A Program of Collaboration Engineering Research and Practice: Contributions, Insights, and Future Directions

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ABSTRACT: Collaboration Engineering (CE) is an approach for the design and deployment of repeatable collaborative work practices that can be executed by domain experts without the ongoing support of external collaboration professionals. Since 2001, CE has been an active and productive topic of research that has attracted scientists from different backgrounds and disciplines. CE research started with studies on ways to transfer professional collaboration expertise to novices using a pattern language called thinkLets. Subsequent research focused on the development

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of theories to explain key phenomena, the development of a structured design methodology, training methods, technology support, design theories, and various field and experimental studies focusing on specific aspects of the CE approach. This paper details the contributions from CE research and practice based on a literature assessment of 331 publications. It extracts the key insights from the body of CE research thus far, identifies significant areas of inquiry that have not yet been explored, and looks ahead at the CE research opportunities that are emerging as our society, organizations, technologies, and the nature of collaboration evolve.

KEY WORDS AND PHRASES: Collaboration Engineering, collaboration, thinkLets, patterns of collaboration, online collaboration.

Introduction

Teams form to create value that would be challenging to achieve by individual effort. In recent decades, teamwork became a dominant structure for achieving organizational goals. In the 1970s, researchers began developing rudimentary collaboration technologies, and by the early 1990s, reported major benefits of using advanced tools such as Group Support Systems (GSS) and Group Modeling tools for complex creative teamwork [70, 71, 90, 131, 132]. Despite strong results in the lab and in the field, though, team collaboration technologies were slow to transition into the workplace [1]. Many organizations that invested in such technologies reported strong return on investment (ROIs) (see, e.g., [131]) and yet abandoned the technology even as they acknowledged deriving great value from its use. It turned out that the potential benefits of the technology were typically only realized in teams led by collaboration experts such as professional facilitators. Collaboration experts, though, were scarce and expensive, and their special skills gave them high upward job mobility. They tended to be promoted rapidly, leaving the organization with nobody who knew how to create value with the collaboration systems [1, 20, 116]. Many teams, therefore could not realize the potential benefits of team collaboration technology.

In response to this challenge, Collaboration Engineering (CE) emerged as a scholarly discipline in the early 2000s. Its founding purpose was to make it possible for non-experts to realize benefits of collaboration technology without the support of collaboration experts. CE research had two core foci [20, 52]. First, it focused on how to design effective and repeatable technology-supported collaborative work processes for high-value tasks. Second, it focused on how to transfer the designs to practitioners (task domain experts who lack collaboration expertise) with little or no training on either the tools or the techniques.

The origins of CE as a distinct line of scholarly inquiry trace back to a 2001 publication that lays out the contours of a collaboration pattern language called "thinkLets" to teach novice team leaders repeatable and effective collaboration techniques [23]. Since then, an active research community formed that developed, applied, and studied CE concepts and principles in laboratory and field settings to build the CE body of knowledge. Early work focused on conceptual and theoretical development, followed by action research, design science research, and laboratory experiments. Many studies build on the findings, limitations, and future research directions from earlier work. To date, hundreds of CE related studies have been published, and cited by thousands more. Dozens of minitracks and sessions have been organized at conferences such as the Hawaii International Conference on Systems Science, Group Decision & Negotiation, and the Americas Conference on Information Systems. A special issue on Collaboration Engineering was published in the Journal of the Association of Information Systems in 2009 [52]. PhD Dissertations in CE and CE-related phenomena have been successfully completed in North and South America, Europe, Africa, and Australia. Compelling evidence from the field suggests that the approach may be viable in a number of domains.

Since the inception of CE, the nature of organizational teams and collaboration has evolved. New collaborative structures have emerged, such as community crowdsourcing and open innovation. New technologies and platforms have emerged such as social media, mobile apps, and artificial agents that support individual and team-based problem solving. At this point, it would be therefore be valuable to take stock of the exiting research; to synthesize an overview of what it has already achieved, to identify significant areas of inquiry that have not yet been explored, and to look forward toward new CE research opportunities that are emerging as society, organizations, technologies, and the nature of collaboration evolve. This would provide a foundation upon which senior CE scholars could develop a validated canon of CE concepts that are already known, and from which they could derive a research agenda for the next decade. That is the purpose of this paper.

In this paper, we describe how we identified the CE literature from 2001 to 2017. We then provide an overview of CE research and its key contributions organized into four broad themes: Foundations, Approach, Tools, and Professionalization. We identify areas of research that require more work. Finally, we synthesize a number of overarching insights from past research and outline future research directions to stimulate continued scientific inquiry into ways to improve the productivity of individuals who make joint efforts to create value.

The Collaboration Engineering Literature

The CE literature spans a variety of topics, authors, domains of practice, research methods, outlets, and types of publications. Some CE manuscripts describe CE foundation concepts and aspects of the CE approach. The 2009 editorial, for instance, which introduced a special issue on Collaboration Engineering, summarized the contours of the CE approach as it had developed to that point [52]. Such descriptive overviews, however, are not systematic literature reviews. This paper offers a comprehensive, structured account of the complete CE body of knowledge. It aims to synthesize the CE literature from 2001 onwards, and to propose a CE research agenda that is grounded in both past research and current developments. In this section, we describe our procedure for identifying and analyzing relevant CE publications and summarize some demographic details about the body of CE publications.

CE Literature Identification and Analysis Approach

To develop an overview of past CE research, we followed the process as outlined by Webster and Watson [165]. We scoped our search period from 2001 to 2017, since the first CE publication appeared in January 2001 and our search was conducted in March 2018. We searched the ABI/Inform Global, Scopus, ProQuest, IEEE Xplore, ACM, AISel, and Web of Science indexing databases. To be thorough, we also searched Google Scholar and ResearchGate for articles not yet indexed elsewhere, and we conducted direct searches of a number of high-quality journals and conferences [165] that have traditionally published CE research, among them HICSS, ICIS, the Journal of Management Information Systems, and Group Decision & Negotiation. Initial search terms included "Collaboration Engineering," "thinkLet," "thinkLets," and "patterns of collaboration."

Next, based on the keywords in the collection of CE publications with identified using the initial search terms, we expanded our search terms with "facilitation," "practitioner," "collaboration engineer," "facilitator," "Group Support System," "GSS," "meeting design," "convergence," "shared understanding," "build consensus," and "repeatable process." To determine the relevance of each publication we discovered, we examined keywords, the abstract, and references to gauge whether it was likely that the publication drew on and contributed to the field of CE. This initially yielded well over 2,000 articles. We narrowed the set to publications that, at a minimum, met these two criteria. First the publication was refereed, such as a journal article, conference paper, or scholarly book chapter. Dissertations and technical reports were excluded. Second, the publication did not just reference CE research; rather its aim was to contribute to the CE literature. For example, we excluded publications that provided a discussion of CE in the background section, but did not appear to make a novel contribution to the CE literature such as new or expanded concepts, techniques, technologies, or theories, and laboratory or field assessments of such objects. This analysis was first done by the first author and validated by the second author.

Finally, we performed backward and forward citation chain searches [165] on the resulting set of publications to determine if we missed any studies from the other sources. This did not result in any additional publications, which was taken as an indication that are search had approached completion. The final set of publications consisted of 331 refereed CE publications between 2001 and 2017.

We performed a concept-centric analysis of the set of publications [165]. Each paper was read and analyzed in terms of its focus and contributions, which were captured in a tabular format similar to a Concept Matrix [165]. We piloted several approaches to organizing the review. We first explored creating a time-based description to show how, in certain time periods, researchers focused attention on particular CE topics and methods. We abandoned this approach as it resulted in a choppy description; for example, after the initial thinkLets conceptualization, the thinkLet concept evolved over a long period of years such that each periodic description would have to address the thinkLet concept. We also explored whether it would be insightful to identify different "research cultures" or "subprograms" in CE research by looking at groups of authors that work together. This proved cumbersome as there was an extensive network of collaborations among researchers across the world, and the partnerships were dynamic. In the end, we found it useful to classify contributions by topic, rather than by publications, authors, or time periods. Some publications made multiple kinds of contributions, and so contribute to several categories of contributions. A concept-centric approach gave clarity to the descriptions of the research.

After identifying the findings and contributions of each publication, we developed a two-tiered organizing structure. The top tier consisted of four broad themes that emerged from our analysis: Foundations, Approach, Tools, and Professionalization. Each top tier theme consisted of a number of subthemes. Finally, we placed notes on each publication's focus and contribution into this two-tiered structure, and organized all the subthemes into a logical flow that allowed us to explain how the research evolved in that particular area.

As we describe and synthesize of the CE literature presented in this paper, we typically cite the "terminal" publications in which researchers reported on their study: we refer to the refereed journal publication, but do not cite earlier conference papers. Thus, the references in this paper are not a complete list of all CE publications.

CE Literature Demographics

The publications the set of 331 provide a rich picture of the variety and scope of CE research, in terms of locations around the world where the research is conducted, research methods employed, and application domains addressed. A large number of CE researchers employed research methods that focused on relevance and used data from the field, such as case studies, action research, and Design Science Research. CE researchers have used CE methods and techniques in a broad range of application domains, including but not limited to service-oriented and enterprise architectures (e.g., [122, 126]), aerospace design [112], software engineering (e.g., [3]), Internet-of-Things (e.g., [10]), deception detection (e.g., [61]), open source communities (e.g., [115]), and citizen engagement and participative governance in communities (e.g., [2, 4, 34, 138, 161]). A more detailed account of specific CE applications will be given in the section on CE field experiences.

