The Impact of ICT Usage on Collaborative Product Development Performance: A Conceptual Model and Industry Perspective

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Abstract—**Collaborative product development (CPD) is a vital strategy adopted by many manufacturing firms for higher competitiveness. Efficient processing of information via information and communication technology (ICT) tools is essential for practicing CPD. Uncovering the impact of ICT usage on performance of CPD projects with varying characteristics will provide valuable insights to CPD practitioners. So far, the practical relevance and appropriateness of criteria used in previous research models evaluating the ICT impact have not been sufficiently confirmed. This study develops a research model based on relational resource-based view and organizational information processing theory to evaluate the impact of ICT usage on CPD performance. The study qualitatively examines this model, using data collected through interviews from manufacturing and ICT vendor firms for assessing various ICT usage dimensions, project characteristics representing information processing requirement, and CPD performance outcomes. The results support the concepts and relationships conceptualized in the model while identifying project complexity as the project characteristic that predominantly represents the information processing requirement of a CPD project. The findings offer valuable insights to practitioners with significant theoretical implications for future studies addressing the role of ICT in CPD.**

Keywords— ICT usage; collaborative product development; qualitative studies; relational resource-based view; organizational information processing theory

I. INTRODUCTION

Introducing new products with customer required quality, speed, and cost is a key challenge for many manufacturing organizations in today's competitive business environment. Collaborations with external and internal partners such as suppliers, customers, and cross functional teams enable firms to bring valuable technological and market knowledge to the new products from various sources. Firms possessing differing levels of collaborative competencies realize varied levels of project and market performance [1]. Communication between partners and exchange of quality information timely are vital for determining the degree of collaborative competence [2]. Therefore, right processing of information needs to be guaranteed for successful collaborative product development (CPD). Information and communication technologies (ICTs) including tools for face-to-face communication provide the key media for processing information required by CPD teams [3, 4]. Real-time communication, concurrent operations, and increased information access facilitated by ICT tools help firms overcome social, technical and organizational barriers for CPD [5, 6]. Since higher use of ICT tools leads to substantial costs in companies, selection of the tools may need planning to simply meet information processing requirements in the R&D projects. Exploring a holistic view on the impact of ICT usage would be vital for planning these technologies effectively for CPD.

Prior research that examined the impact of ICT usage on product development performance, have tested research models developed based on literature, and often found contradictory evidences or unexpected low impact of ICT usage [7-11]. However, several limitations in selecting ICT usage and CPD performance dimensions and project characteristics that moderate the ICT–CPD performance relationship were observed in these research models. Understanding the industry perspective on the appropriateness of variables/measurement criteria adopted in the models and usefulness of the associations examined, have also been paid little attention [e.g., 12]. Based on these premises, and drawing on relational resource-based view (RRBV) (which emphasizes achieving competitive advantage through collaborations [13]) and organizational information processing theory (OIPT) (that suggests the need for balancing information processing capability with information requirements to achieve organizational performance [14]), this study, first, develops a conceptual research model for evaluating the impact of ICT usage on CPD performance. Second, it evaluates the constructs and the relationships conceptualized in the model through a qualitative investigation of data gathered from product development and ICT professionals. Finally, the study identifies and classifies the barriers that disrupt the effective ICT use in CPD. The model contains three main constructs – (1) ICT usage comprising the dimensions: frequency, proficiency, and intensity of ICT use, (2) CPD performance in terms of collaboration performance and new product performance, and (3) moderating project characteristics such as complexity and uncertainty that indicate the information processing requirement of CPD projects. Since the model comprises several new constructs (e.g., collaboration performance, intensity of ICT use) and most empirical evidence for the impact of ICT usage on CPD performance are inconclusive, a practical examination of the constructs and their conceptualized relationships is important. Therefore, this study answers the following main research question and sub-questions:

How do manufacturing firms use ICT to manage and improve collaborative product development?

1. How do manufacturing firms select ICT tools and use these tools in their collaborative product development programs?
2. Are frequency, proficiency, and intensity of ICT use relevant dimensions of ICT usage in understanding the role of ICT in collaborative product development projects?
3. Which characteristic of a CPD project predominantly represents the information processing requirement in the project and which dimensions are useful for evaluating it?
4. What are the positive CPD performance outcomes expected from using ICT in manufacturing CPD projects and what are the barriers for achieving these outcomes?

This research offers significant value to technology management theory by developing a new improved conceptual model based on appropriate theoretical grounds, for evaluating the impact of ICT usage on CPD performance, and supporting the model with industry experts' perspectives. The findings were useful to improve measurement scales for the model constructs that have been suggested by literature. Furthermore, the results drawn by relating the qualitative research findings with relevant literature provide important theoretical and practical implications.

II. Literature Review and Conceptual Model Development

This section reviews the dimensions of ICT usage and CPD performance, and their association, in order to develop a conceptual model that fills existing research gaps in the impact of ICT usage on CPD performance.

