Teamwork quality in multi-disciplinary design: extending the frontiers of design in education

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Abstract. Design is a complex activity that requires disciplinary areas to work in collaboration. However, how multi-disciplinary design teamwork affects the quality of collaborations from a social and task-related perspective, and how it can inform about extending the frontiers of design should be investigated. An empirical study comparing multi- with mono-disciplinary teams was conducted in the context of project-based education. Participants were students from two master's courses: one involving different disciplines, and the other mechanical engineering only. A series of semi-structured interviews were carried out, and the produced transcripts were analysed qualitatively. Multi-disciplinary teamwork was found to enable a comprehensive understanding of the design task. However, this requires skills and competencies different from those of mono-disciplinary teams, challenging team dynamics and collaboration. The implications for extending the frontiers of design in higher education are discussed.

Keywords: higher education in design, mono-disciplinary teamwork, multi-disciplinary teamwork, teamwork quality, teamwork in design education

1 Introduction

The merits of teamwork have captured much attention in social psychology and new product development (NPD) literature (e.g., Barczak & Wilemon, 2003). The importance of teamwork has also been extensively debated in design (e.g., Badke-Schaub et al., 2007; Casakin et al., 2015). In this domain, team composition regarding disciplinary background has gained vital significance due to the complex nature of the 21st century's global challenges (Ou et al., 2022; Gruenther et al., 2009). Today, society must tackle problems of unprecedented scope that contest established approaches and solutions. To deal with this situation, a multi-disciplinary collaboration offers a more comprehensive approach than that of teams composed of members with similar backgrounds, also known as mono-disciplinary teams.

In this context, trans-passing the traditional borders of scientific disciplines, including those of the design domain, turns out to be a crucial and necessary step. Bearing in mind the increasing complexity of design problems, such transition requires the development of dedicated skills (Blessing et al., 2021).

Hence, the attention given to this issue in design education. Among the first initiatives in this direction, design studio courses aim at fostering multi-disciplinary project collaborations (De Vere et al., 2010; Dederichs et al., 2011). Courses like these can play a fundamental role in extending the frontiers of design. Nonetheless, there is an apparent lack of appropriate educational reference practices to encourage the development of multi- and trans-disciplinary skills and competencies (Cascini, 2015).

The disciplinary composition of a team can largely affect interactions in collaborative approaches, with consequences for teamwork quality. This notion was investigated focusing on social-related and task-related aspects (Hoegl & Germunden, 2001). For example, Keating and co-workers (2013) studied the impact of multi-disciplinary team collaboration on educational outcomes, showing that the most influential issues were related to interpersonal relationships, personal expectations, as well as to team dynamics and management.

While studies about multi-disciplinary team collaboration can be found in design literature, most of them focus mainly on design performance (e.g., Nesterkin et al., 2016). Moreover, none investigated multi-disciplinary collaborations from a teamwork quality view or compared them with mono-disciplinary teams. Hence, no related studies can be found in design or in design education. Therefore, this study – which is contextualised in higher education in the framework of project-based design studio – deals with the following goals. The first goal is to identify the social- and task-related aspects of multi-disciplinary and mono-disciplinary design teamwork. The second goal is to investigate how teamwork quality from the perspective of social-related and task-related dimensions might differ when comparing multi-disciplinary with mono-disciplinary teams. Based on these, implications about how to extend the frontiers of design education are presented.

The research questions that will be addressed are:

- RQ1: What are the comparative social-related and task-related dimensions of multi-disciplinary and mono-disciplinary design teamwork?
- RQ2: How does multi-disciplinary compared to mono-disciplinary team composition influence the quality of design teamwork in terms of social-related and task-related dimensions?
- RQ3: How can an analysis of teamwork quality inform the debate about extending the frontiers of design in the context of higher education?

The work revealed that although working in multi-disciplinary teams enables a more comprehensive understanding of the design task, it requires capabilities and competencies different from those of mono-disciplinary teams, which may challenge the quality of team dynamics and collaboration. Furthermore, working in multi-disciplinary teams can result in partly underexploiting specialist knowledge and competencies. It is proposed that these issues should be taken into consideration by both educators and practitioners, as well as by those interested in extending the frontiers of design. Implications for teamwork in design education, and particularly for multi-disciplinary design studio courses, are discussed.

2 Background

Designing has become a more complex activity than it used to be, and consequently, information and knowledge other than from a single discipline are necessary to tackle problems (Gero & Milovanovic, 2022). Design practice must deal increasingly with objects at different scales, from small industrial artefacts to cities, services, and organisations (Leblanc, 2021). Hence, a broader approach of not only technological but environmental, scientific, social, and economic subjects is also necessary to cope with the new challenges that design poses nowadays (Blessing et al., 2021). Understanding and tackling such multifaceted phenomena demands more developed and interrelated knowledge, skills, and expertise.

In higher education, the increasing interconnectedness among academic disciplines and the vast knowledge originating from the application of a variety of subjects has transcended specific academic fields (Kozmetsky, 1997). Consequently, the university started to be seen as the educational environment where to nurture ideas that may go beyond the frontiers imposed by the current and rather conservative organisation of the fields (Ertas et al., 2003). Such a conception is gaining interest in design courses and is influencing design teachers to go beyond a mono-discipline educational approach to centre on domains that step ahead of traditional learning areas (Gericke et al., 2021). This is partly due to the rich knowledge needed to deal with current design tasks, even in lab environments such as the design studio. Moreover, solving new and unique design problems demands the involvement of a spectrum of disciplines working in collaboration. However, there is a substantial lack of truly multi-disciplinary design educational programs and in most cases, these are not standard programs but honours ones. As part of an integrative pedagogical approach, teamwork can help rethink how design can be taught through the different disciplines in higher education.

2.1 Multi-disciplinarity, Inter-disciplinarity and Trans-disciplinarity

Three terms are being used in reference to the type of cooperation between different disciplines: multi-disciplinarity, inter-disciplinarity, and trans-disciplinarity. In spite of their differences, they are frequently and mistakenly used interchangeably (Grieke et al., 2021). Tharp and Zalewski (2001) defined multi-disciplinarity as a topic of research shared by many disciplines. Multi-disciplinarity is also related to studying a subject in multiple disciplines simultaneously (Nicolescu, 2005). The aim is to gain a large and shared understanding of the phenomena by combining the different standpoints of the disciplines. While multi-disciplinarity extends disciplinary boundaries, it is achieved mainly in the framework and for the benefit of a specific domain. Inter-disciplinarity, on the other hand, is about transferring methods from one discipline to another. Like multi-disciplinarity, inter-disciplinarity transcends the disciplines but with the goal of creating new disciplines (Nicolescu, 2005). Whereas trans-disciplinarity includes multi- and inter-disciplinarity approaches, its primary goal is to understand the disciplines to unify knowledge (Nicolescu, 2005). Indeed, trans-disciplinarity encapsulates the notion of an integrated utilisation of the techniques, tools, and methods from various disciplines (Ertas et al., 2003; Kozmetsky, 1997).

This work is based on an empirical approach that centres on complex design problem-solving in higher education. In this context, we propose that studying design collaboration among students from a multi-disciplinary perspective constitutes a suitable approach for exploring the possible extension of design frontiers. As noted before, the intricacy of products has overcome the narrow frontiers of the disciplines, and dealing with design entails the collaboration of specialists from different disciplinary areas (Eckert & Stacey, 2021). When design collaborations are materialised in the framework of a multi-disciplinary team, opportunities for gaining new cross-cultural knowledge and skills emerge (Casakin & Badke-Schaub, 2015; Leblanc, 2021). Teams of this kind are supposed to have the specialised knowledge necessary for focusing on specific aspects, jointly with a holistic understanding on the topic (Fernandez-Orviz, 2021). A capability for sharing different views at different levels of detail can lead to the development of inspirational ideas. Not less important, multi-disciplinary teams can contribute to more meaningful, feasible and creative outcomes and eventually expand the existing frontiers of the design domain.