As can be seen in Figure 1, CE research was most active in terms of publications between 2006 and 2013. While the trend appears to have slowed over recent years,

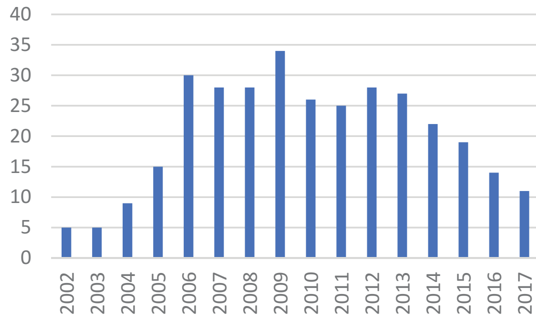

Figure 1. Number of CE publications per year

the data from 2017 may not yet be complete and CE researchers have recently begun addressing new forms of collaboration such as crowdsourcing, social media collaboration, and AI-infused team work [149, 162]. This is expected to result in an uptick in CE publications for the coming years. Table 1 gives an overview of the different countries and their authorship frequencies where authors of CE research are located, illustrating the globally diverse origins of CE research. Among these countries, the United States, the Netherlands, and Germany are the most frequently occurring. Interestingly, peer reviewed CE research has taken place on every permanently inhabited continent, except Australia.

In the next four sections, we will discuss the results of our literature assessment in terms of the key CE research contributions, organized into the four broad themes that emerged from our analysis: Foundations, Approach, Tools, and Professionalization.

Theme I: Foundations

The foundations for CE research were based on an interesting phenomenon discovered by GSS researchers: Many organizations abandon GSS installations after one-to-three years, even in with compelling evidence in hand of triple-digit returns on investment [1, 20]. Research showed a root cause to be complexity [20]. The

Table 1. Authorship Countries for CE Publications 2001–2017

Algeria (1)	Germany (34)	Scotland (1)
Austria (21)	Greece (1)	South Africa (7)
Brazil (6)	Ireland (2)	South Korea (1)
Canada (2)	Italy (1)	Spain (6)
Chile (5)	Luxembourg (2)	Sweden (1)
China (22)	Mexico (1)	Switzerland (10)
Columbia (14)	The Netherlands (111)	Taiwan (1)
Denmark (5)	Portugal (3)	Uganda (3)
Finland (10)	Romania (6)	United Kingdom (20)
France (11)	Saudi Arabia (1)	United States (154)

most widely-used GSS had millions of possible configurations. Most teams did not know how to design effective collaboration processes, much less how to configure the many capabilities of a GSS could offer to support their processes. They therefore resorted to professional facilitators, with whose help they could realize significant improvements in speed, cost, and quality. Organizations, however, found that professional facilitators were rare and, therefore, expensive to hire and train; as a result, most groups could not afford their services. Furthermore, facilitators were difficult to retain over time. Their skills gave them rapid upward mobility in their organization.

Researchers therefore developed ways to codify a facilitator's expertise such that it would be easy for team members to learn and reuse. This codification produced the thinkLets pattern language [20, 128, 55]. Researchers further defined six patterns of collaboration: observable, changes-of-state that characterized the way teams moved through their activities. Teams could reliably invoke known variations on these patterns by executing a series of thinkLets [107]. The details of these foundational contributions to CE research are discussed in the next two subsections.

ThinkLets

A thinkLet is a named, scripted procedure that reliably creates predictable variations in the patterns of collaboration by which a group moves through its activities [55]. They are facilitation best practices. ThinkLet documentation distills to its essence the concepts a team leader needs to know to reproduce a desired effect in groups working toward a joint goal. ThinkLets codify techniques that collaboration professionals use time and again across many situations. For example, a professional facilitator would use one specific technique when a team needs to brainstorm in depth and detail on a narrow set of topics, a different technique when the teams needs to push for breadth and variety. They would use a different technique when the team needs to organize brainstorming ideas into a set of categories, and yet another when the team need to converge to a single idea out of many. ThinkLets comprise a pattern language as proposed by Alexander: a collection of reusable elements and solutions for recurring design problems.

In its original conceptualization, each thinkLet had a name, and it specified only three elements [23, 20]:

1. The collaboration technology the team should use.
2. The way the technology should be configured.
3. A script specifying what the team leader should say and do to instantiate the technique. The script included prompts to give a team, behaviors, and events to watch for, and decisions that should be made in response to the team leader's observations.

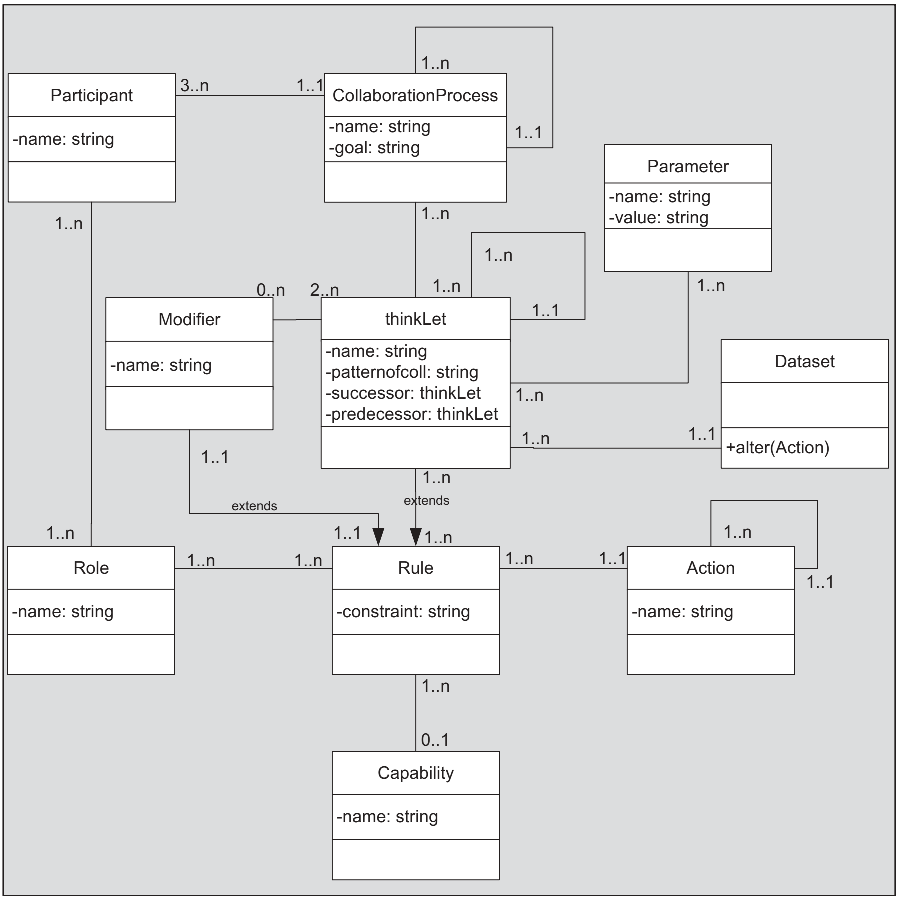

Figure 2. uml class diagram of a ThinkLets Design Pattern [100], reprinted by permission

This conception, though, made the techniques technology-dependent. Further research produced a more detailed and technology-independent conceptualization of thinkLets that situated a technique in a larger context of relationships among objects (Figure 2).

The key elements of the second thinkLet conceptualization [100, 99]:

1. *Name*, an easy-to-remember mnemonic.
2. *Capabilities*, the affordances a collaboration tool would have to provide to support the collaboration procedure. By defining capabilities instead of specifying the configuration of a specific tool, thinkLets could be used on different platforms. For example, brainstorming needs a shared page capability, which could be realized with paper, a wall of PostIt notes, or a computer screen.

3. *Actions*: What individual participants are to do with the capabilities. Six canonical actions turned out to be sufficient to specify a thinkLet: to add, modify, associate, judge, aggregate, and delete ideas.
4. *Rules*: defining what *action* each *role* should take using what *capabilities* under what *constraints*.
5. *Roles*: Subsets of actors who are bound by the same rules. For example, in a brainstorming activity, the rules for a participant in a Devil's Advocate role might require them to add critiques, while the rules for Regular Participant might prohibit the adding of critiques.
6. *Parameters*, which specify the information that a team must have as input to a technique, and what outputs the team will produce. For example, at a minimum, a multiple topic brainstorming technique must have as inputs: a) a brainstorm question and b) the set of topics.

Based on the second conceptualization, a number of researchers made other notable contributions to the thinkLet-foundation for CE research. For example, Knoll and colleagues developed a deeper specification of the script aspect, using thinXels as atomic script elements [87, 88]. Chatterjee and colleagues incorporated the perspective of participants' ethical values in the design and codification of thinkLets so that the resulting collaboration processes have a stronger ethical foundation [35]. Several researchers discovered that the rules for thinkLets could be modified on-the-fly by adding or deleting rules so as to produce predictable variations on their normal effects [94]. One could, for example, add a new rule to any brainstorming technique requiring that new contributions had to be arguably better in some way than the ideas previously contributed. With the additional rule, groups tended to produce fewer, but higher-quality ideas. Researchers codified these reusable rule-changes into the thinkLets design pattern language, and referred to them as "modifiers" [99]. The rule previously described (that new contributions should be better than those already contributed), for example, is called the "One-Up" modifier. Some modifiers are general-purpose, meant to be used in any context where the modification would be useful. Other modifiers are geared toward specific contexts, for example, one collection of modifiers addresses quality assurance during co-creation workshops [105].