A. ICT Usage

There have been several studies that looked into the usage of ICT tools in CPD projects [e.g., 7, 8]. Several limitations were found in operationalization of ICT usage in past research models with similar focus [e.g., 7, 15]. The number of times information is exchanged within CPD teams or rate of using ICT tools in a CPD project could represent the overall ICT usage in the project. Most research has evaluated ICT usage with a single measurement representing the overall usage of a tool in a project. However, in order to achieve high performance standards through virtual teams, ability of members to use appropriate ICT tools efficiently and effectively is more important than making a variety of sophisticated tools available [16]. Durmusoglu and Barczak [17] supported these arguments suggesting frequency and proficiency as two dimensions of ICT usage. In a study addressing the relationship between communication quantity and CPD project's financial performance, Hoegl [18] used two concepts, frequency and intensity to evaluate the amount of communication between project partners. According to Bhatt and Ved [4], intensive use of ICT is important for increasing communication in dispersed CPD teams. Based on these literatures, frequency, proficiency, and a new construct named 'intensity of ICT use', which refers to the degree of utilizing features and functionalities of ICT tools in a CPD project, are introduced as dimensions of ICT usage. Aggregated measures have increased robustness and generalizability which leads to increased predictive validity [19]. Therefore, considering different aspects of ICT usage in a study focusing on both collaboration and project outcomes, will better explore the value of ICT in CPD.

B. CPD Performance

Use of ICT in CPD projects is believed to increase product quality, speed-to-market, and profits. Therefore, earlier ICT-related studies mostly addressed the direct effect of ICTs on success of CPD project indicated by time, quality, and market success. For example, Durmusoglu and Barczak [17] examined the effect of using various ICT tools on new product effectiveness in terms of market performance, innovativeness, and product quality. Barczak, et al. [15] found a significant positive effect of ICT usage on market performance but no significant effect on speed-to-market. Heim, et al. [20] suggested that design/validation software tools have strong and weak positive associations with product performance quality and time-to-market respectively. Therefore, the impact of overall ICT usage on CPD performance is mostly inconclusive. However, performance indicators used in these studies generally capture the tangible aspects of new product performance in terms of financial and quality outcomes rather than overall CPD performance comprising both NPD performance and intangible, long-term outcomes that could be achieved through collaboration.

Another set of studies have shed light on the impact of ICT usage on intangible outcomes such as NPD collaboration [7], knowledge transfer [21] and creation of trust [22]. A few have examined direct and indirect impact of certain ICT tools on NPD performance through collaboration [e.g., 11]. However, such empirical evidences for all types of ICT tools used in CPD programs are absent in literature. In addition, limitations in capturing holistic CPD performance were observed in the performance dimensions considered in past studies. Büyüközkan and Arsenyan [23] defined collaboration process within the main CPD domain suggesting that its success is dependent on trust, coordination, co-learning, and co-innovation between partners. Therefore, the present research model introduces a new construct representing intangible aspect of CPD performance labelled as 'collaboration performance' in addition to the new product performance indicated by quality, time performance, and commercial success. According to Littler, et al. [24], the success of product development collaborations is primarily determined by the factors: (1) how much collaborating partners contributed as expected, (2) how successfully knowledge was shared between partners, (3) how successfully important ideas and information were shared, (4) how successfully the benefits of the project were shared, (5) how successfully the risks were shared, and (6) how much trust existed between partners. Since the above six concepts essentially cover the collaboration process performance dimensions defined by Büyüközkan and Arsenyan [23], these measures are suggested as indicators for the proposed collaboration performance construct. The relational view, an extension to the resource-based view (RBV) argues on the resources and capabilities shared by interconnected firms as a source of competitive advantage of these firms [25, 26]. The unit of analysis in relational view is a network of firms rather than a firm which is in the RBV. CPD is a joint business activity connecting distributed R&D teams, suppliers, customers, and various other external partners. ICT usage (frequency, proficiency, and intensity) in a CPD project reflects the resources and capabilities shared by a set of networked firms that provide inputs for the success of the project. Relational resource-based view relies on informal self-enforcing safeguards such as sharing of knowledge unique to partners, trust, and exchanging invaluable resources, and emphasizes their contribution to increased competitive advantage [25]. Therefore, the proposed direct effect of ICT usage on CPD performance comprising collaboration performance and new product performance (quality, time performance, and commercial success) and indirect effect on new product performance through collaboration performance are theoretically supported by the RRBV.

C. Project Characteristics Representing Information Processing Requirement of CPD Projects

In CPD, processing of information is mainly performed via ICT tools. This information processing could vary across different project and organizational characteristics [27, 28]. As the OIPT argues, performance of an organization depends on the balance between its information processing capability and information requirements [14, 29]. The extent of ICT tools used in a firm represents the firm's information processing capability. Tatikonda and Rosenthal [30] identified technology novelty and project complexity as key contributors to the uncertainty associated with new product development. Therefore, arguing on the OIPT, this study suggests that success of a CPD project depends on how much a firm is capable to match their ICT usage with the information processing requirement of the project, based on its characteristics. However, no study that investigates on how much organizations are capable in doing this was found in literature. Such investigations supported by relevant industry evidence would be useful to understand the moderating project characteristics and nature of their impact on ICT usage–CPD performance relationship. In an OIPT based study examining the moderating effect of project complexity on the relationship between ICT tools and NPD collaboration, Peng, et al. [7] defined product size, interdependency of tasks, and project novelty as three dimensions of project complexity. However, based on empirical evidences [31], and differences in information processing challenges created by these dimensions [20], project novelty has been often classified as a distinct concept named project uncertainty. In addition to the complexity and uncertainty, Swink [32] identified project urgency as another characteristic that does not decrease new product manufacturability, in the presence of proper external and internal integration of development teams. Since ICT usage reflects the level of integration between partners in a CPD project, project urgency is also proposed to be a moderator for the relationship between ICT usage and CPD performance. Fig. 1 illustrates the conceptual research model developed based on the above reviews of literature and the practical justifications provided.