2.2 Multi-disciplinary and mono-disciplinary teams and design

The advantages of multi-disciplinary teams over traditional mono-disciplinary ones have been studied in several fields with a focus on team outcomes. A frequent approach in comparing the performance of these types of teams is to analyse quantitatively the produced outcomes by means of bibliometric indexes (e.g., Schummer, 2004; Levitt & Thelwall, 2008). The healthcare domain is a meaningful example of this, where numerous research activities on multi-disciplinary teams were carried out based on surveys and interviews. While related studies discussed a rich range of health issues that were efficiently tackled by multi-disciplinary teams, they also exposed several conflicts spanning from misalignments of team roles to problems in social dynamics (Jones, 2006). A central finding was the need to educate professionals capable of working in teams with members of diverse specialisations (Dyer, 2003). Studies on multi-disciplinarity can also be found in design literature and in project-based design education. A few examples are works focusing on ICT technologies (e.g., Nelson & Ahn, 2018), and virtual environments supporting team collaboration (e.g., Mengoni et al., 2009). Nonetheless, comparative design studies dealing with the dynamics of multi-disciplinary versus mono-disciplinary teams have yet to be carried out.

However, the diversity that characterises multi-disciplinary teamwork can be counterproductive to the possibility of successful collaboration. Many involved disciplines may not have worked in cooperation yet to solve a design problem. Over the years, they have constructed their own knowledge, terminology, approaches, culture, preferences, and priorities (Eisenbart et al., 2012). Specialisation in a domain enables the development of design expertise for the sake of improving task performance, while enhancing the quality of the produced outcomes. Nevertheless, it can also narrow the perspective on the broad picture (e.g., restrict the capacity of designers in a specific field to recognise the value of issues from other disciplines that are alien to them) (Rees, 2010). In this regard, transcending the frontiers of mono-disciplinary approaches is challenging and demands understanding commonalities and differences with other disciplines (Gericke et al., 2021). In the context of our study, the notion of extending the frontiers of design is understood as the sharedness of existing knowledge, tools, methods, and experiences from a certain discipline and unknown to other disciplines, with the goal of contributing to a common understanding of the design situation while gaining new knowledge. To this aim, successful design collaboration plays a critical role when it concerns complex and multifaceted projects. However, this may be affected by the quality of team collaboration.

2.3 Teamwork quality and design

The concept of teamwork quality, introduced by Hoegl and Germunden (2001), assumes a critical role in studying multi-disciplinary collaborative design and its influential factors. Teamwork quality is a thorough notion of the excellence of team interactions (Dayan & Di Benedetto, 2009). It is a critical aspect of team collaboration that was studied by focusing on social interaction factors – e.g., cohesion and mutual support, and task-related factors – e.g., communication and coordination (Hoegl & Gemuenden, 2001). These researchers found the two teamwork quality factors strongly related to team performance.

In another study, Dayan and Di Benedetto (2009) showed that the quality of interactions among team members is a fundamental skill needed to create good and innovative products. However, they showed that teamwork quality could be reduced due to difficulties in getting members to communicate successfully and work jointly. Teamwork quality was also found to affect educational outcomes and the success of collaborative learning (Curşeu & Pluut, 2013). The quality of social interactions at a team level showed to impact on knowledge creation, and eventually on team performance (Hong & Suh, 2017). Additional studies in the fields of R&D management and cognitive psychology highlighted the influence of task-related factors on teamwork quality. Kratzer et al. (2006) showed that low complexity tasks have a negative impact on the creative performance of R&D teams. In spite of the variety of works on teamwork quality, a primary focus tends to be set on its effect on team performance (Nesterkin et al., 2016). Some of these focus on the impact of training styles of multi-disciplinary teams on design performance (Reich et al., 2009), or on reflections on learning outcomes from cooperative project-based approaches in engineering education (Abdulaal et al., 2011). A milestone is the work by Cooke et al. (2003), who investigated task-relatedness to teamwork knowledge, but still with focused attention on team performance.

Relatively few studies can be found on collaborative design dealing with social aspects and teamwork quality, and no studies on multi-disciplinary design investigated teamwork quality based on social-related and task-related factors simultaneously. Therefore, in this work, we investigate how multi-disciplinary compared to mono-disciplinary design teamwork affects the quality of collaborations in an educational environment from a social and task-related perspective. Given the potential effect of teamwork quality on knowledge creation, we propose that studying the quality of team collaboration can inform about extending the frontiers of design.

3 Methodology

3.1 Design courses

To address the research questions, a study was conducted in the context of two programs. i) A master's degree with students from architecture, industrial design and all branches of engineering disciplines. This took place in the 2019 edition of the "Design Methods and Processes" course of Alta Scuola Politecnica – ASP (Benedetto et al., 2010; Ajmone et al., 2016), a program jointly fostered by the Politecnico di Milano and the Politecnico di Torino. ii) A master's degree in the Mechanical Engineering study program at Politecnico di Milano, which included students who were enrolled in the "Inventive Design and Problem Solving" course.

The ASP is an honours program that comprises several courses organised as residential full-time weekly schools and a design project lasting one year on real-world problems (https://www.asp-poli.it/home/our-projects/). On the other hand, the Mechanical Engineering course aims to deliver theoretical competencies and practical skills on methods and tools supporting technical creativity in conceptual design activities. It involved an annual project proposed by an entrepreneur from a company. Examples of project themes are household appliances (e.g., washing machine, dish washer) for single users and an integrated system intended for regulating the vehicle tire pressure.

The ASP project – representing the multi-disciplinary team activity – was used as a test group, whereas the Mechanical Engineering project – representing the mono-disciplinary – was used as a control group, i.e., as a benchmark to identify differences and similarities in teamwork quality in the context of design.

The comparison between the two case studies is considered relatively unbiased since one of the authors was the coordinator of both courses and provided similar directions and tutorship in both projects. Through a retrospective analysis of the team activity in the ASP and Mechanical Engineering courses, participants can offer important insights that transcend the courses themselves and be of value to identify key aspects in the design educational context, with possible implications for extending the design borders.

3.2 Participants

Students were requested to opt out if they were not interested in participating in the study. Eight out of 140 ASP students representing different disciplinary backgrounds and course grades, and another five out of 50 Mechanical Engineering students accepted the invitation to take part in the study.

3.3 Research approach

The research method is based on semi-structured interviews (e.g., Kallio et al., 2016). The use of semi-structured interviews was successful in several studies that analysed the dynamics of teamwork (e.g., Sandoff & Nilsson, 2016). In the present work, they were characterised by a dialogue partially based on a predefined protocol, adapted to the ad-hoc circumstances as demanded by the interactions with the participants. The structure of the interview sessions was partly based on teamwork quality (task and social-related aspects). The interviews also included other topics that are beyond the scope of this research. To avoid potential biases, they were carried out after the evaluation process – when all students were assigned the grades for the two courses. Both authors coordinated the interview sessions and complemented each other by proposing topics for discussion. These were carried out in English, as both courses were delivered in this language.

3.4 Data collection and preparation

Due to the COVID-19 outbreak, interview sessions were held via the internet using Microsoft Teams software and lasted for about 60 minutes. The meetings were video-recorded under the explicit consent of the participants. Then, the anonymised recordings were transcribed and segmented, each segment representing an exchange in the conversation between the interviewers and the interviewee. Video recordings were transcribed using an external transcription service. Thereafter, transcriptions underwent a quality check to ensure that the verbalisations were captured correctly. Transcript segments were also assigned a timestamp as a reference in the data collection. The final data set contained all utterances produced by the participants in the 13 sessions, which were classified according to the participant and team type.