ThinkLets also have also been recognized as a theoretical lens through which collaboration techniques and processes can be studied. For example, the thinkLet conceptualization offered a way to compare brainstorming experiments to explain apparently conflicting findings [144]. ThinkLets also provide a foundation for research tools to collect, document, and analyze team processes in terms of the behaviors of individual team members in distributed or co-located groups (see, e.g., [151]). Another significant stream of research involved the use of thinkLets to structure and study processes related to trust development in co-located, hybrid, and fully distributed teams of individuals that were working together through computer-mediated collaboration [43, 36, 38, 45, 15].

Finally, thinkLets provide a conceptual framework to study collaboration in specific application domains. Notable examples here include the design and exploration of collaborative mechanisms in serious games (e.g., [5, 160, 13]), collaborative modeling in the context of system dynamics (e.g., [82, 81]), and learning strategies in virtual teams [63, 64].

In summary, the CE literature on thinkLets appears to have transitioned from developing and expanding the thinkLet concept itself to using it as a theoretical lens and design concept in different domains. The conceptualization of thinkLets appears to have stabilized; there have been few revisions in recent years. Yet, the use of thinkLets as a theoretical and design lens appears to be gaining momentum, especially in the area of learning and gamification.

Patterns of Collaboration

When teams collaborate, their behaviors produce observable changes-of-state that move them toward their goals [107]. Kolfschoten and colleagues [96, 107] performed an in-depth analysis of data from numerous workshops to identify these regularities. This led to the definition of six distinct patterns of collaboration, each defined as a change-of-state [22]:

- *Generate*: To move from having fewer concepts to having more concepts in the shared set (e.g., brainstorming).
- *Reduce*: To move from having many concepts to a focus on fewer concepts deemed worthy of further attention (e.g., through filtering concepts or abstracting a general concept from multiple instances).
- *Clarify*: To move from less to more shared understanding of the meaning of the concepts in the shared set.
- *Organize*: To move from less to more shared understanding of the relationships among the concepts in the shared set (e.g., by organizing concepts into categories or modeling their relationships).
- *Evaluate*: To move from less to more understanding of the value of concepts toward goal attainment (e.g., estimating the required effort needed to realize a set of user stories and estimating the likely utility that could be realized if they were implemented).
- *Build Commitment*: To move from having fewer to having more stakeholders who are willing to commit to a proposed course of action (e.g., stakeholders negotiate a set of system requirements that produce value for each individual as well as achieve the team goal).

CE researchers have published a number of exploratory, theoretical, experimental, and applied science studies on some of the collaboration patterns since they were formalized, and fewer studies on others. To the best of our knowledge, though, no CE research has taken place on the "evaluate" pattern of collaboration. We summarize the key studies and findings for the other patterns of collaboration as shown in the following section.

Generate: Idea generation techniques such as brainstorming have been a popular topic for researchers in various disciplines since the 1950s [136]. ThinkLets to support generation have also been researched extensively by CE researchers. For example, Santanen and de Vreede contrasted the work products from four variations on a Generation thinkLet in which a moderator prompts the group with several categories of stimuli [145]. Santanen and colleagues [146] proposed the Cognitive Network Model of Creativity, and demonstrated that changing the degree to which categories of stimuli were intermingled led to predictable differences in idea uniqueness and usefulness, and in the degree to which creative ideas were paradigm-breaking vs. paradigm-preserving. Knoll and Horton [86] showed that, under certain conditions, thinkLets focused on "change of perspective" techniques could enhance team ideation performance.

Early brainstorming researchers assumed that the more ideas a group produced, the more good ideas there would be [136], and based on that assumption, many CE researchers who studied generation thinkLets measured only the number of unique ideas a group produced. Helquist and colleagues [79] demonstrate that the quality of brainstorming ideas may drop over time in participant-driven thinkLets-based workshops. Reinig and colleagues [143] analyzed several paradigms for measuring ideation quality and demonstrated that two widely used measures, "sum-of-quality-scores" and "average quality scores," had inherent mathematical biases; under some conditions these measures would produce opposite results when comparing the quality of the same ideas sets. They demonstrated "count-of-good-ideas" was an unbiased and stable measure of ideation quality. In addition, Briggs and Reinig [32] proposed Bounded Ideation Theory, a cognitive model of the relationship between idea quality and idea quantity to demonstrate that the presumed relationship between idea quality and idea quantity would only hold under a narrow set of conditions.

CE researchers also explored special forms of generation processes. For example, Azevedo et al. [6] demonstrate that, under some conditions, graphical brainstorming could be integrated with traditional text-based generation thinkLets to produce better outcomes. Another study shows that using the same generation thinkLets in large teams could to different outcomes depending on whether subteams work independently or interdependently: subteams that continue with the results from previous subteams produced deeper elaboration of generated ideas and reported higher levels of satisfaction [53].

Reduce and Clarify: In combination, the patterns reduce and clarify are also defined as *convergence*: to move from having many concepts to having a focus on and understanding of fewer that are worthy of further attention [20, 150]. CE researchers found that, from the team leader's perspective, convergence is the most challenging of the patterns of collaboration [60]. Yet, contrary to the broad popularity of brainstorming research in general, convergence has received comparatively limited attention.

The first conceptual foundations for the convergence pattern were proposed by Davis and colleagues [49]. They describe convergence as a combination of three subprocesses: filtering (selecting), generalizing (reducing through abstraction or synthesis), and establishing shared meaning (clarifying). They further propose a set of ten quality indicators for the convergence process and outcomes. A further theoretical exploration of convergence from a cognitive load perspective was proposed by Kolfschoten and Brazier [97].

After an initial foundation was established, early research efforts focused on gaining a deeper understanding of this pattern through the detailed analysis of convergence field data [7]. To this end, researchers proposed sophisticated ways to code field data so that it could be quantitatively analyzed in terms of reduction and clarification [8]. Initial coding schemes allow researchers to identify unique elements in team contributions, which would make it possible to compare different teams' convergence performance. Later developments focused on the quality and elaboration of converged ideas, again to enable performance comparisons between teams [150].

Different CE researchers developed specific convergence thinkLets and reported on their effectiveness. For example, shared understanding, representing the clarification aspect of convergence, was explored by Bittner and Leimeister [11] who successfully fielded a dedicated thinkLet (MindMerge) in a car company leading to increased team learning and shared understanding of complex team tasks. Görs and colleagues [75] developed a filter algorithm to extract the ideas that are worthy of more attention and demonstrated that the quality of this convergence process was comparable to team-driven approaches yet much less demanding in terms of cognitive load.

In recent years, one can see an increase in in-depth studies of the convergence process and convergence thinkLets. Seeber and colleagues [150, 153] performed a series of detailed explorations of the efficacy of several convergence thinkLets for outcome quality and participant satisfaction. They first report on the execution and outcomes of different convergence thinkLets in the context of a crisis response task. Under the conditions of that study, the elements of attention guidance and discussion encouragement correlated with higher convergence quality. They further found that under the observed conditions, unlike other studies, participant satisfaction was higher after idea convergence than after idea generation. A separate study based on Control Theory [80] found that teams that used engineered convergence processes had deeper interactions and a greater degree of idea development than did self-managed teams [154]. In his study they also found a positive correlation between leaders' and members' agreement on their depth of interaction and the extent of development of the ideas in the set of convergence results.

Finally, another set of studies focused on the organization of the overall team process in terms of whether a team converged their own or another team's brainstorming results. Davis and Murphy [48] found that, under the conditions of their study, teams who converged another team's ideas were more creative and more satisfied than teams that converged their own ideas. Seeber and colleagues [151,153] explored this concept in a crowdsourcing context. They found that teams converging on self-generated ideas have better social exchange processes in terms of dominance and coordination than did teams who converged the ideas of others. The crowdsourcing context was also the focus for Fu and colleagues [73]. They propose that different approaches to scoping, presenting, and guiding a convergence task are related to differing levels of intrinsic, extraneous, and germane cognitive load [135].

Organize: The organize pattern has been subject to minimal CE research. Druckenmiller [65] proposed a knowledge-centric perspective on the organizing pattern and demonstrated how organizational schemas could support this pattern of collaboration. While CE researchers subsequently proposed a detailed organization research agenda [142], no additional research on the organization pattern of collaboration has been reported to the best of our knowledge.

Build commitment: Originally, the build commitment pattern was referred to as build consensus. Early work by CE researchers focused on developing a theory, the Consensus Building Theory (CBT), to explain why individuals working in teams would be more or less likely to reach consensus and build commitment to a set of proposals [21]. Additional work in this area uses CBT to propose a diagnostic to determine the source of poor consensus in requirements workshops [92]. Finally, researchers also provided a theoretical exploration of the build commitment pattern from a cognitive load perspective [104]. Similar to the organize pattern, however, build commitment has, to date, received comparatively minimal research attention.