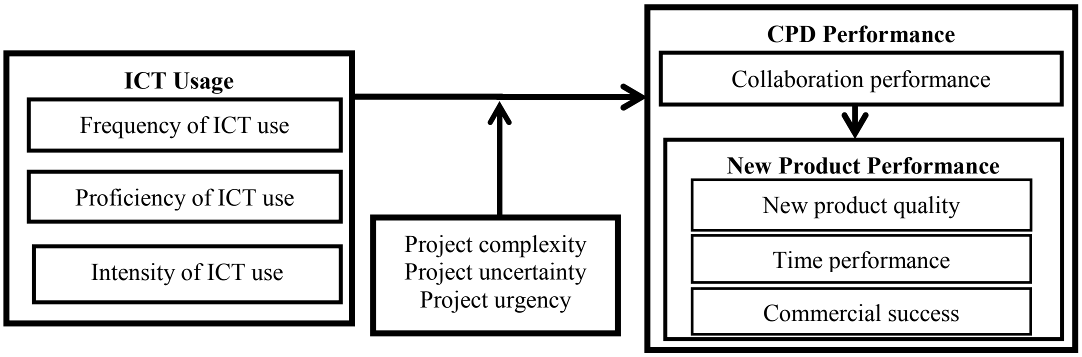

Fig. 1. Conceptual model for the impact of ICT usage on CPD performance

III. Methodology

A. Sample and Data Collection

The selected sampling procedure in this study was purposive as it allows reaching findings through investigating a few information rich cases [33]. Maximum variation sampling strategy that enables studying a broad range of subjects [33, 34] was followed for capturing a great deal of heterogeneity in the participants' views on the conceptual model constructs. Accordingly, both ICT vendor and manufacturing firms were selected to include varying viewpoints on ICT usage in CPD projects. Manufacturing firms from all levels of technology (high, medium, and low) and vendors of different types of CPD enabling ICT tools were represented in the selected samples. Interviews were the selected method of data collection. R&D managers directly involved in CPD projects in each of the five manufacturing firms – M1 (electronic), M2 (machinery), M3 (fabricated metal products), M4 (furniture), and M5 (apparel) and a knowledgeable manager from each of the four ICT vendor firms were interviewed. By the time of the interview, the participants had more than three years of experience in the chosen firms. Initially, the participants were contacted through e-mails providing all relevant information on the study. Each interview lased between 45-60 minutes and all the interviews were audio-recorded. The questions were posed to answer the research questions that evaluate the modelled concepts and associations leading to an understanding of the ICT usage practices in collaborative product innovation. Each concept was introduced to the respondents with a descriptive operational definition developed based on literature. Although the interviews were semi-structured and broadly directed by the pre-defined conceptual model, the participants were given substantial freedom to express their ideas openly, by administering open-ended questions.

B. Validity

Findings of the study were reviewed thoroughly through the transcripts by one of the researchers to ensure the validity [35]. Responses from manufacturers and ICT vendors triangulated the results; thus established construct validity by providing multiple measures for the same phenomenon [36]. Using a sample of nine companies justified the external validity [37]. Reliability was achieved by using a conceptual model developed based on current literature.

C. Data Analysis

This study used directed qualitative content analysis approach which permits validating or extending a conceptual, theoretical framework, or theory through subjective interpretation of the content of text data [38]. Constructs of the conceptual model were used as the key themes for coding data. Matrices displaying the patterns in the participants' views and typical quotations [39] were used in presenting and justifying findings of the analysis. In directed qualitative content analysis, additional information which could not be categorized with the initial coding scheme can either offer a contradictory view of the phenomenon or further refine, extend, and enrich the theory [38]. Therefore, data gathered on the barriers for effective use of ICT were used for refining and improving findings obtained through analysing the benefits of ICT usage.

IV. Results and Discussion

A. Usage of ICT Tools in CPD Programs

For answering the first research question concerning selection and use of ICT tools in manufacturers' CPD programs, the manufacturing participants were asked to broadly describe on the selection and use of five ICT types: communication/collaboration tools, product design/development tools, information/ knowledge management tools, project management tools, and market research/analysis [12] in their CPD projects. The following are the key findings derived from the analysis of detailed responses.

1. Sophistication of ICT tools used in manufacturing firms is varied on the following factors:
   - Size and distribution of the CPD network.
   - Intensity of involvement of the CPD partners.
   - Knowledge intensity of information to be communicated.
   - Frequency of new product introductions.
2. Increased convenience, transparency, and traceability provided by simple communication ICT tools (e.g., e-mails) are highly valued by manufacturers.
3. Technology level of a firm is a key factor differentiating the ICT usage in CPD projects.
4. Firms with higher ICT usage maintain higher competitiveness in their industries.
5. Manufacturers pay great attention on the extent to which ICT tools are able to provide benefits that face-to-face communication offers.