4 Findings

Firstly, the social-related and task-related dimensions are identified. Secondly, an analysis is carried out on the themes and topics related to the social-related dimension, and then on the task-related dimensions of teamwork quality. Illustrative short excerpts identified from the interviews are included to provide empirical evidence of the findings[1].

4.1 Identification of social-related and task-related dimensions

To deal with RQ1, a qualitative analysis of the segmented transcripts followed a 3-step process:

- The authors carried out an independent analysis of the transcripts to identify and retrieve relevant topics addressed in the interviews, regardless of the disciplinary team composition.
- By consensus, they selected the topics they considered relevant to deal with the research goals and clustered them according to general themes. Thereafter, they classified the themes and related topics

[1] MLT: quotations from ASP students; ME: quotations from Mechanical Engineering students.

according to two main reference dimensions: i) teamwork quality, represented by social-related versus task-related issues; and ii) disciplinary team composition, represented by mono-disciplinary versus multi-disciplinary team background.

- Finally, authors revisited the transcripts to check the consistency between the identified topics and themes, and to select illustrative excerpts for each theme.

Figure 1 shows the themes and related topics identified in the second step, which are organised according to the two above-mentioned comparative dimensions. The social-related dimensions that are common to the two types of teams are characterised by four main themes that included: mutual trust, leadership, and project management and design process management. On the other hand, the task-related dimensions are classified into simplification of ideas, design novelty, robustness of solution, and common goals.

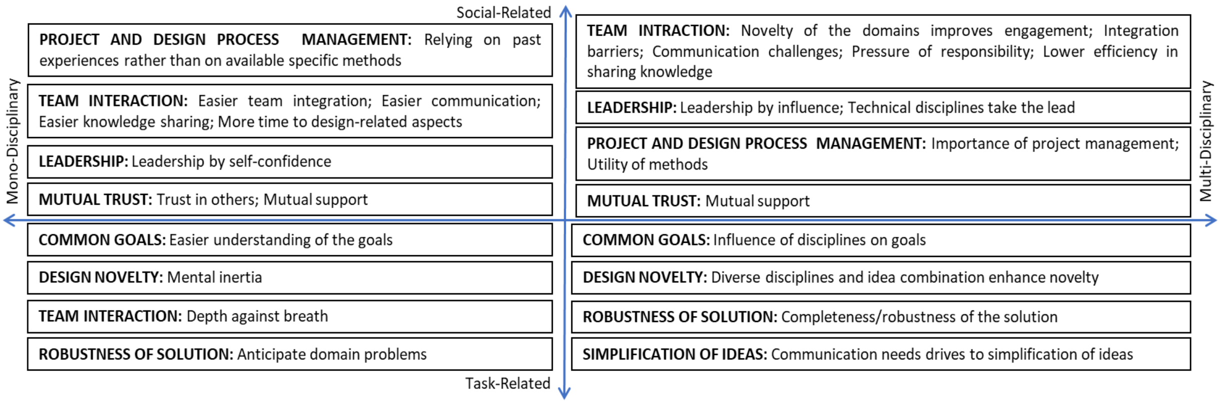

Figure 1. Themes (bold text) and related topics identified from the interviews with students.

To address RQ2, the following two sub-sections present the main findings of the 3-step process described above. Accordingly, the identified themes are analysed into social-related and task-related dimensions, and compared according to multi- and mono-disciplinary team composition.

4.2 Analysis of social-related dimensions

Teamwork quality is used as an overarching concept referring to the quality of team collaborations including social-related facets. In this sense, a team can be defined as a social system in which members collaborate on a common task. To capture the social nature of design team members working together, in this section, we elaborate on the social-related themes identified in the study as follows.

4.2.1 *Team interaction*. A recent review (Nguyen & Mougenot, 2020) on team interaction in multi-disciplinary collaboration in the industrial sector summarises the way that team composition affects the design process. The study mentions several key aspects deserving consideration such as: strengthening trust among team members, and dealing with team cohesion and communication barriers, caused not only due to language and jargon differences. In this regard, students from multi-disciplinary teams, even without being explicitly prompted on these issues during the interview, highlighted communication difficulties met in the team collaboration activities that led to the emergence of communication barriers and reduced cohesion[2].

While no students highlighted criticalities due to limited trust, possibly because of the variety of team-building opportunities offered by the ASP school, they commented about a lower efficiency in sharing knowledge[3]. On the contrary, participants in mono-disciplinary teams explicitly manifested the ease of interaction with their teammates[4]. Some of them also stressed the importance of being a specialist in the industry related to the design task[5].

Interestingly, students in multi-disciplinary teams did not show the same confidence in their discipline field. Those who hold unique and critical competencies critical for the project's success, supported huge pressure. This was due to their role and responsibilities and the impossibility to discuss in detail important decisions with others[6]. Participants also mentioned the high engagement they felt from the novelty of the viewpoints and competencies brought by their teammates[7].

4.2.2 *Mutual trust*. What concerns multi-disciplinary teams, when the knowledge needed to deal with the task was too specific to be understood by all disciplines, members of certain disciplines had no choice but to trust the expertise from other disciplines[8]. However, trusting mates while dealing with a part of the design contributed not only to generate a better atmosphere and to enhance team cohesion, but also to learn from others, gain a broader picture of the design situation, and understand how to move on in the process[9]. In the mono-disciplinary teams, trusting other members was easy and advantageous, but for different reasons. The common knowledge of the engineers enabled them to understand design

[2] MLT "the main difficulty is in the communication, because if you have different backgrounds you put different values on […]. Also small things could lead to infinite discussions […] slow down all the process and […] lose track of important things […]".
[3] MLT "you can speak about two different levels of knowledge: one that is very technical, that I can only share with the disciplines that are related to my own. And there is another one that I [must] trust".
[4] ME "having the same [background] of mechanical engineers, we were able to evaluate the capacity of each other in a more precise way".
[5] ME "One aspect of bringing out good design is to […] have good knowledge about the state of the art […]".
[6] MLT "communication with the other members […]is important; I need a person [with whom I] could share opinions deeper on the theme. […] if you find a person that knows what you are doing and how you work […] we can work faster and explain better the work to others"; ME "If there were at least two people from the same background […] there could be some conversation between teammates […]".
[7] MLT "I'm an expert in fluids. But for what concerns the yearly project, I didn't see any fluid. So actually, in my field of study doesn't really show up. But at the same time, I'm really satisfied because I really put a lot of effort and also because I learnt a lot [from others]".
[8] MLT "for example, the algorithm […] I can understand how it works. But if you say that it's better to use five instead of ten, I trust you. Otherwise, I have to have another degree in computer science"
[9] MLT "I worked really well in my team because we shared knowledge and trusted each other […] and this was useful to me because I also learned something new […and it helped to] be aware about the pros and cons of the solutions and then together we could decide how to proceed".

situations quickly even when the information shared by others was not completely apparent[10]. This enhanced their confidence in the team[11], reduced work pressure, and created opportunities to collaborate and help each other[12]. Eventually, trusting others played a role in improving the quality of the final solution[13].

4.2.3 *Leadership*. The influence of leadership on team interactions has been widely studied in the literature, both at the individual and group levels. At the individual level, leadership was connected to several positive aspects that include performance, work engagement, and creativity (Grandey et al., 2005), and work satisfaction (Giallonardo et al., 2010). In the context of multi-disciplinary teams, leadership at the individual level was related to the personality of the team member. The leader was not seen as an individual with a strong personality who fought to inflict power to dominate the others[14]. Rather, she was considered an open-minded individual, cognitively flexible, and able to solve conflicts that emerged during the task[15].