In summary, CE research on the patterns of collaboration has seen a decreasing trend in terms of attention for the generate and build commitment patterns, while there has been an increasing trend for the convergence (reduce and clarify) pattern. On the generate pattern, most research activity appears to focus on thinkLets and creativity perspectives. However, there have been few, if any, CE publications on the generate pattern in the last decade. On the organize and build commitment patterns, research efforts to date have been exclusively theoretical and conceptual. As stated, on the evaluate pattern, no CE publications were identified. One possible explanation is that there is already a body of knowledge on how individuals and teams evaluate ideas and options in the creativity and decision-making literatures. In contrast, convergence research appears to be maturing in recent years: From initial studies to define the pattern and its measures, a variety of researchers have engaged in exploratory experimental and field studies. This has resulted in a deeper understanding of the convergence process and outcomes. Although recent studies have begun to propose theoretical explanations for their findings, there is still limited theoretical advancement on the convergence pattern in terms of a causal theory that predicts convergence performance. Yet, the steadily increasing number of conference publications on convergence may be an indication that more research is currently underway.

Theme II: Approach

ThinkLets provided a foundation for CE researchers to transfer a distilled set of proven collaboration techniques to novices. Building on this foundation, the next major thrust for CE research focused on designing and transferring fully engineered collaboration processes. To this end, researchers developed a structured design approach, which was called "Collaboration Engineering." De Vreede and Briggs [51] provided the first description of CE: They highlighted CE's elements in terms of the Five Ways framework which can be used to provide a structured description of a design methodology [155]:

- *Way of Thinking*: defines how an approach conceives the object of design. It defines key terms, models key phenomena, and details an approach's design philosophy.
- *Way of Working*: defines the design steps, their interrelationships, and deliverables.
- *Way of Modeling*: defines ways to represent aspects of designed objects (e.g., structured visualizations and descriptions of designed objects).
- *Way to Control*: defines the project management aspects of an approach.
- *Way of Supporting*: describes the tools and technologies to support design activities.

The main subthemes of research on CE as an approach are threefold: a) a structured methodology to design collaborative work practices, b) transferring engineered work processes to practitioners so that they can be deployed in their organizations, and c) theoretical foundations to explain key collaboration phenomena that the engineered collaboration processes were expected to improve. Initially, most of the research on the CE approach focused on the Ways of Thinking, Working, Modeling, and, to a limited extent, Control. The research that has been conducted for these ways is described in the following section. The Way of Supporting received significant attention in later CE research and will be described in the next section, along with other tool development efforts to support CE.

Way of Thinking

Researchers define CE as an approach to designing collaborative work practices for high-value recurring tasks, and to deploying those designs for practitioners to execute for themselves without ongoing support from professional facilitators [22]. The key object of design, collaboration, is defined as joint effort towards a common goal [22]. A collaboration process is defined as a sequence of activities performed by a group to achieve a goal [92].

The CE design philosophy consists of four cornerstones. The first concerns *collaboration "engineerability,"* the assumption that the object of design in CE, collaboration, can be engineered. Kolfschoten and colleagues [102] explore this assumption and argue that the "engineerability" of collaboration is substantiated when three conditions have been met:

- One can evoke with some predictability the commitment of resources to a group goal. This condition is based on goal setting theory, which has received broad support in empirical studies [117].
- One can structure or focus joint effort through a specified sequence of actions that move a group predictably towards the attainment of a group goal. This condition is grounded in past research that shows that thinkLets can be used as a pattern language where each thinkLet produces predictable patterns of collaboration in a group and where thinkLets can be strung together to create a sequence that allows groups to attain their goals [55].
- One can use a systematic approach to the design of collaboration processes. This condition has been met through the efforts of the CE research community itself and its rich collection of field studies and empirical assessments.

The second cornerstone of the CE Way of Thinking concerns *a pattern perspective on design*. A collaboration processes is conceived as a sequence of design patterns: solutions for recurring collaboration problems [55]. The pattern perspective in CE is embodied in the thinkLets pattern language, which has been previously described. Furthermore, pattern thinking in CE goes beyond the design aspects of the CE approach; patterns have also been shown to be easier teach to novices as solutions for recurring collaboration challenges [108].

The third cornerstone relates to the *roles in the context of a CE effort*. Researchers identified two unique roles in CE [128]. In traditional collaboration settings, there are participants (e.g., team members) and a facilitator. The participants execute the process that the facilitator has designed and moderates. This process design is typically specifically created for the challenge that the team has to address. In CE, the first new role is the *Collaboration Engineer*, a collaboration expert that can design a collaboration process in such a way that team leaders to execute it by themselves with little or no training on either the tools or the techniques. Thus, a collaboration engineer creates "leave-behind" collaboration process designs. The second new role is the Practitioner. A *practitioner* is a domain expert who is not a collaboration expert but is in charge of conducting the collaboration process. Examples of practitioners are risk managers who guide risk assessments, SCRUM Masters who guide user story generation and convergence exercises, or military leaders who lead After Action Reviews. A practitioner has experience in the team's task, but has limited facilitation expertise. A practitioner typically must guide repeated execution of a set task on a regular basis.

In a series of experiments, Kolfschoten and colleagues demonstrated that domain experts can indeed lead successful collaborative work by following an engineered work practice. For example, their initial experiment compared the performance of inexperienced students and organizational practitioners with the performance of professional facilitators [92]. The students and practitioners were provided with a CE design and brief training on the execution of the thinkLets in the design. A comparison between students/practitioners and professionals found no significant difference in terms of participants' satisfaction with process and outcomes and participants' commitment to outcomes. Further support for these findings came in a follow-up field experiment in a service organization, where researchers compared practitioners with an engineered work practice to professional facilitators, and demonstrated there were no significant performance differences between the two groups for a specific organizational collaboration process [106].

The final cornerstone of the CE approach's way of thinking concerns the notion of 'design guided by theory'. CE researchers have developed a number of causal theories that explain phenomena of interest that are critical to CE, such as satisfaction (Yield Shift Theory [31], transition of work practice (Technology Transition Model/Value Frequency Model [1, 20, 24, 25], creativity (Cognitive Network Model of Creativity [146]), and consensus (Consensus Building Theory [21]). These theories support collaboration engineers as they inform their designs when they determine the sequence of activities in a collaboration process or the selection of specific thinkLets. Furthermore, some of these theories also provided a research foundation in other domains, for example, the Value Frequency Model has been used in the domain of knowledge sharing [14].

In summary, as the Way of Thinking lays the foundation for an approach and defines its design philosophy, it is not surprising that most CE research in this area occurred early on when researchers developed the CE Approach. Once these foundations were laid, no further publications on the "engineerability," pattern thinking, and CE roles was identified. However, research that aims to develop causal theories appears to be still ongoing. Interestingly, most theoretical CE research focuses on theory-development, rather than the application or extension of existing causal theories to CE issues.

Way of Working

CE researchers distinguish between two phases in the CE approach: the design phase, where the collaboration engineer works with practitioners to create a thinkLets-based collaboration process prescription for a repeatable task, and the deployment phase, where the process prescription is implemented in the organization following the training of a number of practitioners [92]. During the deployment phase, the process prescription can be further updated based on the practitioners' experiences.

Design Phase

To understand the design practices of experienced facilitators and collaboration engineers, CE researchers collected surveys and conducted in-depth interviews [94, 92]. This informed the initial design approach, which was further fine-tuned in a series of four field studies [92]. The resulting way of working for the CE design phase consists of five main steps:

1. *Task diagnosis*, consisting of an analysis of the task, the stakeholders, available resources, and practitioners.
2. *Task decomposition*, consisting of pattern decomposition and process result decomposition.
3. *ThinkLet choice*, focusing on mapping thinkLets to the steps in the process.
4. *Agenda building*, including the creation of the Facilitation Process Model and Agenda Notation Model.
5. *Validation*, which takes place by performing one of more of the following: pilot testing, walk-through, simulation, and expert evaluation.

The other significant contribution concerning the CE design phase was the development of a CE reference model, consisting of an organized collection of design aspects that a collaboration engineer must consider when designing a repeatable collaboration process. The first version of the reference model was the Seven Layer Model of Collaboration (SLMC) (Figure 3). The SLMC considers collaboration processes at seven levels of abstraction [26]: the *goals* a team must meet, the *products* they must create to meet the goals, the *activities* they must execute to create the products, the *patterns of collaboration* that are required for the activities, the *techniques* that are needed to create the patterns of collaboration, the *tools* that the team must use as a platform to implement the techniques, and finally the *script* that the practitioners must follows during the execution of the collaboration process. The SLMC became an organizing structure for the multitude of constructs, metrics, theories, design concerns, and best practices in the CE domain. Design choices at a higher layer constrained design choices at the lower layers, such that the model could be used to structure CE design activities. The separation of design concerns aims to reduce cognitive load for collaboration engineers and improve completeness of their collaboration process designs.