B. Dimensions of ICT Usage

In answering the second research question on the relevance of measures of ICT usage, the participants' views on frequency of ICT use were nearly consistent. They particularly emphasized the significance of frequency of using communication ICT tools in CPD projects. As majority of manufacturers highlighted, frequent communication with external partners in early development stages is particularly important for introducing successful new designs with customer specified standards. According to the M3 manager, this frequent information exchange is more important when the customer or the product is new to the firm. The product development manager at M5 (apparel) noted *"sometimes even our customers are not able to provide right specifications for the products because they have limited information on end-user requirements. So, we need to review designs several times by frequently contacting the customer".* However, this could not be equally valid for industries such as high-tech where the customers are aware of most of the end-user requirements. Frequent communication is although valuable for such industries in some other ways. For example, the respondent from M1 explained that storing frequently gathered information in one project help largely in their current as well as future projects for improving new products' quality. Additionally, higher frequency of using communication/collaboration ICT tools can lead to an increase in the frequency of using other types of ICT. Therefore, this study confirms the validity of defining frequency of use as a dimension of ICT usage.

Suggesting proficiency of use as one aspect of ICT usage, the manager at M5 noted *"correct understanding of the specifications sent by the customers is really important and low-proficient R&D staff is not able to use the available ICT tools effectively to get these details".* All of the manufacturing participants stressed that proficiency is mainly relevant for advanced ICT such as product design/development tools. However, some participants noted the significance of proficiency in using other ICT tools. For example, the respondent from V4 highlighted that since various alternatives for online market research tools are available, users need to be well-experienced and knowledgeable in selecting the best and have capability in handling technical issues such as multi-user problems when Web-based tools are used synchronously by several partners. In addition, the product development specialist from M1 emphasized the importance of having considerable level of proficiency in data analysis software. As the owner of V1 highlighted, commitment of manufacturing firms in obtaining training offered by ICT vendors is not satisfactory. Thus, he suggested 'training effectiveness' and 'perceived ease of adaption' as suitable criteria of staff's ICT proficiency. Several participants (M1, M2, M5, and V2) stressed that low commitment of employees and inflexible work environment sometimes reduce the effectiveness of the training programs. These findings suggest proficiency of use as a dimension of ICT usage particularly in evaluating the usage of advanced tools in CPD projects.

As a new measure of ICT usage, views of the participants on intensity of use concept are extremely useful for operationalizing this as a dimension of ICT usage. Engineering manager at M1 noted *"people's commitment to use new and advanced features in software tools is highly important to get the maximum benefit from these tools".* As this study interviewed purposefully selected representatives from ICT vendor firms who are well-informed about all the features and functionalities available in the tools they offer, their opinion on intensity of use is of much value. All of the ICT vendors emphasized that their customer manufacturers do not have sufficient knowledge, or need, for using many of the functionalities available in the ICT tools in CPD projects. The V3 respondent noted "s*ome users get the benefit of almost all the features available in software packages and it may depend on the proficiency level of the user as well as the requirement of the tasks in the product development project".* These views confirm that the degree to which available features and functionalities in ICT tools are utilized is an important facet of overall ICT usage. However, incompleteness of proposed definition of intensity of ICT use was indicated in some responses. For example, M5 manager noted that they use simple ICT tools such as e-mails even for vital product development activities such as sending designs and videos etc. In contrast, M1 use e-mails only for lean purposes such as text messaging or sending text files while using more advanced tools (e.g., shared drives) for sending drawings and videos. As this implies, utilized capacity of an ICT tool could provide some meaning to the proposed intensity of use concept. However, as V1 noted, although usage of features and functionalities in ICT tools is important to consider, it is somewhat difficult to measure. The manager from M3 suggested that ICT tools need to be separately considered when understanding intensity aspect of ICT use. Based on these views and comments, intensity of ICT use is defined as the degree to which the available capacities, features, and functionalities of ICT tools have been utilized. Table I summarizes the key results obtained from the above analysis on three ICT usage dimensions in the model, related literature and implications derived through comparison.