At a team level, leadership was also found to enhance reflective discussions about the level of agreement among members, values, strengths, weaknesses, and progress to achieve shared goals (Yammarino et al., 2008). When members perceive the legitimacy of team's leadership and seek to comply with team rules and decisions, they would remain more attached to and supportive of the team (Naumann & Bennett, 2000). In this work, students with an engineering background emerged as group leaders of the multi-disciplinary teams. Due to the nature of the addressed design tasks, they were those who coordinated the team's actions to deal with the problem[16]. The leader was considered to have special managerial capabilities to organise and coordinate design actions among the sub-teams, which were formed based on disciplinary background[17]. The leader was also responsible for the team's cohesion and for enhancing communication and understanding between the disciplines[18]. In the mono-disciplinary teams, there was no natural leader. Partly due to their similar background, there was an efficient

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[10] ME “Even if it was 60 to 70 percent clear, we still understood what he meant because of our engineering background”.
[11] ME “The engineering background allows you to understand more deeply what others were saying and you didn't have to trust”.
[12] ME “it [trust] helped a lot because if one is forgetting about one small detail, let's say about designing something, the other [engineers] can intervene and help him […] so that the [work] pressure will not be really high on that member”.
[13] ME “[due to] the mutual support and collaboration with my teammates, we polished this idea that was really rough into the final design”.
[14] MLT “It's not a matter of being the one who will control everything […] or tries to impose its own ideas [to others]”.
[15] MLT “The team leader is a person that is more open to the opinion of all of us”.
[16] MLT “people who are related to the more like technical school, they're trying to be leaders”.
[17] MLT “There was usually the team leader that was going around and seeing what the subgroups were doing and trying to give coherent indications too”.
[18] MLT “the leader […] was able to keep all the elements of the group together. So the communication worked […] well”.

interaction between members, and a balanced responsibility for dealing with the project[19]. When leadership emerged, it was mainly to mediate conflicts and help to make decisions by considering the opinion of the majority[20].

4.2.4 *Project management and design process management*. The need to develop designers' multi-disciplinary team working capability has been discussed for over 20 years. Project-based learning has been proposed as a reference educational practice to develop such soft skills since (Denton, 1997). Considerable attention was dedicated to influential factors such as the composition of the design teams, the nature and complexity of the task, and the assessment criteria. In this regard, past editions of the ASP school on "Design methods and processes" were analysed to recognise the educational impact of this practice (Cascini et al., 2017). However, such studies did not compare the reflections of participants of multi- and mono-disciplinary teams.

In this work, participants from the multi-disciplinary teams often referred to team collaboration and the design process to describe how they managed the task distribution, the interaction between teammates, and the fulfilment of the deadlines. Compared to their colleagues from mono-disciplinary teams, they showed a more extensive understanding of the importance of applying systematic methods for project management and guiding the design process[21]. As recognised since early studies in the field, team-working capabilities cannot be developed from a one-off exercise (Denton, 1997). Relying on past experiences rather than on available specific methods was characteristic in mono-disciplinary teams[22]. Moreover, it turned out that for multi-disciplinary teams struggling with team management issues came at the cost of less time and effort dedicated to the task itself[23]. In contrast, much of the focus of mono-disciplinary team members was set on the task and its related details, but at the expense of overlooking the design process and team management aspects. Besides, this sometimes turned out in useless iterations in the team, with a consequent waste of time[24].

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[19] ME "Communication was crystal clear, although we had no leader as such, we all took equal responsibility for the tasks.".

[20] ME "the sort of leader […managed] conflicting situations […] democratically".

[21] MLT "It was strongly requested to have a common view on the management and the organization between the team members, especially between very different disciplines. A main point to organize communication was to create a channel dedicated to a single topic that all of us can set in. […] team building is prior to anything else. Even, prior to the understanding of the problem, because you need to know each other to understand the problem".

[22] ME "I did projects during my bachelor, my teammates […] already did projects in teams. So all of us already know how we should structure our work in order to be proficient.".

[23] MLT "There is a critical number of people over which you don't have really effective coordination and collaboration".

[24] ME "If we had someone from product design, our product would have been better because those people know some nuances we don't. […] We spent some time on it [a solution] and we didn't like it. We had some ideas about some things we would like to change, but we didn't know whether it is possible".

4.3 Analysis of task-related dimensions

A main concern about the quality of a team's collaborative work is how well its members share and process task-relevant information. To gain insight into the task-related interactions of design team members working together, in this section, we elaborate on the themes into which design issues identified in the interviews were categorised. These include simplification of ideas, design novelty, robustness of solution, and common goals.

4.3.1 *Simplification of ideas*. Further insights that emerged in the interviews focused on the simplification of ideas generated in multi-disciplinary teams. Successfully transmitting design ideas in a common space may require some level of simplification (Craig & Zimring, 2000). Some interviewees reflected on the difficulties of interacting with colleagues with different backgrounds. They concluded that to enhance common understanding and communicate with others, specialistic disciplinary knowledge had to be simplified[25]. To convince and increase the chances to get their ideas approved by other teammates, it turned out that simpler ideas were more effective and likely to prevail compared to other ones[26]. Such a tendency towards simplification of ideas suggests that as far as specialistic knowledge is not requested by the task at hand, multi-disciplinary teams are more likely to avoid complex solutions, and instead they naturally prefer simpler and possibly more elegant alternatives. We found no indication of this behaviour in the mono-disciplinary teams.

4.3.2 *Design novelty*. Design is a creative activity that mainly takes place in the conceptual phase and is characterised by the generation of ideas and solutions (Pahl & Beitz, 1996). In this process, designers jointly work with the aim of developing not only functional but novel outcomes. Novelty can be defined as "a new or unfamiliar thing or experience" or as "an object intended to be amusing because of its unusual design" (Oxford Dictionary, 2021). Some metrics have been proposed to evaluate the degree of novelty of a design process either in terms of "uncommonness", or the degree of change from a known solution (Fiorineschi et al., 2020). The creation of novel outcomes in teams with different design backgrounds is a relatively underexplored issue.

In our work, it was found that the various backgrounds of the multi-disciplinary team contributed to thinking about the design situation anew. Members invested efforts in reframing the problem and

[25] MLT "my teammates try to explain me in a simple way […] the problems and something like this. And it works in both directions. So, for example, if there were problems related to the biomedical field, I tried to explain in a simpler way so they can be managed in a general way, not more in the medical field".

[26] MLT "it was a little bit difficult […] to introduce a debated discussion […] it was difficult to obtain the opinion of some engineers, let's say, because they tend to limit their work on computational things or stuff, but they tend not to explain their position".

redefining the design task[27]. The variety of views of the disciplines helped enhance the novelty of the final solution[28]. Interacting with other domains aided students to open their minds and to reason about the task in less familiar ways[29]. Such interactions led to the production of unexpected solutions[30]. Novelty was also the outcome of a balance between designers – who tried to push the borders of the familiar by envisioning unique ideas – and engineers – who thought about how to materialise these ideas in practice[31]. In some cases, the novelty of the solution did not reside in producing revolutionary outcomes, but in considering existing solutions from different disciplines and combining them into a single solution[32].

In the mono-disciplinary team, the produced solutions were considered more valuable than novel[33]. Rather than thinking of revolutionary ideas, the mechanism that contributed to the search for novelty consisted in adapting knowledge from existing products to the problem at hand[34]. Although not completely novel, within-domain displays served as sources of inspiration to deal with the task[35]. Potentially novel ideas were discarded since there was no member with the required skills to develop them[36]. Hence, the chance of developing a novel outcome depended more on individual than on collective creativity[37].