Why	1. Goals
	2. Products
What	3. Activities
How (Logical Design)	4. Patterns of Collaboration
	5. Techniques (ThinkLets)
How (Physical Design)	6. Tools
	7. Scripts

Figure 3. Seven layer model of collaboration (based on [26])

1. Collaboration Goals Layer: Considers the *group goals*, the *private goals* that motivate individual effort toward the group goal, and *goal congruence,* the degree to which members perceive that effort toward the group goal will advance their private goals.
2. Group Products Layer: Concerns the work products a group will create to attain its group and private goals.
3. Group Activities Layer: Concerns the sequence of activities a group must execute to create the group products.
4. Group Procedures Layer: Concerns the patterns of collaboration and techniques for moving a group through each of its activities.
5. Collaboration Tools Layer: Concerns the design and configuration of tool capabilities the group will need to instantiate its procedures.
6. The Collaboration Behaviors Layer: Concerns designed constraints on the things people should say and do with their tools to instantiate the procedures to move through the activities to create the deliverables to achieve their goals.

Figure 4. Six Layer Model of Collaboration (based on [29])

The utility of the SLMC was demonstrated in a study by Read and colleagues [141] who applied it to improve a Military Decision-Making Process. However, subsequent research revealed some anomalies in the model. There were, for example, constructs, metrics, theories, best practices, and techniques for five of the seven layers, but those were lacking for the Patterns of Collaboration and Techniques layers. Researchers argued that those two layers were components of a more general *Procedures* layer. The second version of the reference model was thus reduced to six layers, at which point the classes of objects associated with other five layers manifested for the procedures layer as well. Researchers also noted that Scripts were a specific instance of an approach for guiding participant behaviors, and that there were also other approaches available. For example, a script could instruct participants to refrain from deleting one another's brainstorming contributions, but the same goal could be achieved by switching off the delete capability in an electronic brainstorming tool. The second of version of the reference model therefore re-labeled the Scripts layer to the Behaviors layer (Figure 4). The SMLC provided the backbone for measuring the quality of an engineered work practice, and the performance of collaboration engineers [139]. This is discussed in more detail in the section on CE standardization and certification.

Finally, additional research on the CE design phase focused on the "front end" of the approach. Dean and colleagues [58] proposed a way for organizations to make the CE investment decision before actual design activities would take place. Furthermore, Briggs and Murphy [27] developed and fielded a protocol to support the systematic identification and selection among CE opportunities in an organization. In a two-year field study with a large organization with a multinational presence, they used the protocol to correctly predict the outcomes for 26 of 29 process-change initiatives.

Deployment Phase

Researchers proposed a structure for a CE training program using Cognitive Load Theory (CLT) as a foundation [135]. CLT distinguishes between three types of cognitive load that impact individuals' learning. *Intrinsic* cognitive load is the interaction of an individual's capabilities and task complexity. *Extraneous* cognitive load relates to how information is presented. High levels of intrinsic and extraneous cognitive load may cause cognitive overload if they leave too little working memory capacity available. *Germane* cognitive load relates to the designs and procedures that aid the processing, construction, and automation of schemas. A schema is a knowledge framework that represents a class of things, events, and situations. CE researchers crafted the specifications of the documentation that results from the CE design phase to minimize intrinsic and extrinsic cognitive load, while stimulating germane load [103]. They also developed a training program structure consisting of lectures, simulation, coaching, observation and self-study [110]. The effectiveness of the training program was demonstrated in a longitudinal field study [109]: 155 practitioners in a financial institution responded predominantly positively to a survey instrument that was based on the theoretical foundations of the training program and collected perceptions on mental effort and self-efficacy.

In summary, the development of design and training approaches took place in an intensive fashion over the course of about a decade. During this time, the CE research concerned moved in two phases: First the approaches (or parts thereof) were conceptually proposed and illustrated. Next, the approaches were evaluated through experimentation and field applications. After the publications of initial successful demonstrations, we did not identify any studies that made conceptual advances to the design and deployment ways of working. However, the successful application of the design approach has been demonstrated and reported in a large number of field applications (see the section on CE field applications).

Way of Modeling

The way of modeling deals with representing essential aspects of a designed object. Research on CE's way of modeling yielded two modeling techniques that in common use among CEs in the field. The first, Facilitation Process Model (FPM), is a CE-specific flowchart, depicting the activities of a work practice along with the conditional logic for their order of execution. Each activity appears with a name, a brief description, the pattern of collaboration it aims to produce, the technique to be used, the nominal start time and length of the activity, and activity deliverables. The logical flow between the steps is depicted by arrows for flow direction and circles for decision points. An FPM is a high-level map of the process design that is often a training aid for practitioners. Examples of FPMs can be found in [20, 50]. FPMs are particularly useful for training practitioners to execute an engineered work practice, and for maintaining group orientation as the work practice unfolds [101]. In recent years, researchers have identified some limitations to the original FPM technique and have proposed extensions. For example, Solano and colleagues [157] expand the FPM technique using concepts from HAMSTERS (Human-centered Assessment and Modeling to Support Task Engineering for Resilient Systems); specifically, they add elements to model input/output, and assigned roles.

A second modeling convention, an Agenda Notation Model (ANM), captures a more-detailed representation of how to execute the process flow represented by an FPM. It provides a compact, structured, textual representation of everything a practitioner would need to know to conduct an engineered work practice. A collaboration engineer uses it to capture details of the physical design for the process. A practitioner uses it as a cheat-sheet to guide the process at execution time. An ANM specifies the name and duration of each activity, and for each activity specifies the thinkLet and modifier(s) to be used, the input and output parameters of the thinkLet(s), the tool(s) and their configuration(s) for the activity, and any task-specific guidance for the group to initiate, conduct, and/or close the activity. An example of an ANM can be found in [52]. The ANM is particularly useful for transferring the details of an engineered work practice to practitioners in a compact format. For example, before the advent of ANM, complete documentation of an engineered requirements negotiation work practice called EasyWinWin required 162 pages of text; the same work practice could be captured in fewer than five pages using ANM [12].

In summary, research on the way of modeling of the CE approach has predominantly focused on proposing and using two specific modeling techniques. While especially the use of FPMs has been reported in CE field applications, little additional research has taken place on these modeling techniques.

Way of Control

Relatively little research attention has yet been paid to the CE Way of Control. One study found in our literature search concerns the proposal of a CE Maturity Model [146]. This maturity model can be used to benchmark and analyze the CE efforts within an organization. It addressed both phases of the CE approach and defines a number of associated maturity levels. To date, to the best of our knowledge, no application of this model has been reported. More recently, researchers proposed an approach to measuring the performance of collaboration engineers based on the Six Layer Model of Collaboration, combined with an approach to designing collaborative work practices [92]. This work subdivided CE methodology into fine-grained phases, activities, and action items, and proposed goals, deliverables, design concerns, and key performance indicators for each subdivision [139]. Researchers tested the approach with collaboration engineers in an international consulting firm on projects in the USA, Europe, and Africa, and the organization adopted it as the foundation for evaluating their collaboration engineering personnel [139]. No research has been identified that evaluates the merits and limitations of this approach.

In summary, CE research on the way of control has been limited and conceptual in nature. While researchers have proposed different frameworks to benchmark and assess CE efforts, no empirical applications and assessments of these frameworks have been found.

Theme III: Tools

There have been various research efforts to develop and field tools to support the collaboration process design and execution. Many of these tools represent the CE Way of Support—tools that support collaboration engineers to design collaborative work practices—while others support practitioners in the execution of a work practice.

Early efforts in this area focused on providing collaboration engineers with automated support regarding the selection and combination of thinkLets for a collaboration process based on the characteristics of the task, team, and practitioner. For example, some researchers proposed automated *thinkLets libraries*: Kolfschoten and colleagues [98] propose a library of patterns that can be selected when creating a design, while Druckenmiller and colleagues [66] use the thinkLet concept as a foundation for a general database of facilitation techniques. Other researchers prototyped *thinkLet selection tools* that offered some limited guidance to support agenda building [e.g. 95, 163]. Finally, CE researchers have proposed *expert systems* that recommend thinkLets for specific situations and group needs [9, 124]. For example, Ducassé [67] reports on a CE expert system that recommends process designs based on past experiences and past designs of similar processes.

Another group of researchers focused on operational execution tools that are based on CE concepts and principles. These tools are meant to support both practitioners and professional facilitators. For example, different studies show how intelligent agent-based indicators can alert a team leader and automatically launch or recommend specific thinkLets in the context of virtual teams [118, 93]. Others propose how to measure real-time group dynamics in electronic idea generation [166]. Veiel and colleagues [164] explore automated facilitation using context adaptive technology and report promising initial findings of their acceptance in small teams.

Finally, more recent research on CE technology aims to make it possible for practitioners to execute engineered work practices without any training. These studies investigate the feasibility of packaging the collaboration expertise together with the technology in a form that practitioners can use with no prior instruction. Initial efforts in this area propose generalizable component-based collaboration tools [33] and collaboration technology that adapts automatically to a collaboration process design [89]. A comprehensive solution, the 'Facilitator-in-the-box' concept, was prototyped in a CE design environment consisting of three elements [28]: A Computer Assisted Collaboration Engineering platform (CACE), a Process Support System (PSS) runtime platform, and a library of Process Support Applications (PSA) for practitioners to execute. The CACE allows a collaboration engineer to create PSAs tailored to the specifics of any particular task. The PSS runtime platform allows practitioners to instantiate a given PSA as a workspace for their specific process needs, and to use it to guide participants through the work practice it embodies. A PSA presents a practitioner with a sequence of activities. Each activity presents just the right tools in just the right configurations, displaying just the right data, and just the right guidance they needed to execute that step of the task. For example, a collaboration engineer could use the CACE to capture the design of an agile user story generation process as a thinkLets-based activity sequence and collection of user interaction screens. A SCRUM Master (practitioner) can select the User Story PSA from a library, instantiate it for a specific workshop (e.g. giving it a name, defining the start date and time, number of team members, and filling in specific thinkLet parameters), and can then execute it with the team.