TABLE I. EVALUATION OF THE CONCEPTUALIZED ICT USAGE DIMENSIONS BASED ON INDUSTRY PERSPECTIVES AND LITERATURE EVIDENCE

Key findings from the interviews	Literature evidences	Implication for the modelled constructs and relationships
Frequency of ICT use • Frequency of using communication ICT tools would be of relatively higher importance in a CPD project than the frequency of other ICT types [M1, M4, M5, V3]. • Frequent communication is really important in early development stages especially when the customer, technology, or the product is new (uncertain) to the firm [M1, M3, M4]. • Frequent ICT use in collaborative projects helps in resolving complex product and project-related issues and achieving customer required standards in the new products developed [M3, M5].	• Commonly used as a measure of ICT usage [3, 8]. • Frequency is used for evaluating usage of all types of CPD-enabling ICT tools (communication/collaboration tools, product design/ development tools, information/knowledge management tools, project management tools, and market research/analysis tools) [8, 40]. • Frequent information exchange between collaborative partners in early product development stages contributes to the success of projects [5, 24] • Frequency of ICT use improves NPD process [8]	• Findings confirm prior research by identifying frequency as a relevant measure of ICT usage in CPD projects. • Supports and extends existing literature, suggesting a positive effect of ICT usage (including frequency as one dimension) on CPD performance. • Capturing frequency as an ICT usage dimension would be useful in establishing the moderating effect of project complexity and uncertainty suggested in the conceptual model (based on practitioners' viewpoint). • Defines 'frequency of ICT use' in the conceptual model as how often CPD facilitating ICT (communication/ collaboration tools, product design/development tools, information/knowledge management tools, project management tools, and market research and analysis tools) have been used in a CPD project.
Proficiency of ICT use • Proficiency is more relevant for advanced ICT tools (e.g., product design software) [M1, M2, M3, M4, M5]. • On-the-job training is vital to achieve high proficiency in advanced product development ICT tools [M2, M5]. • Ease of adaption and training effectiveness of ICT tools could measure the level of proficiency [V1]. • Manufacturers' attention on increasing ICT proficiency of R&D staff is not sufficient and training programs provided by ICT vendors need to be more utilized [V1, V2]. • Human factors such as attitude towards improving expertise and organizational factors such as availability of resources and work environment may affect achieving required ICT proficiency [M1, M2, M5, V2].	• Proficiency in using ICT tools is a possible measure of ICT usage when evaluating ICT impact on product development performance [8, 17]. • Proficiency of employees in gathering knowledge with the use of ICT, increases innovation capability of a firm [41].	• Extends literature by identifying proficiency of ICT use as a key dimension of ICT usage, with the support of relevant industry evidence. • Training effectiveness and ease of adoption are appropriate indicators of proficiency of ICT use in CPD. • Using proficiency of use as a dimension of ICT usage will enable exploration of the role of ICT in terms of employees' and organization's ICT orientation in CPD. • Defines 'proficiency of use' in the conceptual model as expertise and experience of the R&D staff in using ICT tools for CPD.
Intensity of use • Utilizing many features and functionalities available in ICT tools is an important factor of the success of CPD projects [M1, V1, V2, V3, V4] • Utilized proportion of available capacity of ICT tools is varied based on project requirements [M5] • Intensity is relevant for evaluating usage of all types of CPD facilitating ICT [M4, V3] • Intensity of use (or utilized proportion of ICT) could be largely associated with the characteristics of the project [V2]. • Intensity and proficiency of ICT use are interrelated as more proficient users tend to use more features in the tools [V3]	• Heavy or lean use of ICT tools can have varied impact on performance of CPD teams [3]. • The concept 'intensity' has been used in addition to the 'frequency' for measuring amount of communication between CPD partners [e.g., 18]	• Extends current literature and identifies intensity as a relevant dimension of ICT usage • Defines intensity of ICT use in the conceptual model as the extent to which the available capacities, features, and functionalities of ICT tools have been utilized within a CPD project.

C. Information Processing Requirement of CPD Projects

Answering the first part of research question 3, all of the participants identified project complexity as the major project characteristic that represents the information processing requirement of a CPD project. In developing the conceptual model (Fig. 1), complexity was defined as a combination of product complexity (product scope, size, and interdependence of tasks) and collaborative network complexity (number of partners involved in the project). However, the responses analyzed in this study suggest several modifications to this definition. In Table II, the key interview findings on the three project characteristics are discussed with related literature evidence. Participants from M1, M2, M3, and M5 stated that the collaborating partners and their involvement which differs from one project to another, primarily decides the information processing requirement in the projects. Supporting Peng, et al. [7], the respondents also viewed product complexity as one aspect of a CPD project's complexity. Several respondents (M5, V3, and V4) interpreted lack of clear information (particularly in early stages) to carry out a project, simply as project complexity. They agreed that this information shortage occurs when the product, process, or market is new to their firms. These findings imply that project uncertainty can have common roots with project complexity as a representative of information processing requirement. M1, M3, and M5 stated that they often experience increases in ICT usage in highly complex projects. The two large ICT vendors (V1 and V3) noted that the use of ICT tools help R&D teams to decrease the effects of information absence in CPD projects, although sometimes they fail to balance the usage according to project's requirement. These findings confirm the conceptualized moderating effect of project complexity in the research model. Four manufacturers (M1, M3, M4, and M5) and three ICT vendors (V1, V2, and V3) identified project urgency as another characteristic representing information processing requirement of a CPD project. According to their explanations, more ICT resources are allocated for urgent projects due to top management's drive towards them. When the product development staffs are more committed towards the outcomes of a project, ICT tools are utilized more efficiently to achieve project goals. Thus, a positive moderating effect of project urgency can be expected in a large sample study based on the conceptual model developed. However, all the above participants identified urgency as a secondary characteristic that represents the information processing requirement of CPD projects. In Table II, the key interview findings on the three project characteristics are discussed with related literature evidence.