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[27] MLT "we use [considered] a novel topic to address a not so novel solution because the solution already exists. [But] not as defined as one would expect […] and having [a team with] multiple backgrounds […] and different experiences helped a lot".

[28] MLT "you can apply knowledge and concepts that come from different fields. This generates something that is completely different and disruptive".

[29] MLT "the other disciplines take us to reason in a different way. So we were less focused on the daily path"; MLT "an idea from a completely different background expands your way of seeing things […and this] enhances your creativity […] you come up with some solution that is not just an addition between your knowledge and the others knowledge, but […] makes something more because it stimulates to think in a different way".

[30] MLT "it's part of the multi-disciplinary nature of the task […] because they thought about some solutions that I could not have imagined [before]".

[31] MLT "we are dreamers [the designers] and we are always trying to create something like extraordinary, super unique. And sometimes it runs out of our budget or the reality so that […] the engineers are always trying to […]to balance those things".

[32] MLT "the solution is quite innovative […] we integrated in a device a lot of things that came from other devices and that were not in a unique device.".

[33] ME "although we put in a lot of effort, which they [the company] appreciated a lot, the idea in itself was not so novel"; ME "the idea was not so novel […but] in terms of value it was a step in the right way for the project…".

[34] ME "we took a concept that is normally used in the automotive industry, and we completely changed [adapted] it to the context [of the task], something that it has never been done before in […] this context".

[35] ME "we took inspiration from the lipstick, how it works when you rotate, and it comes from a rotation that transforms into an actual axial motion […] but I would say it [the solution] was not novel in general".

[36] ME "if we had someone from the aerospace field, we feel he could have taken up the task and he could have made [developed] it into a creative idea, which might have been a good idea if it was economical for the company".

[37] ME "not everybody had innovative solutions, but it was all about […] if there was an innovative person".

4.3.3 *Robustness of solution*. Students from mono-disciplinary teams mentioned ease in the interactions with their teammates, and the possibility of analysing and sharing with others details of the design task with an adequate level of common understanding (See section 4.1.1). However, they manifested difficulties in how to anticipate possible drawbacks when discussing new solutions[38]. Moreover, to ensure the viability of their concepts, students expressed their wish to revisit their solutions with the aid of colleagues from different disciplines, even at the expense of unexpected variations in the operating conditions of their designs[39]. This situation reflects the limited robustness of ideas generated by mono-disciplinary teams, meant as a reduced ability to fulfil the requirements under unexpected conditions. Issues like these were already noted by others, who recommended engaging multi-disciplinary teams in the evaluation of the robustness of product concepts (e.g., Goez et al., 2019).

Students from multi-disciplinary teams showed to be aware of the boundaries in disciplinary competences[40]. However, they recognised the advantages of combining complementary points of view and knowledge resources from the disciplines to prevent drawbacks and limitations of their designs because of unknown aspects of the task[41].

4.3.4 *Common goals*. Design problems are ambiguous and can be defined by no clear initial conditions and no completely specified goals (Simon, 1996). Hence, while dealing with the design task, team members must define the goals to be accomplished at the different stages of the design process (Coyne, 2005). Establishing and sharing common goals requires a large range of interdependencies of individual information among the team members (Casakin & Badke-Schaub, 2017; Badke-Schaub et al., 2007). Defining common goals is critical to successfully tackle the related sub-problems and arrive at a well-integrated solution. The disciplinary background is supposed to play a role in the way that designers approach problems and establish such goals. This situation seems more radical in teams where designers differ in knowledge, skills, and experience.

Differences in interests in the multi-disciplinary team influenced how members perceived the design situation, and how they prioritised the goals and approach the problem[42]. Hence, a challenge for the

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[38] ME "So if we were not expert in materials, we searched them on the net. But obviously it's different with respect to having a certain background there where people made courses on this".
[39] ME "to solve a certain problem, we made a solution for which all the weight was on the user […] being mechanical engineers, we dedicated much time to problems that… [led to] a quite instantaneous solution".
[40] MLT "not about the knowledge, because, of course, we cannot be engineers in six days, but in terms of approach".
[41] MLT "their [teammates] point [of view] having elements with a completely different background helped a lot in trying to force us to view the thing from a different perspective".
[42] MLT "the architects pushed a lot towards the management of the user experience"; MLT "because of the difference in background, as a computer engineer you can develop more easily the final product and is […] a different approach than a space engineer".

multi-disciplinary teams was to agree upon shared design goals[43]. On not few occasions, they had to consider and negotiate their differences to deal with the goals[44]. When they realised that their initial goals were difficult to achieve, they tried to adapt them to meet the know-how of others[45]. Generally, team members had shared main goals, but their final solution not always reflected it. A main reason was that teams were subdivided into specialised sub-teams that worked independently of one another while developing a part of the solution. A sub-team organisation affected the possibility of clarifying goals and sub-goals with other groups and reaching more integrated solutions[46]. In some cases, the voice of the engineers was louder than others, and they imposed their goals over less influential disciplines such as design or architecture. The consequence was a lack of balance in the contribution of the disciplines to the final solution[47].

In contrast, members of the mono-disciplinary teams worked guided by task requirements from the outset. Since they were aligned with the kind of design to be developed, there was a common understanding of what the design goals were[48]. Eventually, there were a few minor conflicts, which were quickly resolved as soon as the idea of what they wanted to achieve became clear[49]. Due to their common background, they communicated easily, shared their knowledge, helped each other, and balanced their contribution to achieve the goals[50]. Because of these, the final solution largely reflected the initial goals of the team.

5 Discussion

To deal with the research goals, in the following sections, we elaborate on the differences between multi- and mono-disciplinary teamwork and their importance for extending the frontiers of design in

[43] MLT "maintain a sort of dialogue [among the team members] that could work and led to a common goal. This was a main issue because there were very complex arguments [goals] that […] if not managed in a correct way […] could be very messy".
[44] MLT "people have different opinions. We have always like to […] take into consideration all their opinions to make a decision".
[45] MLT "we have the chance to go more in the hardware part or more in the software project. So, we decided to proceed more in the softer partly because of the type of team members we have. We had people from computer science that are very good in doing software and we decided to proceed in this direction instead of the other".
[46] MLT "we had a more specific goal that we shared in common [… however] […] we were working more independently […] and sometimes the solution that other subgroups developed was hard to put together".
[47] MLT "there were two mathematical engineers and three computer science engineers. So, you can imagine that it was really computer oriented […] and not really focusing on the architectural aspect of the project".
[48] ME "We already knew what exactly we are targeting".
[49] ME "In terms of the goals […] one part of the group wanted to go with one project and the other wanted to go with another, but at the end we all made the decision to pursue a common goal and just focused on one type of project"; ME "there were frictions […] but when we started to have a firmer idea of what we were considering, we started again …working in one direction".
[50] ME "we tried to help everyone as much as we can because we knew that we share a common goal, and this would largely affect everybody".

higher education. We refer to collaboration in teams by using teamwork quality, represented by the task-related and social-related themes identified in this study.

5.1 Social-related and task-related dimensions in design teamwork

The first aim was to study comparative social- and task-related dimensions of multi-disciplinary and mono-disciplinary design collaboration into which teamwork quality can be categorised. Exploring these dimensions enabled to identify and gain insights into relevant themes regarding design teamwork quality. Hence, the theoretical approach concerned with teamwork quality proposed by Hoegl and Gemuenden (2001) proved to be effective in gaining further understanding about design team collaboration in general, and particularly regarding team disciplinary composition. The themes that emerged in common allowed analysing and comparing key aspects of multi-disciplinary and mono-disciplinary design collaboration in the context of higher education. These are discussed in the next section.