Experiments with this rapid-development environment showed (1) that it reduces the development time for online collaboration systems by three orders of magnitude, (2) that it allows non-programmers to design and develop PSAs, and (3) that it packages enough collaboration expertise in the PSA that non-experts could execute a well-designed process *without* training [28]. Further field experiences with the CACE/PSS/PSA concept showed similar promising results [41, 39, 37].

In summary, there has been a varied and substantial amount of CE research on tool support. The reported studies demonstrate the viability of implementing many of the CE concepts into automated tools. Most field evaluations yield positive results. Yet, most research effort appear to focus on isolated prototypes. With the exception of the CACE suite, there are no integrated tool environments. The first experiences with CACE-based PSAs are promising, but a structured, programmatic assessment of such tools has not been reported yet.

Theme IV: Professionalization

The previous sections highlighted the scientific contributions of the CE research community. Apart from academic efforts, there have also been several initiatives to professionalize the CE approach and concepts in order to provide practical benefits to individuals and organizations directly. In this section we discuss the field applications of CE, educational initiatives related to CE, and efforts related to CE standardization and certification.

CE Field Applications

A key aspect of CE research is its relevance to practice. Since CE's origins were grounded in practical challenges that many organizations experienced, there has

Table 2. Field applications of Collaboration Engineering

Application	Key findings
EasyWinWin – Software Requirements Negotiation [12, 76]	Application of repeatable process in 8 universities across the globe teaching requirements negotiation through demonstrations and course projects and field projects in industry. Students are able to successfully run the workshops by themselves and report high levels of satisfaction and project success in the lab and in the field.
Collaborative writing [119, 91]	High levels of satisfaction, perceived performance, commitment to results, perceived value of process, and intention to use.
Risk & Control Self-Assessment [163]	Process considered effective by panel of subject matter experts.
Scenario logic design [68]	Enhanced scenario design experience.
Team Cognitive Task Analysis [77]	25% Time savings compared to the old process.
Business process improvement & document review [78]	89% Time savings compared to the old process.
Software code inspection [56]	Increase process efficiency and effectiveness. High levels of reported satisfaction.
Usability testing [54, 72, 123, 120]	High levels of productivity, positive perceptions on satisfaction, less duplication of effort compared to traditional groups, and more effective use of novice evaluators.
Incident Response Planning [47]	High process productivity and effectiveness. Modestly positive satisfaction.
Product line scoping in software engineering [129, 130]	higher productivity and high quality compared to traditional approach.
Strategy Development [18]	Process more productive, more democratic, and easy to transfer. High satisfaction.
Continuous user feedback for web-based IS [16, 17]	Demonstrated feasibility to involve very large groups of participants in process. High perceived usefulness, efficiency, and effectiveness.
Organizational Policy Making [125]	Moderate satisfaction, high efficiency, and satisfactory policy results.
Innovation design [69]	High satisfaction and solution quality.
Participative organizational change [59]	Low feeling of psychological safety in group process due to presence of supervisors.

Case studies and other (virtual) learning techniques [42, 46, 40, 44]	Higher learning effectiveness and lower required learning time. Improved student interest and satisfaction. High practicality and achievement of learning goals. Effective in trust development.
Innovation ideation & development [50]	High levels of satisfaction, perceived performance, commitment to results, perceived value of process, and intention to use. Easy to transfer.
SCRUM Backlog creation [50]	High levels of satisfaction, perceived performance, commitment to results, perceived value of process, and intention to use. Easy to transfer.
Improving student team processes [121]	Process design helped overcome communication, coordination, and motivation challenges. ThinkLets facilitate transfer of teamwork skills.
Software requirements elicitation [113]	High effectiveness and perceived requirements completeness.
Integrity Risk Assessments [106]	Practitioners' performance comparable to professional facilitators' performance.
Dyadic service meetings [148]	Improved intention to adopt a service, higher reported empowerment from customers.
Collaborative sensemaking [84]	Enhanced articulation and elaboration of understanding.
Citizen advisory services [74]	Increased interaction between advisors and clients, higher advisor empowerment, improved collaborative behaviors.
Business Model Development [156]	Practitioners' performance comparable to professional facilitators' performance.

been a steady stream of publications that report on professional applications of the CE approach and concepts. An overview of reported field applications as they were published over the years is given in Table 2 along with their key findings. The applications in this overview are focused on designing CE solutions for practical challenges and determining their worth. They represent actual design and/or deployment efforts to contribute a self-sustaining CE solution for a collaborative work practice.

From this overview, it appears that, when compared to existing processes, researchers consistently report improvements in terms of efficiency, effectiveness, and various quality indicators for the new collaborative work practice that was designed using the CE approach. Furthermore, when researchers report an assessment of the design work practice by itself (i.e., a non-comparative evaluation), results predominantly show high levels of satisfaction, productivity, and other phenomena of interest for the work practice concerned. Also, all studies that addressed the transferability of the designed collaborative practices to practitioners appear to be positive in their reports.

In summary, there has been a consistent stream of published CE field applications since 2001. These field studies took place in a variety of industries for a variety of collaborative work practices. Overall, their findings offer strong support for the practical applicability and value of the CE approach in terms of the quality of the designed collaboration processes.

CE Education

The growing body of CE knowledge has enabled researchers to develop university courses on facilitation techniques, on foundations of collaboration, and on CE design techniques. For example, graduate courses on thinkLets-based facilitation have been successfully organized at universities in the Netherlands, the United States, Germany, Austria, South Africa, and China. An undergraduate and graduate version of a course on Principles of Collaboration has been developed using the SLMC as an organizing framework. It is currently offered in at least three US universities. Other efforts report on how CE concepts were successfully used to teach students collaboration methods to improve their collaborative problem-solving strategies (e.g., [63, 117]).

Furthermore, graduate special topics classes on CE have been offered in Germany, the United States, and China. Also, a model syllabus for a graduate course on CE was developed and published under the auspices of the Association for Information Systems (AIS). This course focuses on theories and models of group collaboration, computer-supported collaborative work, methods and tools for designing group collaboration, and the application of CE techniques to solve a real-world problem [30].

While we have not been able to identify any structured assessments of the impact of the various CE-related course offerings, the various courses and course levels demonstrate that the research findings appear to make their way into the classrooms as well.

CE Standardization and Certification

Finally, a number of CE researchers have been working on professionalizing the CE area from a certification and standardization perspective. They have contributed a more formalized and detailed description of CE's underlying philosophy [140]. They also formalized a number of quality indicators that can be used to assess and benchmark the performance of collaboration engineers for each step in the CE approach and its deliverables [139]. These benchmarks and the articulation of the underlying philosophy of the CE approach pave the way for articulating a set of professional standards for practicing CE, for formalizing a professional training and certification program for collaboration engineers that create thinkLets-based processes, and for developing an online resource of CE materials for researchers, consultants, and organizational managers and team leaders [140]. As these all represent fairly recent studies, it appears that this is a fairly nascent CE research theme that may see increase activity in the near future.

Discussion and Conclusions

Since 2001, CE has been an active and productive area of research that has attracted scientists from different backgrounds and disciplines. As can be seen from the previous sections, the CE research community has produced a significant body of knowledge that has made contributions to theory, technology, and practice. In this concluding section, we first highlight a number of key insights that can be made based on our assessment of the CE research to date. Then, we outline an agenda for future CE research to stimulate continued scientific inquiry. Finally, we discuss the limitations of our efforts to review the CE research to date and provide our concluding comments.

Key Insights

The analysis of the CE literature has shown the value of the approach towards collaborative value creation in organizations. The practical usefulness of the CE approach has been demonstrated by the various field applications where collaborative work practices were designed and deployed. The scientific quality of the CE approach has been assessed through the structured peer review process to which the CE publications included in our analysis have been subjected. From the findings in the field and lab that have been previously detailed, we extract a number of insights about CE research and practice.

CE Reduces Organizations' Need for Collaboration Professionals

The CE field experiences demonstrate that the CE approach has the potential to reduce organizations' need for collaboration professionals across different application domains. For example, at ING Group over 600 risk professionals were trained during a period of 10 years in a collaborative risk and control self-assessment (RCSA) process [101, 50]. These practitioners have conducted thousands of assessment workshops across the world. Before adopting the CE approach to develop a repeatable RCSA process to be executed by their own risk professionals, the organization was actually considering to hire external consultants to conduct assessment workshops. The cost savings as a result of the CE approach are thus significant. Significant costs savings were also reported in other organizations (e.g., [77, 78, 50]).