TABLE II. KEY FINDINGS ON CPD PROJECT CHARACTERISTICS REPRESENTING INFORMATION PROCESSING REQUIREMENT

Key findings from the interviews	Literature evidence	Implications for the modelled constructs and relationships
Project complexity and uncertainty		
• Project complexity is usually characterized by the number of participants involved in the project, intensity of their involvement, and product complexity [M1, M2, M4, V2] • Project uncertainty (or novelty) also indicates project complexity [M5, V3, V4]. • The amount of information required by a CPD project is primarily determined by the complexity of the project [M1, M5, M3, V2, V4]. • Receiving inadequate information in early development stages makes projects complex for CPD teams and increased use of ICT helps in reducing the consequences. However, firms rarely balance their ICT usage with the information processing requirement determined by project complexity [M4, M5, V1, V3].	• Project complexity and uncertainty are project characteristics that have often been jointly addressed in product development literature [e.g., 31, 32]. • Project complexity dimensions: product size, task interdependence, and project novelty have varied moderating effects on NPD collaboration [7]. • Project complexity (number of employees involved) and increased design outsourcing reduces new product's manufacturability (an important factor for the project success) while product newness, and project acceleration improves this [32]. • Project complexity has a direct positive effect and negative interaction effect with project uncertainty on NPD performance [31].	• Project complexity is the characteristic that predominantly represents the information processing requirement of a CPD project. • Collaborative network complexity (number of participants involved and intensity of their involvement) and product complexity are the major dimensions of a CPD project's complexity. • Project uncertainty can have common underpinnings with project complexity. • Based on these evidences and contradictory extant literature, exploring the conceptualized moderating effects of project complexity and uncertainty is identified as important to extend current understanding on the role of ICT in CPD.
Project urgency		
• Urgency is a secondary project characteristic (not as important as project complexity) that also represents the amount of information to be processed in a CPD project [M1, M3, M4, M5, V1, V2, V3]. • Managements and R&D teams tend to use more ICT in urgent projects. This leads to achieving better outcomes in such projects. [V2, V3]	• Project urgency is assessed as the priority given to a CPD project and the time pressure felt during the project [27]. • Project acceleration or planned duration for the project relative to a firm's norm [32] is a concept related to project urgency.	• Examining project urgency as a moderator is less important in comparison with studying project complexity and uncertainty. • A positive moderating effect of project urgency on the association between ICT usage and CPD performance can be expected.

D. The Positive CPD Performance Outcomes Expected from ICT Usage

In order to assess the relevance of performance constructs proposed in the conceptual model, the participants were questioned on their experiences and opinions about the positive outcomes or benefits of using ICT tools in CPD programs. The results are used to refine measurement scales of the performance constructs conceptualized. Majority of the participants emphasized the significance of ICT usage for achieving higher product quality. According their views, this could happen in several ways. First, ICT tools enable R&D teams to gather product ideas from a wider customer base. Second, these tools facilitate simulation, evaluation, and analysis of technical, market, and financial feasibility of several design alternatives that include customer-desired features. Some participants were aware of the contribution of ICT in increasing certain aspects of collaboration. According to the respondent from V1, the use of right ICT for transferring information on required changes during product design and development stages helps manufacturers to reduce the potential risks in commercialization stage. The manager from M4 noted *"providing frequent updates of project progress to the stakeholders [customers] through our online systems is important to improve their trust in our operations. This helps increasing our market share and turnover"*. Such observations imply relevance of the conceptualized indirect effect of ICT usage on final project success through collaboration performance. Table III presents the findings drawn from the interviewed data on positive outcomes of using ICT for CPD, related literature, and implications derived. The outcomes were classified as time, quality, financial, and collaboration related performance. The results confirm the validity of hypothesizing positive effect of ICT usage on the four performance dimensions – collaboration performance, new product quality, time performance, and commercial success.