5.2 Effect of team disciplinary composition on design teamwork quality dimensions

Regarding task-related issues, it was found that disciplinary background affected how design goals were established. In line with what several authors observed (e.g., Leblanc, 2021), multi-disciplinary teams managed to set goals that overcame in scope and complexity those established by the mono-disciplinary teams. A main influential factor was the variety of interests and views of the different disciplines, which in contrast to the mono-disciplinary teams, contributed to extending the borders of the known and the familiar. The different backgrounds of the multi-disciplinary teams helped not only to define the design goals from several perspectives, but to rethink the design task. With the insight of the different disciplines, framing the problem played a role in enlarging the understanding and conceptualisation of the task (Paton & Dorst, 2011), and ultimately in enhancing the generation of novel and unexpected outcomes (Suwa, et al., 2000). In contrast, the intra-disciplinary knowledge shared by the engineers in the mono-disciplinary teams aided in developing a deep understanding of the design situations and producing more valuable than novel solutions. This is consistent with Leblanc (2021), who noted that disciplinary expertise is useful when it relates to and enhances the understanding of complex phenomena. However, expertise often showed to miss accepting alternative approaches and thinking out-of-the-box.

Regarding social-related issues, maintaining a balance between the different views and goals of multi- disciplinary team members required management skills, which demanded great effort and sometimes at the expense of task-related aspects. From this viewpoint, finding the appropriate balance between these conflicting aspects remains an open issue to be addressed. Moreover, working in multi-disciplinary teams required adapting communication to the profile of the team members. An unexpected finding was that simpler ideas, i.e., less grounded on specialist knowledge, were preferred because they were easier to communicate to teammates from different backgrounds. However, this tendency occasionally occurred without making a proper assessment of whether the more complex discarded ideas would have been better to meet the requirements of the task at hand. In this vein, Fox et al. (2017) showed that simplifications in communication may be counterproductive to matching the complexities of the task.

Mutual trust was found to be a critical aspect for generating a positive work atmosphere in multi-disciplinary teams, as highlighted by Maier et al. (2008). Mutual trust was required when the specific knowledge necessary to deal with the task could not be understood by all members, and hence it was shared in the team at a less deep level. Although trusting other disciplines implied renouncing control of every detail in the design process, it enabled to coordinate actions more effectively and learn new knowledge. In turn, the opportunity to learn new knowledge resulted in higher engagement of students in multi-disciplinary teams. A further consequence was the gain of a more comprehensive understanding of complex tasks from the perspectives of the other fields, thus leading to more robust designs, thanks to the anticipation of problems that might emerge.

In mono-disciplinary teams, mutual trust strengthened team collaboration and performance in the different tasks. These probably enhanced the performance of the final solution but did not contribute to the creation of new knowledge. Maintaining a balance between mutual trust and constructive criticism can contribute to enhancing a positive team climate and foster design thinking (Casakin & Badke-Schaub, 2013).

Those students with an engineering background and high self-confidence emerged as natural leaders of the multi-disciplinary teams. They were seen as flexible-minded individuals open to the ideas of others, with singular managerial skills to coordinate actions among the disciplines. Jacoby-Volk and Bar-Eli (2021) emphasised the importance of encouraging natural leadership as opposed to formal management roles. In our study, while engineering leaders possessed the basic knowledge needed to organise and harmonise the work of various disciplines, they were found to largely interfere with the contribution of students belonging to other less represented disciplines than engineering. Hence, in multi-disciplinary teams, the role of dominant leaders could be counterproductive when the aim is to challenge the design borders to expand the knowledge space.

5.3 Extending the frontiers of design: implications for design education

A main pillar for extending the frontiers of design resides in promoting a more integral education based on a proactive interaction among different disciplines. Multi-disciplinary education can be implemented and encouraged by supporting team collaboration. Whereas design programs interested in extending the frontiers of design should contemplate the possibility of implementing multi-disciplinary team-based projects, they may also benefit from the findings of this study. Critical issues to be considered in a transition from mono-disciplinary to multi-disciplinary design education, specifically in the design studio are how to:

- Clearly communicate and share disciplinary knowledge and methodologies that are alien to others, to enhance cohesion and facilitate a common understanding among team members. These will require adapting own knowledge, terminologies, tools, approaches, and priorities to meet the needs of other disciplines (Eisenbart et al., 2012).
- Define common goals while taking care of an appropriate balance of interests among the disciplines. Sharing common goals is fundamental for efficient team performance, dealing with sub-problems, and developing well-integrated solutions (Badke-Schaub et al., 2007). However, disciplinary background affects the way that students perceive problems and prioritise goals. Hence, how to reach a consensus is a primary challenge that can be dealt with by negotiating differences with other disciplines. This can be achieved by establishing priorities based on the know-how of the team members and adapting design goals accordingly. Such an approach would enable not only to align design intentions among team members with different backgrounds and interests, but also reduce the chances of producing unsuccessful solutions.
- Reflect and discuss ideas with other disciplines, being clear, flexible, and simple but not simplistic. Explaining, reflecting, and communicating ideas efficiently is a critical prerequisite for reaching a common understanding among students with different backgrounds, as well as for developing novel solutions. These activities can be implemented by the construction of a shared mental model of the team about the task to be achieved (Mohamed et. al., 2000). To this end, an essential activity should consist in communicating, applying, and adapting pre-existing individual mental models from the different disciplines, for the sake of progressively developing a common language in support of the construction of a shared mental model of the design task and the process.
- Develop mutual trust among the parties, guided by good leadership. Supporting mutual trust between the disciplines is advisable from the beginning of the process (Casakin & Badke-Schaub, 2013), particularly when the task is too complex to be fully understood by all disciplines. An open-minded team leader can help not only mediate conflicts and keep a harmonious and positive team climate, but also enhance confidence and encourage engagement and opportunities for collaboration among the disciplines. Eventually, all these will contribute to gaining a broader understanding of the design situation and learning how to coordinate actions to move forward.
- Manage and coordinate design actions effectively to produce novel ideas and robust solutions, trying to anticipate problems that have never been experienced before. To overcome the uncertainty of the early stages of innovative design process, it is recommended to integrate competencies from multiple disciplines, being open to the complementary input of members with different backgrounds and views (Goez et al., 2019). Distributing tasks in specialist sub-teams and coordinating actions with other sub-teams at different stages of the process can help to efficiently integrate sub-solutions and produce creative outcomes, with a consequent time and effort reduction.

All these issues may play an important role in not only consolidating existing knowledge, but also in creating new one. Eventually, these will contribute to transcending the frontiers of the design disciplines, particularly in higher education.

6 Study limitations

The authors selected mechanical engineering as a control group among all possible mono-disciplinary backgrounds. Hence, reflections on multi-disciplinary teams were made in contrast to mono-disciplinary teams with a strong engineering background. Compared to other engineering disciplines, mechanical engineering students have larger horizontal competencies, which may have softened differences with multi-disciplinary teams to some extent. Moreover, the task assigned to the multi-disciplinary teams was not always relevant to all the students to the same extent. The disciplinary background could have biased the way that the interviewees perceived and reflected on their teamwork experience.

Another issue is concerned with the sample since the multi-disciplinary teams were composed of honours students, who presumably have higher capabilities than the "regular" students from the mechanical engineering course. However, it is believed that the effect of such limitation is moderated by the fact that the analysis between the teams focused on the interactions among members rather than on their outcomes. A further limitation is that students had limited professional experience as designers. Hence, their insights should not be generalised to multi-disciplinary teams of expert practitioners.

