 personality questions are used to calculate cognitive-mode scores which range between -20 and +20. Then, for each cognitive mode, members with large cognitive-mode scores are identified (i.e., strong cognitive modes). The number of strong cognitive modes among members may be used as a team characteristic [30].

*Team cohesion:* Team cohesion may be measured by (1) similarity of members' team-based mental models or (2) a survey asking the level of enjoyment working as a team. In the first approach, a matrix is generated for each member which represents his/her team-based mental model (as discussed in Section 4.2). Then, the matrices are compared between members using a network analysis program for sharedness (similarity) [121, 122]. Examples of network analysis software are Pathfinder [127] and UCINET [128]. Each node in the network is an attribute, a dimension, or a statement that describes a team-based mental model. The links between nodes illustrate relatedness between each pair of attributes, dimensions, or statements. Similarity scores are calculated as the proportion of common links between two networks in Pathfinder (after retaining only the minimum length paths between nodes), or as the correlations of relatedness ratings in two matrices in UCINET [124]. If members are more cohesive, they have similar team-based mental models and the similarity scores approach 1. While both software programs calculate different similarity scores, there is a large correlation between Pathfinder similarity scores and UCINET similarity

scores [124]. In the second approach, the level of enjoyment working as a team may be measured by a seven-point scale (1: low to 7: high) [9, 129].

*Team size:* Too small of a team may not have enough capacity to achieve project goals, whereas too large of a team may cause some members to contribute less to the team [46]. Optimum team sizes may exist for design projects.

#### 4.5 Intermediate evaluation

Intermediate evaluation may be measured by whether or not intermediate evaluation is provided (0–1 variable). If intermediate evaluation is provided, it may be measured by how teams are evaluated in the middle of the projects. Intermediate evaluation may include mid-project course grades and peer evaluations [40–44].

#### 4.6 Team member collaboration

Team members are expected to collaborate well if social loafing does not occur, if members equally contribute in the team projects [108], and if members feel safe in taking interpersonal risks [130]. The magnitude of social loafing may be measured using a peer evaluation survey [44]. Equal contributions by the members may be measured with the equal distribution of conversational turn-taking [108]. The team environment for taking interpersonal risk may be measured using the survey scale of *Team Psychological Safety* [130].

#### 4.7 Design process

Team performance depends on design-team processes such as ideation of design solutions [48, 49], prototyping of design ideas [50, 51], and the coherence of the description of design concepts in design documentation [52]. The design process may be quantified by using the following measurements.

*Ideation:* As discussed in Section 3, a goal of the ideation process is to generate as many ideas as possible without regard to their quality [53]. If there are many ideas, there is a greater chance of a good idea. The number of concept sketches have been shown to have a positive correlation to design outcomes [54, 55]. Thus, the ideation process may be measured by the number of and creativity of concept sketches generated by the design team. Creativity may be measured by using a novelty metric developed for evaluating the unusualness or unexpectedness of a design idea [131, 132]. The novelty score is calculated by first identifying key product functions for achieving design goals. Then, a score is assigned for each function based on how the product satisfies each key function in terms of novelty. Finally, the novelty score is calculated as a weighted sum of these scores and the weights of corresponding functions. Another approach is to use the 55-

item CPSS [56, 133–135] to evaluate three dimensions of creative products (Novelty, Resolution, and Elaboration and Synthesis).

*Prototyping:* Much like the ideation process, it is argued that the more prototypes there are, the more successful the final products [50, 51]. Thus, prototyping process may be measured by the number of and the creativity of prototypes generated by the design team. The creativity of prototypes may be measured using CPSS [56, 133–135].

*Design task cohesion:* One measurement of cohesion among the team members is the similarity of members' design-task mental models [136, 137]. Latent semantic analysis (LSA) is a text analysis method that has been used to show significant correlations between the semantic coherence of members' design documents and design outcomes [52]. LSA has recently been used for measuring sharedness (similarity) of mental models [138, 139] and to analyze the coherence of design activities among designers [140]. In LSA, the frequency of design-relevant keywords in each communication or design document is counted for each designer and stored as a vector. Then, these vectors are compiled in a matrix, and an orthonormal basis is found by singular value decomposition (SVD). The premise is that this orthonormal basis is a mathematical construct for the team mental model [138]. After retaining only a subset of the orthonormal basis that corresponds to large singular values of the SVD, each designer's original vector of design keyword frequencies is projected onto the selected subset of the orthonormal basis. The designer's mental model is calculated as the row average of the projected vector. The team's mental model is calculated as the row average of all members' projected vectors. The similarity of members' and team's mental models is measured by the cosine of angle between the corresponding vectors. If two mental models (vectors) are more similar, two vectors are aligned and the cosine of the angle between two vectors approaches a value of one [138].

#### 4.8 Team outcomes

Team performance consists of product performance, product creativity, and members' satisfaction working as a team (team satisfaction). Product performance and creativity may be evaluated by external evaluators and the design course instructors.

*Product performance:* Product performance may be evaluated using a seven-point scale (1: poor, 7: excellent). Another method is numerical evaluation with respect to product requirements. Indeed, the most common assessment method for product performance for capstone courses was found to be subjective assessment [141]. DeBartolo [141]

attempted to quantify the fraction of engineering requirements that were satisfied as assessed by student teams and sponsors. However, these were based on self-reported numbers and the methodologies and the response rates for both populations were different. One approach may be to use Suh's Information Axiom in Equation (1) [142]. This axiom states that the design with lowest information content is the more optimal design. The probability of satisfying a Functional Requirement (FR) can be estimated by integrating testing results that estimate mean performance and variance of the FR and coupling that information with the tolerance range of the FR. Monte Carlo simulation is another approach that can be leveraged to generate probability estimates that would be capable of not only integrating the variance information generated from testing, but also uncertainty and ambiguity information (e.g., from imprecise tolerance range information).

$$\sum_{i=1}^n I_i = \sum_{i=1}^n \log_2 \frac{1}{p_i} \quad (1)$$

$$p_i = \text{Prob}(\text{Satisfy } FR_i | \text{Design Parameter}_i)$$

**Product creativity:** Product creativity may be measured by using the novelty metric developed to evaluate unusualness or unexpectedness of an idea [131, 132] or by using the 55-item CPSS [56, 133–135], which is used for evaluating three dimensions of creative products (Novelty, Resolution, and Elaboration and Synthesis).

**Team satisfaction:** Team satisfaction may be measured by 5-point-scale questions on *work satisfaction* (three items) and *learning* (five items) [143].

## 5. Conclusions and future work

In this paper, we reviewed instruments for measuring design-team factors (i.e., inputs, processes, and outputs) that may be used for collecting data for forming effective and collaborative design teams. To guide the literature review, we first reviewed existing team-effectiveness models. Next, we proposed a new model for student design teams and illustrated possible associations between design-team factors. We then reviewed instruments for measuring design-team factors using the new model as a literature-review framework.

We reviewed papers in various fields including design, engineering education, and psychology. The review indicated that there are a wide variety of instruments that have been used for measuring individual characteristics, team characteristics, and design processes. The review further indicated that a design-team effectiveness model has recently

been proposed in the context of teaching teamwork in design education. However, associations among inputs, processes, and outputs specific to design teams have not yet been studied. We believe that research is needed to investigate which instruments are most appropriate for measuring various factors of the design-team effectiveness model and to establish a theoretical foundation that helps guide formation of design teams. Future work includes (1) measurement of inputs, processes, and outputs using surveys and instruments reviewed in this paper, (2) analysis of the associations among design-team inputs, processes, and outputs, and (3) development of guidelines to form design teams using instruments that correlate with team outputs.

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