TABLE III. FINDINGS ON IMPROVING COLLABORATIVE PRODUCT DEVELOPMENT USING ICT

Key findings from the interviews	Literature evidence	Implications for the modelled constructs and relationships
Collaboration-related outcomes • Sharing of knowledge and skills between partners [M1, M2, M3, V1, V2, V3]. • Information security (controlled access to critical product data) [M1, M4, V4]. • Sharing project risks [M1, V1, V4] and benefits [M3,V2,V3]. • Improved partner trust and relationships through providing continuous project updates [V1, V2, M4]. ***Quality-related outcomes*** • Increased potential to introduce products with customer desired features through frequent sharing of quality information/knowledge [M1, M2, M3, M5, V2]. • High conformance to the design specifications [M4, M5, V1, V3]. • Increased potential to higher quality in future projects using the knowledge stored [M1,M2,V3]. • Improved quality in the NPD process [M1, M4, V1]. • Increased technical performance [M3]. ***Time-related outcomes*** • Increased responsiveness via fast engineering changes as customer required [M5, V1, V2, V3]. • Fast and updated market information [M1,V2]. • Fast finalization of technical specifications of the new product [M4, M5]. • Better time management [M3]. • Short product development times [M2, M5]. • Greater speed to market [M5, V1]. ***Financial outcomes*** • Reducing wastages of resources (money, labour, and material) [M2, M4, V1]. • Better cost management [M3, V3]. • Creating and identifying new market opportunities through external collaborations [M3, M4]. • Increasing financial returns [M4, V2].	• Collaboration software (PLM) improves NPD collaboration which in turn improves new product performance (product design cycle time and product quality) [11]. • Adequate, accurate, and timely communication behaviour contributes to creation of trust between CPD partners [42]. • The use of ICT provides collaboration benefits such as knowledge/information transfer and developing informal network [5, 21]. • Level of supplier integration improves the likelihood of collaboration outcomes including risks and reward sharing [43]. • IT usage has a positive impact on market performance and no significant impact on speed-to-market [44]. • ICT strength of a firm has a positive association with global NPD program performance (time-to-market, windows of opportunity, financial performance) [28]. • Use of knowledge management ICT improves NPD performance (financial and time) [45]. • Exchange of technical knowledge with suppliers improves NPD performance [46]. • Design/validation software tools have positive influence on product quality and time-to-market [20]. • Product design tools and project management tools have significant positive effects on NPD collaboration while communication tools has no significant impact on that [7]. • Frequency of ICT use has an indirect effect on NPD performance (financial) through NPD task proficiency [8].	• Results of the study support conceptualizing the 'collaboration performance' concept in terms of the perceived degree of creation of trust, sharing of knowledge, risks, and benefits between CPD partners. • The study extends current literature suggesting a positive impact of overall usage of ICT tools on collaboration performance and new product performance (quality, time, and commercial success). • The study findings linked with literature evidences supports the proposition that collaboration performance will in turn improve new product performance (quality, time, and financial success).

E. Barriers for the Effective Use of ICT in CPD Programs

Although many participants agreed upon the positive impact of ICT usage on the four performance aspects (quality, time, commercial success, and collaboration) the study identified several barriers to achieving these performance objectives. Most of the manufacturers emphasized that they face huge difficulties in maintaining uniformity in product development processes due to version update problems and frequent changes in ICT tools used. Technical issues such as synchronized access to online tools, less-user friendliness, and unnecessary features in ICT tools can be interrelated with human-related issues such as lack of proficiency and outcome-related issues such as high-costs. As the engineering manager at M1 noted *"regardless of the availability of excellent ICT tools and IT-supportive work environment, lack of commitment of R&D staff towards resolving problems with the use of right tools at right time sometimes leads to project failures"*. Several manufacturers identified lack of IT background as a key problem of R&D staff in their organizations. The respondent from M4 highlighted that management's commitment is a significant measure to resolving human related issues in using ICT in CPD projects. According to V1 and V3, *"firms need to invest in providing adequate resources, training and development opportunities for better results"*. V3 manager noted *"switching to advanced software or frequently changing ICT tools is not sensible, if the companies do not have solid plans to expand their project scopes in near future"*. This view is consistent with the respondent from M5 who noted that the initial problem occurs at the ICT tool selection stage. Table IV presents the barriers identified in the study, classified as technical, human, and other. The other barriers are further divided into four groups – context-specific, outcome-related, organizational, and collaboration-based, indicating their prominent root causes.

TABLE IV. BARRIERS FOR THE EFFECTIVE USE OF ICT TOOLS IN CPD PROJECTS

Technical	**Human**
1. Version updating problems [M2, M3, M4, M5]. 2. Including many unnecessary features [V2, V3, V4]. 3. Less user-friendliness [V2]. 4. Disruptions due to technical/power failures [M5]. 5. Synchronized access problems [V4].	1. Inadequate background and little knowledge on using advanced tools [M2, M3, M4, M5, V2]. 2. Low commitment and less self-motivation to use the right tool at the right time [M1]. 3. Difficulties in connecting required personnel at the time of need [M1]. 4. Resistance to change [M2, M4].
Other	
1. ***Context-specific*** • Less effectiveness of ICT tools when customers are unable to provide correct specifications [M5]. • Difficulties of on-the-job training in advanced tools due to inability of having the same staff throughout the development process [M4, M5]. 2. ***Outcome-related*** • Difficulty of recovering high costs of ICT tools [M2, M3, V3, V4]. • Not utilizing the capacity of existing ICT tools [M1, V1, V4]. • Less reliance on the performance of advanced features and functionalities of ICT tools [V1, V2]. • Not understanding or valuing non-financial, long-term outcomes of ICT use [V1, V2, V3].	3. ***Organizational*** • Less staff training due to insufficient staff or interruptions to regular operations [V1, V3]. • Less flexibility of work due to high technology dependency (this restricts switching to simple tools where necessary) [M1, M2]. • Frequent changing of ICT tools [M5, V1]. • Not doing a proper analysis of tools before purchasing (which leads to availability of inappropriate tools) [V3]. 4. ***Collaboration-based*** • Low responsiveness and contribution of the partners [M1, M3]. • Failure in sharing or making information available as required due to not using ICT tools appropriately [M1, M2].