CE designs are Transferable to Practitioners

Various studies demonstrate that thinkLets-based collaborative work practices can be successfully transferred to groups of practitioners. CE designs can be trained in hours or days, for example, the RCSA process at ING Group [101], the innovation process at Verisk Analytics [50], the SCRUM Backlog process at HHMI [50], and the Integrity Risk Assessment process in a governmental department [104]. This compares favorably to the months of on-the-job training that is typically required to teach someone to become an effective internal facilitator [1]. These experiences further lend support to make foundational concepts such as thinkLets and patterns of collaboration part of school and university core curricula. These concepts have value in practice and can be successfully taught and practiced in an efficient manner.

CE Designs are Based on Capabilities, Not Technologies

A CE design focuses on the capabilities that collaboration tools would have to afford to support the application of a thinkLet. A given capability could be afforded by any number of different tools and technologies. An audio channel capability, for example, could be afforded by a face-to-face meeting room, a telephone, or a computer-based conferencing tool. Likewise, an allocation polling capability could be implemented with electronic voting software, a spreadsheet, or sticker dots on a list of items written on a flip chart. Thus, thinkLets represent a technology-independent pattern language. This enables practitioners to execute CE process designs using tools they have at hand, whether they be electronic, paper-based, or something else. For example, the early pilots at ING Group were executed on a GSS, whereas the worldwide rollout was mostly paper-based using flipcharts, notepads, PostIt notes, and voting stickers [163, 101]. The Verisk Analytics process was paper-based, whereas the HHMI process used a GSS [50].

CE Focuses on Practices, Not Just People or Just Technology

The core design focus of the CE approach is the collaborative work practice. Unlike the majority of GSS research in the 1980s and 1990s, this focus is not technology-centric. It is not stakeholder-centric either as it does not focus on a specific participant, team, or team leader. A focus on the work practice with a specification of the execution patterns, the required technological capabilities, and the required roles, ensures that designs are more likely to last over time. Technologies change continuously but different or updated technologies can be aligned with the designs' required capabilities. Thus, a collaboration process design can become technology-independent. Internal facilitators, team leaders, and other organizational actors may leave the organization or move to new positions. A design solution that is specific to these actors will be difficult to transfer to their successors. Thus, taking a work practice centric perspective that maps out a sequence of best practices that are easy to transfer in a short period of time, increases the likelihood that an organization can sustain access to the process design for as long as there is a need for the practice. In short, people move on, technologies change, yet practices stay as long as there is a need for the practice. This makes it more likely that CE designs last and survive organizational and technological change.

CE Standards Enable Professionalization

CE researchers have contributed toward making collaboration expertise explicit, codified, teachable, learnable, and replicable. A recent stream of CE research has begun to develop preliminary Key Performance Indicators (KPIs) for collaboration engineers and practitioners. Further, structured courses that followed standard course designs will facilitate establishing a community of CE specialists that follow specific standards and structured approaches. Together, these developments will professionalize CE and will increase the value that organizations can derive from working with professionals in this area.

CE Research is an Example of "The Last Research Mile"

Finally, CE research is an example of researchers going "the Last Research Mile": successfully transitioning a scientific solution to a real-world problem into the workplace [134]. CE researchers have navigated all elements of the last research mile: They have performed *proof-of-concept* research to demonstrate the feasibility of solutions, for example, the thinkLets pattern language to transfer facilitation skills and process designs or the prototype of a CE design studio consisting of the CACE, PSS, and PSAs. They have performed a variety of field studies that demonstrate *proof-of-value*: CE designs have been successfully used for issues such as software code inspections, collaborative standards writing, and incident response planning. Finally, *proof-of-use* has been demonstrated through the adoption and routine use of CE process designs by various organizations (e.g., ING Group, Verisk Analytics, and HHMI). By taking the research through the last research mile it can be argued that the CE research community is making a significant impact on both science and society.

An Agenda for Future CE Research

The analysis of past CE research shows that the field of CE research has developed a significant body of knowledge consisting of, but not limited to, techniques, structured design approaches, conceptualizations, and causal theories. The final step in our review process is to build on the existing body of CE research to outline an agenda for future efforts. The foundation for this research agenda is twofold. First, it is grounded on current developments in organizations and society that have given rise to a new reality concerning collaboration and teams. Second, it is based on our interpretation of past research and the opportunities for continued research in each of the four major themes: CE foundations, CE approach, CE tools, and CE professionalization.

The New Reality: The Expanding Conception of Collaboration

The conception of collaboration has expanded over the past decade. Organizations still use established teams working toward specific deliverables during a planned period. Newer collaboration models, though, have emerged. These are characterized by dynamic teams, dynamic deliverables, and endless engagement. For example, crowdsourcing approaches have given rise to new problem-solving models where organizations assemble large numbers of people to contribute to specific organizational challenges to the extent and for the duration they wish to be involved [137]. The nature of products has changed to the point where innovation and development teams continuously update and deploy new versions, creating a cycle of constant co-creation.

This new reality represents a fertile ground for CE research. Researchers can build on the existing knowledge base to develop new theories, techniques, and design approaches. While there has been some limited experience with CE in distributed environments (e.g., 983, 158]), CE research has, to date, predominantly focused on same-time same-place team settings. In recent years, some CE researchers have begun to explore CE research in the context of crowdsourcing. For example, Kipp and colleagues [85] proposed a collaboration process design to let participants in an open innovation context elaborate on their own ideas. Nguyen and colleagues [127] used CE concepts, in particular, the patterns of collaboration, as a theoretical lens to analyze current collaboration models in crowdsourcing. Other researchers are exploring convergence processes in crowdsourcing contexts such as community crowdsourcing and open innovation (e.g., [73, 153]). Notwithstanding these initial efforts, important CE-related questions need to be answered. These include, but are not limited to: how to design for sustained engagement [57]; what are best practices for facilitation and governance in crowdsourcing projects; what repeatable techniques could be and would be executed by crowds themselves without any practitioner or facilitator support; and what should be included in a library of design patterns for crowdsourcing processes?

The New Reality: The Expanding Conception of Teams

We commonly think of a team as a collection of people working together toward a goal. Recent technological advances make us broaden this conceptualization. With the introduction of digital agents like Siri, Alexa, and Watson, there is a growing realization that in the near future it will be common for some team members to be robots or artificial agents [149, 124, 167]. Early studies have demonstrated the effectiveness of so-called Special Purpose Embodied Conversational Intelligence with Environmental Sensors (SPECIES) Agents to support individual and team decision-making [62]. Current prototypes such as the social robot Jibo give a glimpse into a future where artificial agents will become fully functional members of teams and families [19]. Key CE-related questions include, but are not limited to: can artificial agents perform the role of a practitioner; how can we design processes that establish and sustain trust between human and artificial team members; and which collaboration monitoring and advising tasks can automated agents perform [166]?

Future Research on CE Foundations

Future research in the area of the CE foundations could develop in three directions.

Cultural context: To date, a minimal amount of attention has been paid in CE research to the cultural context in which collaborative work practices take place. Reported field applications have predominantly originated from North America and Western Europe. While there are studies that took place in other contexts, for example, China (see the work by Cheng and colleagues) [33–46] and South Africa (see the work by Twinomurinzi and colleagues) [160], there has been structural assessment of the suitability of the CE foundations in different "non-Western" situations. Furthermore, the aspect of situational culture has been ignored in the body of CE research as well. For example, are there differences in the extent to thinkLets and other CE concepts are accepted and productively applied in military, business, government, and non-profit organizations?

ThinkLets: Second, research concerning the thinkLets pattern language could start expanding by blending thinkLets with pattern languages that focus on other collaborative challenges. For instance, initial explorations of thinkLets in the domain of gaming and gamification are promising. Future efforts could, for example, explore the combination of thinkLets with gaming strategies and concepts to develop a ‘gameLets’ pattern language to support the gamification of collaborative learning and training processes.

Since the inception of CE research, a large number of thinkLets have been codified and developed. Yet more work is required to perform a comprehensive analysis of broader collection of ‘best collaboration techniques’ for each of the six patterns of collaboration and to codify these according to the structured thinkLet rules. This would result in a large set of thinkLets that can be compared and used as a starting point to distil a canonical, nonredundant set of collaboration techniques and modifiers, and an approach to combining these elements into techniques for any given collaborative work practice.

Patterns of collaboration: Finally, several opportunities exist to expand research on the patterns of collaboration. In CE research to date, the six patterns of collaboration appear to have been sufficient to classify the changes of state that characterize the ways groups move through their activities and, therefore, to design interventions that will move a group to its goals with predictable success. Future research, however, may reveal as yet unnoticed patterns. It would be useful to conduct detailed analyses of team processes to discover other changes-of-state that move groups toward their goals. Such analyses could use process sampling and coding approaches such as proposed by Seeber and colleagues [151].

In terms of specific patterns of collaboration, more research is required on the *generate* pattern as it pertains to crowdsourcing processes. Important questions include how the presence of certain types and quantities of ideas inspires future contributions in open innovation and community crowdsourcing efforts, or, how to stimulate creativity through targeted practitioner feedback and directions. For the *converge (reduce and clarify)* pattern, we recommend theoretical research to establish the causal relationships that result in better convergence performance and the development and exploration of convergence techniques for mass-collaboration settings such as community crowdsourcing. The *organize* pattern, dedicated efforts are required given the limited amount of effort that we found in our review. It can be argued that the purpose of an organize task is to reduce the cognitive load of a follow up activity. Using Cognitive Load Theory as a lens, empirical explorations would be insightful comparing teams executing a complex collaborative task that focuses on sense making and decision support under two conditions: one with the organize thinkLet preceding the task and one without an organize thinkLet. Finally, for the *build commitment* pattern, additional theoretical work on Consensus Building Theory would be useful as well as the empirical evaluation of this theory through the development and assessment of specific thinkLets for building commitment in teams.