Due to the COVID outbreak, we did not have the possibility to design a setup aimed at exploring how to expand the frontiers of design specifically. Rather, we collected data using interviews from students who had participated in courses based on an established multi-disciplinary educational model. Nevertheless, we believe that the insights that emerged from analysing and comparing these interviews with those from students of mono-disciplinary teams revealed interesting differences that may have helped identify influential aspects for enriching the design experience. From this standpoint, we hope to have contributed to the central theme of DTRS13.

7 Conclusions

This study explored the comparative social-related and task-related factors of multi-disciplinary and mono-disciplinary design teamwork, which is an underdeveloped topic. A further aim was to gain understanding of the ways that teamwork quality can benefit from social-related and task-related interactions among designers with different disciplinary backgrounds, and what the main challenges are. We also expected to gain insight into how multi-disciplinary teamwork can contribute to extending the frontiers of design. Data collected from 13 semi-structured interviews was analysed, with a focus on the quality of the interactions developed during the design activity. While comparing multi-disciplinary and mono-disciplinary teamwork quality, this study contributed to shedding light on the existing dichotomy between the more comprehensive approach of the former and the narrower but deeper approach of the latter. It showed that this demands skills and competencies different from those of mono-disciplinary teams, challenging team dynamics and collaboration.

In addition to nurturing the development of knowledge and design skills, caring for teamwork quality is crucial to improve multi-disciplinary team collaboration. To this aim, universities should implement curricula supporting multi-disciplinary environments where design students could be trained to collaborate with pairs from other domains. However, changing the way design is taught nowadays will demand overcoming existing disciplinary boundaries and preconceptions set in higher education. This work can be seen as an attempt in this direction. Additional studies should be conducted to improve understanding of design multi-disciplinarity in education and practice. Eventually, they will contribute to the further development of a trans-disciplinary and better-integrated design science.

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References

Abdulaal, R. M., Al-Bahi, A. M., Soliman, A. Y., & Iskanderani, F. I. (2011). Design and implementation of a project-based active/cooperative engineering design course for freshmen. *European Journal of Engineering Education*, 36(4), 391-402.

Ajmone, M., Ceri, S., Verganti, R., Zanino, R. (2016). Alta Scuola Politecnica: Innovation, multi-disciplinarity and passion. In Banerjee, B. & Ceri, S. (eds.). *Creating Innovation Leaders* (pp. 215-225). Cham: Springer.

Badke-Schaub, P., Neumann, A., Lauche, K., & Mohammed, S. (2007). Mental models in design teams: a valid approach to performance in design collaboration? *CoDesign*, 3(1), 5–20.

Barczak, G., & Wilemon, D. (2003). Team member experiences in new product development: views from the trenches. *R&D Management*, 33(5), 463-79.

Benedetto, S., Bernelli Zazzera, F., Bertola, P., Cantamessa, M., Cerie, S., Rancif, C., Spazianteg, A., & Zanino, R. (2010) Alta Scuola Politecnica: an ongoing experiment in the multidisciplinary education of top students towards innovation in engineering, architecture and design. *European Journal of Engineering Education*, 35(6), 627-643.

Blessing, L. (2021). Preface. In L. Blessing, A. J. Qureshi, & K. Gericke (eds.), *The future of transdisciplinary design* (pp. vii-ix). Cham: Springer.

Casakin, H., & Badke-Schaub, P. (2017). Sharedness of team mental models in the course of design-related interaction between architects and clients. *Design Science*, 3(e14), 1-21.

Casakin, H., & Badke-Schaub, P. (2015). Team mental models in design problem solving: An interdisciplinary perspective. In A. M. Columbus (ed.), *Advances in Psychology Research*. NY: Nova Science Publishers: (pp. 169-182).

Casakin, H., & Badke-Schaub, P. (2013). The psychology of creativity: Mental models in design teams. In A. Antonietti, B. Colombo, & D. Memmert (eds.), *Psychology of Creativity*. NY: Nova Science Publishers (pp. 167-180).

Casakin, H., Ball, L. J., Christensen, B., & Badke-Schaub, P. (2015). How do analogising and mental simulation influence team dynamics in innovative product design? *AIEDAM*, 29(2), 173-183.
Cascini, G. (2015). Engineering grand challenges demand for trans-disciplinary design science. *Journal of Integrated Design and Process Science*, 19 (4), 1-2.
Cascini G., Graziosi S., Montagna F., & Rotini F. (2017). On the factors affecting design education within a multi-disciplinary class. *Journal of Integrated Design and Process Science*, 21(2), 21-44.
Cooke, N. J., Kiekel, P. A., Salas, E., Stout, R., Bowers, C., & Cannon-Bowers, J. (2003). Measuring team knowledge: A window to the cognitive underpinnings of team performance. *Group Dynamics: Theory, Research, and Practice*, 7(3), 179.
Coyne, R. (2005). Wicked problems revisited. *Design Studies*, 26(1), 5-17.
Curşeu, P. L., & Pluut, H. (2013). Student groups as learning entities: The effect of group diversity and teamwork quality on groups' cognitive complexity. *Studies in Higher Education*, 38(1), 87-103.
Dayan, M., & Di Benedetto, C. A. (2008). Procedural and interactional justice perceptions and teamwork quality. *Journal of Business & Industrial Marketing*, 23(8), 566–576.
Dayan, M., & Di Benedetto, C. A. (2009). Antecedents and consequences of teamwork quality in new product development projects: An empirical investigation. *European Journal of Innovation Management*, 12(1), 129-155.
De Vere, I., Melles, G., & Kapoor, A. (2010). Product design engineering – A global education trend in multi-disciplinary training for creative product design. *European Journal of Engineering Education*, 671(35), 33–42.
Dederichs, A., Karlshøj, J., & Hertz, K. (2011). Multi-disciplinary teaching: Engineering course in advanced building design. *Journal of Professional Issues in Engineering Education and Practice*, 137(1), 12–19.
Denton, H. G. (1997). Multi-disciplinary team-based project work: planning factors. *Design Studies*, 18(2), 155-170.
Dyer, J. A. (2003). Multi-disciplinary, interdisciplinary, and transdisciplinary educational models and nursing education. *Nursing Education Perspectives*, 24(4), 186-188.
Eckert, C., & Stacey, M. (2021). Overconstrained and underconstrained creativity: Changing the rhetoric to negotiate the boundaries of design. In L. Blessing, A. J. Qureshi., and K. Gericke (eds.). *The future of transdisciplinary design* (pp. 207-219). Cham: Springer.
Eisenbart, B., Gericke, K., & Blessing, L. (2011). A framework for comparing design modelling approaches across disciplines. *Proceedings of the 18th International Conference on Engineering Design (ICED11),* August15-19, Copenhagen (pp.344-355).
Eisenbart, B., Blessing, L., & Gericke, K. (2012). Functional modelling perspectives across disciplines: A literature review. *Proceedings of the 12th International Design Conference DESIGN 2012*, Cavtat, Croatia (pp. 847- 858).
Ertas, A., Maxwell, T., Rainey, V. P., & Tanik, M. M. (2003). Transformation of higher education: the transdisciplinary approach in engineering. *IEEE Transactions on Education*, 46(2), 289–295.
Fernandez-Orviz, A. (2021) Ineffective collaboration in multi-disciplinary teams. In L. Blessing, A. J. Qureshi., and K. Gericke (eds.). *The future of transdisciplinary design* (pp. 27-38). Cham: Springer.
Fiorineschi, L., Frillici, F., S. & Rotini, F. (2020). Impact of missing attributes on the novelty metric of Shah et al. *Research in Engineering Design*, 31(2), 221–234.
Fox, T., Gabor, E., Thomas, D., & Ziegler, J. (2017). Cultivating a reluctance to simplify: Exploring the radio communication context in wildland firefighting. *International Journal of Wildland Fire*, 26(8), 719-731.
Gericke, K., Adolphy, S., Quareshi, A. J., Blessing, L., & Stark, R. (2021). Opening up design methodology. In L. Blessing, A. J. Qureshi, & K. Gericke (eds.), *The future of transdisciplinary design* (pp. 3-14). Cham: Springer.