V. CONCLUSIONS

Drawing on relational resource-based view and organizational information processing theory, first, this study develops a conceptual model (Fig. 1) for investigating the impact of ICT usage on CPD performance. The subsequent qualitative investigation of industry perspectives supports the variables and the relationships in the research model while explaining the modelled concepts appropriately. With relevant industry evidence, this research significantly contributes to current literature [e.g., 8, 17] by identifying frequency, proficiency, and intensity of use as three dimensions of ICT usage, which helps in revealing ICT impact on CPD performance. The moderating project characteristics for the relationship between ICT usage and CPD performance found in this research, extend recent studies that have addressed such moderating effects with limited focus in terms of ICT usage, moderating factors, and CPD performance [e.g., 7, 28] . With descriptive practitioner point of views, the study identifies project complexity as the characteristic that predominantly represents the information processing requirement of a CPD project and could have an interaction effect with ICT usage on CPD performance. Furthermore, it identifies network complexity of a development team (number of partners involved and intensity of their involvement), and product complexity as key elements of overall complexity of a CPD project. In addition, project uncertainty can have common underpinnings with project complexity. While project urgency is confirmed as a project characteristic indicating information processing requirement of a CPD project, relative importance of exploration of its moderating effect was found to be lower in comparison with that of project complexity and uncertainty. In conclusion, this qualitative investigation offers inputs to fine-tune the measurement scales for the conceptual model constructs (Fig. 1) as described below.

Frequency of ICT use: The rate of using the following ICT tools in a CPD project (1) communication and collaboration ICT tools (in early product development stages), (2) communication and collaboration ICT tools (in development and commercialization stages), (3) product design and development ICT tools, (4) knowledge and information management ICT tools, (5) project management ICT tools, and (6) market research and analysis ICT tools.

Proficiency of ICT use: The level of proficiency of R&D staff attained (1) in simple ICT tools, (2) in advanced ICT tools, (3) through effectiveness of training given to staff on new IT tools, (3) by how easily the project staff adapted to new ICT tools implemented, and (5) via considering ICT proficiency as a major factor when recruiting R&D staff.

Intensity of ICT use: Utilized percentage of capacities, features, and functionalities in (1) communication and collaboration ICT tools, (2) product design and development ICT tools, (3) knowledge and information management ICT tools, (4) project management ICT tools, and (5) market research and analysis ICT tools used in a CPD project.

Collaboration performance: The level of success of a CPD project in terms of (1) sharing project benefits (2) sharing important ideas and information (3) knowledge sharing (4) risks sharing (5) contributing partners as expected and (6) creation of trust between partners.

New product quality: Achievement of new product's (1) customer satisfaction, (2) conformance quality, (3) quality relative to competing products, (4) technical performance, and (5) target scope.

Commercial success: The level of success of new product in meeting (1) sales objectives, (2) profit objectives, (3) market share objectives, and (4) price targets.

Time performance: Meeting new product's time targets in (1) concept formation, (2) development, (3) commercialization stages, and (4) overall development cycle.

VI. Practical Implications

This study explores the industry perspective on ICT usage in manufacturing collaborative product innovation projects. Findings from this study emphasize that technology level and ICT orientation of firms are basic criteria for differentiating ICT usage in CPD programs in manufacturing firms. Increasing quality and reducing time-to-market are the key expectations of manufacturers through the use of ICT tools. Although, the participants' emphasis on the indirect effect of ICT usage on project success through collaboration performance is inadequate, several participants valued collaboration related outcomes of ICT usage. Since a relatively higher competitiveness and market success is found in manufacturing firms that showed higher levels of overall ICT usage, a positive association between ICT usage and CPD performance can be expected. Based on the views of ICT vendors and manufacturers interviewed, performing a detailed cost-benefit analysis before purchase of ICT tools is recommended for manufacturing firms. This will help manufacturing firms in understanding the tangible and intangible, long-term performance outcomes of using ICT tools and reducing risks of not achieving expected results from these tools. Context-specific issues such as not receiving precise information within expected timeframe and human issues such as less commitment in using the right ICT tools at the right time are the barriers that are hard to overcome in achieving the CPD performance objectives. Manufacturing firms that are largely dependent on ICT tools in CPD operations need more caution about the technical issues highlighted in the study (Table IV) that could impact their operations. In order to minimize the consequences of many ICT usage related issues, it is recommended that manufacturers conduct a detailed analysis of their product development requirements and capabilities followed by a specific technology plan for ICT. While these findings provide useful implications to product developers, ICT vendors will also benefit from the study that provides insights for developing ICT tools to better facilitate CPD activities in manufacturing firms

VII. Limitations and Suggestions for Future Research

Although this study offers several significant implications regarding improving a firm's CPD operations with the use of ICT, it has some limitations that could be overcome in future research. The associations between ICT usage and CPD performance dimensions proposed in this qualitative evaluation will need further empirical confirmation with a large sample of data gathered from manufacturing firms involving in CPD. This study broadly considers five ICT types used in manufacturing CPD projects instead of focusing on distinct ICT tools within these categories. Therefore, conduct of in-depth studies on each type of ICT tool would be important to define more specific dimensions for evaluating the usage of each ICT type. Differences observed in the ICT usage in CPD projects can be caused by either lower requirement of the tools based on project characteristics or lack of understanding on the impact of ICT tools on project performance. This can be learned through a further investigation of manufacturing firms from various industries and that undertake CPD projects with various complexities and uncertainties. Since ICT usage can be significantly varied across technology levels of firms, future studies would be worthwhile to focus on firms at different technology levels separately.

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