Future Research on the CE Approach

Future research on the CE approach could develop in five directions.

CE Design Theory: CE is a design approach with the thinkLets pattern language and the SLMC at its core. CE provides guidance and strategies for collaboration engineers to create collaborative solutions for recurring challenges. However, a complete design theory for CE has not yet been developed. To what principles should collaboration engineers adhere when they sequence activities and map thinkLets? How should we translate the logic of theories (e.g., for creativity, satisfaction, consensus, idea quality, and group productivity) into design guidelines that make it more likely that a designed process improves outcomes of interest? What recurring sequences of thinkLets provide superior performance on certain dimensions compared to others? Future research should focus on developing and refining a CE design theory as a body of knowledge that future collaboration engineers and CE researchers can use to develop their own solutions.

Way of Thinking: In terms of CE's way of thinking, it has to be determined and argued to what extent CE design philosophy has to be adjusted based on the new collaboration and team realities outline above. Are crowd-based collaboration processes engineerable? Can they be conceptualized as sequences of design patterns? Are there additional roles in mass-collaboration processes, for example, a problem owner/practitioner combined role? What are the theoretical underpinnings that will explain and predict performance variations in each of the patterns of collaboration in mass-collaboration settings? In addition, it would also be useful for CE researchers to identify established causal theories from different disciplines that address key phenomena a designed collaboration process aims to affect, for example theories on cohesiveness, idea elaboration depth, commitment to outcomes, and psychological safety.

Collaboration engineers have the potential to design and deploy collaborative work practices that improve the productivity of teams and the quality of their work products. Such potential comes with responsibilities as well, for example concerning the practitioners and team members' welfare or the morality of the goal that the team pursues. It will be valuable to conduct axiological research to develop a code of ethics for the practice of CE, building on the early efforts in this area [35].

Way of Working: Future research concerning the CE way of working could build on past research that provided initial evidence that practitioners can get results that are comparable to those achieved by collaboration professionals. These findings—at the core of the purpose of CE—need to be replicated in the field, specifically through longitudinal field experiments that compare practitioners' results with baselines results from collaboration professionals.

Additionally, it would be useful to develop new approaches for practitioners internalize and successfully execute a collaboration process design, for example through online training or remote coaching. Furthermore, additional research is also recommended to further assess the CE training approach in terms of actual cognitive load as experienced by the practitioners. While efforts to date have relied on self-reported cognitive load levels, future efforts should consider using methods based on physiological measures such as eye tracking [158]. Finally, to further inform training approaches in CE it would be valuable to investigate whether different practitioners have different levels of "collaboration aptitude" and, if so, how this could be measured. Researchers could examine the implications of having different levels of collaboration aptitude for the structure and content of training programs, but also issues like team composition and leadership development.

Way of Modeling: The new realities of collaboration and teams pose additional requirements on the techniques that can be used to model collaboration processes. It would be useful to further develop the FPM and ANM techniques that are used extensively in CE research and projects [166]. It would further be useful for researchers to perform a structured assessment of the existing (or improved) modeling techniques to determine their usefulness, ease of use, and effectiveness in capturing the relevant aspects of a collaborative work practice design.

Way of Control: Finally, future research regarding the CE way of control could focus on assessing the usefulness of proposed frameworks to benchmark and evaluate CE efforts. Furthermore, it would be valuable to determine to what extent these frameworks are still applicable and useful given the new reality of collaboration and teams.

Future Research on CE Tools

Early research on PSAs demonstrates the feasibility of packaging the collaboration expertise needed for some work practices with the requisite technology such that practitioners can use successfully with no training. This research, however, is still in its infancy. Early PSAs use comparatively basic technical capabilities and simple techniques. Future research is recommended to advance the state of PSA development and deployment platforms to support rapid development of PSAs for complex tasks requiring sophisticated techniques and technologies. For example, many of the technical capabilities pioneered in early collaboration systems are now on common use (e.g., file sharing, multi cursor simultaneous editing of shared objects, and presence indicators). As a result, an engineered work practice can sometimes be implemented by using a mix of capabilities from the collection of systems that the practitioners already have access to. While the resulting PSA may be less elegant than a bespoke solution, it can be fast to implement and acceptable to the stakeholders involved. Thus, research to identify and classify commonly available collaboration capabilities and matching these to the capabilities required in thinkLet-based PSAs would be useful. In addition, future research is required to develop CACE/PSAs that can support the design and execution of crowdsourcing processes and other forms of mass-collaboration.

Future Research on CE Professionalization

While many CE field applications have been reported, no study has yet been reported that focuses on the sustainability of repeatable processes designed with CE principles. It would be valuable to follow up on past CE projects to determine the extent to which these repeatable processes are still in use, what modification have been made, and what their performance has been compared to previous benchmarks and initial expectations. From the educational perspective, we recommend research studies be designed to investigate how graduates use the CE concepts and techniques that they have been exposed to during their course work.

Limitations

A number of limitations have to be considered with respect to the assessment of the CE literature discussed in this paper. First, while care has been taken to identify as many published CE studies as possible, the resulting collection of CE publications may not be complete. We approached the identification of CE publications from different angles, to minimize the possibility of overlooking certain publications. Apart from searches on various academic indices and repositories, we performed forward and backward searches to uncover additional studies. Regardless, it is possible that a number of CE publications were not found.

Second, not all CE research may have (yet) been published. Some researchers may have performed studies applying CE concepts but due to various reasons (e.g., confidentiality or lack of permission from the client organization) chose not to publish their findings.

Third, this paper provides an in-depth overview of the findings and cumulative insights from published CE research. It does not represent an evaluation by itself of the CE body of knowledge. A holistic evaluation of the CE approach based on the past findings is beyond the scope of this paper. While there have been a few studies that have provided a high-level assessment of the approach (e.g., [92, 28]), a programmatic assessment across studies, context, and conditions has yet to take place. Thus, future efforts are recommended to design and execute a form of meta-analysis of comparable CE studies to assess the value of the CE approach.

Finally, as authors we have been involved in a substantial number of CE studies and publications ourselves. This means there is a risk of subjective bias as we are very close to the portfolio of CE research. We mitigated this risk by following a structured literature identification and analysis approach. Furthermore, we were consistently aware of the need to maintain a neutral and factual tone when sharing the findings and insights from the CE publications. Finally, we presented and shared our overview and assessment in various academic seminars to solicit critical feedback and suggestions.

Concluding Comments

In 2004 a group of CE researchers gathered in Omaha, NE for an event dubbed, CE Summer Camp. These scholars derived the following definition for Collaboration Engineering:

> An approach to designing collaborative work practices for high value tasks, and deploying them to practitioners to execute for themselves without ongoing support collaboration experts.

They did not realize at the time that each clause in the definition would turn out to be a stream within a program of CE research. "*An Approach…*" foreshadowed the research on structured methodologies for collaboration engineers. This research stream will not be complete until a book of knowledge for CE exists, ways for measuring the performance of collaboration engineers have been validated, and a set of formal standards and assessments have been developed to certify professional collaboration engineers.

The clause, "*…to Designing Collaborative Work Practices…*" pointed toward research on design concerns, design principles, pattern languages, best practices, the reference model for collaborative work practices, and design methodologies. It also anticipated theoretical research to explain and predict the values of the constructs that define the success for collaboration and collaboration systems. The logic of such theories can predict the effects of design choices on outcomes-of-interest. The theories, in turn, inform design choices to make collaborative work practices predictable, repeatable, and effective. This stream of research will not be complete until all phenomena relevant to the success of collaboration and collaboration engineering have been discovered and described, and their correlates have been discovered and described, and well-validated general theories exist to explain and predict their variations. Decades of work remain to meet this challenge.

The clause, "…*for high-value tasks…*" foreshadowed research on the economics of collaboration engineering, e.g. discovering and selecting among opportunities for CE projects, and predicting whether users would accept a well-engineered work practice if it were offered. Beyond economic value, this clause also points toward other categories of value that teams create through joint effort (i.e., political, social, cognitive, emotional, and physical value). This research stream will not be complete until all six categories of value are well defined, and collaboration engineers have reliable approaches to designing procedures for creating value in each category, and for measuring that value.

Finally, the clause, "*…and deploying them to practitioners without ongoing support from collaboration experts*" pointed the way to research first on how to train practitioners to use engineered work practices, and then to research on how to design work practices that practitioners could execute with no training. This stream of research will not be complete until practitioners can open a PSA for the first time, and with no training, successfully execute a complex process of interrelated tasks involving many people in many roles interacting via the full range of media over extended, even indefinite time periods.

It is our hope that this paper will help the CE research community to address these challenges and continue progress in each of these streams of research. The need for high performance collaboration has not diminished in recent years and is unlikely to do so in the future. On the contrary, the increasing complexity of organizational innovation, operations, and management has made high performance collaboration a ‘sine qua non’ for organizational survival. New realities concerning the nature of teams, technologies such as social media and AI, and modern collaborative work forms make this an exciting era for Collaboration Engineering science and practice.

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