Gero, J., & Milanovic, J. (2022). What is happening when designers from different disciplines work together: Characterisation of the design behaviors and design spaces of mechanical and electrical engineers working in teams. *DTRS13 -Design Thinking Research Symposium. Technion, ITT,* Haifa, Israel. March 22-24 (243-258).

Giallonardo, L. M., Wong, C. A., & Iwasiw, C. L. (2010). Authentic leadership of preceptors: predictor of new graduate nurses' work engagement and job satisfaction. *Journal of Nursing Management,* 75(8), 993-1003.

Grandey, A. A., Fisk, G. M., Mattila, A. S., Jansen, K. J., & Sideman, L. A. (2005). Is "service with a smile" enough? Authenticity of positive displays during service encounters. *Organisational Behavior and Human Decision Processes,* 96(1), 38-55.

Goetz, S., Hartung, J., Schleich, B., & Wartzack, S. (2019, July). Robustness evaluation of product concepts based on function structures. In Proceedings of the Design Society: *International Conference on Engineering Design* (Vol. 1, No. 1, pp. 3521-3530). Cambridge University Press.

Gruenther, K., Bailey, R., Wilson, J., Plucker, C., & Hashmi, H. (2009). The influence of prior industry experience and multi-disciplinary teamwork on student design learning in a capstone design course. *Design Studies,* 30(6), 721-736.

Hoegl, M., & Gemunden, H. G. (2001). Teamwork quality and the success of innovative projects: a theoretical concept and empirical evidence. *Organization Science*, 12(4), 435-49.

Hong, J., Lee, O. K., & Suh, W. (2017). Creating knowledge within a team: a socio-technical interaction perspective. *Knowledge management research & practice*, 15(1), 23-33.

Jacoby-Volk, C., & Bar-Eli, S. (2021). Project-Based Design and Transdisciplinarity: Rethinking Approaches to Spatial Design Education. In L. Blessing, A. J. Qureshi, & K. Gericke (eds.), *The future of transdisciplinary design* (pp. 221-232). Cham: Springer.

Jones, A. (2006). Multi-disciplinary team working: Collaboration and conflict. *International journal of mental health nursing*, 15(1), 19-28.

Kallio, H., Pietila, A. M., Johnson, M. & Kangasniemi, M. (2016). Systematic methodological review: developing a framework for a qualitative semi-structured interview guide. *JAN*, 72(12), 2954-2965.

Keating, K., Brougham, C., Gavin, G., & Reilly, G. (2013). Issues in organisation and management of multi-disciplinary group design projects. In DS 76: *Proceedings of E&PDE 2013, the 15th International Conference on Engineering and Product Design Education,* Dublin, Ireland, 05-06.09 (pp. 302-307).

Kozmetsky, G. (1997). Generational road maps and commercialisation of science and technology. *Journal of Integrated Design Process Science*, 1(1) 4–8.

Kratzer, J., Leenders, R. T. A., & Van Engelen, J. M. (2006). Team polarity and creative performance in innovation teams. *Creativity and innovation management*, 15(1), 96-104.

Leblanc, T. (2021). Design as common denominator. In L. Blessing, A. J. Qureshi, & K. Gericke (Eds.), *The future of transdisciplinary design* (pp. 15-26). Cham: Springer.

Levitt, J. M., & Thelwall, M. (2008). Is multi-disciplinary research more highly cited? A macrolevel study. *Journal of the American Society for Information Science and Technology*, 59(12), 1973-1984.

Maier, A. M., Kreimeyer, M., Hepperle, C., Eckert, C. M., Lindemann, U., & Clarkson, P. J. (2008). Exploration of correlations between factors influencing communication in complex product development. *Concurrent Engineering*, 16(1), 37-59.

Mengoni, M., Peruzzini, M., & Germani, M. (2009). The impact of virtual environments on humans collaboration in product design. In DS 58-9: *Proceedings of ICED 09, the 17th International Conference on Engineering Design*, Vol. 9, Human Behavior in Design, Palo Alto, CA, USA, 24.-27.08. 2009.

Mohammed, S., & Dumville, B. C. (2001). Team mental models in a team knowledge framework: expanding theory and measurement across disciplinary boundaries. *Journal of Organizational Behavior*, 22, 89-106.

Naumann, S., & Bennett, N. (2000). A case for procedural justice climate: Development and test of a multilevel model. *The Academy of Management Journal*, 43(5), 881-889.

Nelson, M. E., & Ahn, B. (2018). Virtual reality activities for teaching engineering students professional development skills. In 2018 *IEEE Frontiers in Education Conference* (FIE) (pp. 1-5). IEEE.

Nesterkin, D. A., Porterfield, T. E., & Li, X. (2016). Relationship conflict, conflict management, and performance of information technology teams. *Journal of Computer Information Systems*, 56(3), 194-203.

Nguyen, Q., & Mougenot, C. (2020). Dimensions of multi-disciplinary collaboration: a comparative literature review within design context. *Proceedings of the DESIGN 2020 Conference* (vol. 1, pp. 1335- 1344). Cambridge: Cambridge University Press.

Nicolescu, B. (2005). Transdisciplinarity—past, present and future. *Congresso Mundial de Transdisciplinaridade,* September 2-6, Vila Velha, Brazil (pp. 1-24).

Ou, X., Goldschmidt, G., & Erez, M. (2022). Exploring the effect of team composition on creativity in design idea generation. *DTRS13 -Design Thinking Research Symposium. Technion, ITT,* Haifa, Israel. March 22-24 (211-224).

Pahl, G., & Beitz, W. (1996). *Engineering design: A systematic approach*. London: Springer–Verlag. Paton, B., & Dorst, K. (2011). Briefing and reframing: A situated practice. *Design Studies*, 32(6), 573-587.

Sandoff, M., & Nilsson, K. (2016). How staff experience teamwork challenges in a new organisational structure. *Team Performance Management*, 22(7/8), 415-427.

Shah, J. J. Kulkarni, S. V., & Vargas-Hernandez, N. (2000). Evaluation of idea generation methods for conceptual design: effectiveness metrics and design. *Journal of Mechanical Design*, 122(4), 377–384.

Reich, Y., Ullmann, G., Van der Loos, M., & Leifer, L. (2009). Coaching product development teams: A conceptual foundation for empirical studies. *Research in Engineering Design*, 19(4), 205-222.

Schummer, J. (2004). Multidisciplinarity, interdisciplinarity, and patterns of research collaboration in nanoscience and nanotechnology. *Scientometrics*, 59(3), 425-465.

Shah, J. J., Vargas-Hernandez N, & Smith, S. M. (2003). Metrics for measuring ideation effectiveness. *Design Studies*, 24(2),111–134.

Simon, H. A. (1996). *The sciences of the artificial*. 3rd ed. MIT Press.

Suwa, M., Gero, J., & Purcell, T. (2000). Unexpected discoveries and S-invention of design requirements: important vehicles for a design process. *Design Studies*, 21(6), 539-567.

Tharp, T., & Zalewski, J. (2001). Economics of software engineering: Transdisciplinary issues in research and education. *Integrated Design & Process Technology Proceedings*, June 6–11, (vol. 1, pp. 289-295)

Yammarino, F., Dionne, S., Schrieseim, C., & Dansereau, F. (2008). Authentic leadership and positive organisational behavior: A meso, multi-level perspective. *The Leadership Quarterly*, 19(6), 693-707.