THE IMPACT OF VIRTUAL TECHNOLOGIES ON ORGANIZATIONAL KNOWLEDGE CREATION: AN EMPIRICAL STUDY

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Abstract – This study examines the processes of organizational knowledge creation in two highly virtualized teams, one involved in the design of a small city car and the second in the re-design of a small industrial vehicle. Using Nonaka's model of organizational knowledge creation, we explore how the virtualization of knowledge based processes, i.e. the intensive exploitation of ICTs in support of knowledge-based activities, has shaped new forms of knowledge creation both at individual and organizational level. In contrast with previous studies [1] that identified knowledge codification as the main contribution of ICTs, this study provides detailed micro-level evidence on the ability of virtual technologies to support the transfer and the creation of new knowledge both at explicit and tacit levels. Several implications for scholars and practitioners are presented.

1. Introduction

The crucial role that knowledge-based assets play in contemporary business enterprises [2], has propelled system science research towards empirical [2] and theoretical [3,4] studies looking at knowledge creation processes and on their related impact on firm performance [5]. The expectation is that a better understanding of these processes at individual, group and organization levels can help scholars and practitioners improve the effectiveness of critical activities, such as innovation, considered of strategic importance for firms' competitiveness [6].

In this context, literature has unanimously acknowledged that information and communication technologies (ICTs) have a significant impact on knowledge based processes. They can support collaboration among people with different competencies and capabilities [7], facilitate knowledge access and sharing [8], assist the dissemination of explicit knowledge [9], etc. Likewise, they increase the awareness of who knows what and enable virtual joint work [10], as well as support easier and more effective simulations in product development [11], etc.

Despite a general agreement that ICTs can have a significant impact on knowledge based processes, empirical research exploring these issues is very limited [12,13]. Existing work has typically narrowed the analysis to very specific processes such as problem solving [14] and prototyping [15] or to specific ICT applications such as virtual simulation tools [16], enterprise resource planning (ERP) [17], electronic data interchange [18], etc. In other words, current literature has overlooked the fundamental change occurring to individuals and organizations associated with the extensive and massive adoption of virtual technologies in support of almost every relevant activity of their day to day. This theme is particularly relevant in the context of innovation activities because virtual tools are fundamentally modifying the working practices of several important processes such as design [10], prototyping [15] and testing [11].

This study extends current literature precisely by carefully analyzing the effects of *virtualization* of organizational knowledge creation processes in the context of innovation activities. Thus, the question this research intends to answer is: **what impact does the virtualization of a group's knowledge based processes - i.e. the extensive adoption and use of ICTs in support of knowledge intensive activities - have on the creation of new organizational knowledge?**

To answer this question, this study presents an extensive, detailed analysis of two research and development (R&D) projects in the automotive sector. The first is related to the design of a hybrid propulsion system and its implementation in a small industrial vehicle. The second is the design of a small city car.

This paper is organized in seven sections. Section two provides a brief overview of the literature on virtualization while section three presents a brief review of relevant theories of knowledge creation, including a description and motivation that lead to the adoption of the Nonaka's model [19] as theoretical background for the research. Section four presents the research method, as well as general information related to the R&D projects analyzed in this study. Section five provides a detailed description of the contribution of ICTs to knowledge creation processes in the two R&D projects analyzed. Section six presents the discussion followed by the conclusions in the final section.

2. Virtuality and virtualization

During the last decade, words such as "virtual", "virtualization", "virtualized" have been very often advocated by scholars and practitioners in the discussion of social and economic issues. Although the literature lacks a unique definition, the idea of virtualization is always associated with the introduction and extensive use of ICTs [20, 21]. Indeed, it is common knowledge that ICTs are progressively transforming day-to-day activities of individuals and organizations of the developed word. For example, a recent research of the Gartner Group shows that more than 60 percent of professional employees are currently working in environments in which ICTs are massively used [21].

But, it is worth noting that the use of ICTs is not the only feature associated with virtuality. Indeed, there is a conceptual agreement that virtuality is multidimensional [22,23]. For example, [22] conceptualize virtualization on two dimensions (i.e. electronic dependence and geographical distance, [23] on three (level of technology support, percent of time apart on task and degree of physical distance) and [24] on four (geographical dispersion, use of computer mediated communication, temporality and diversity). Our review of the literature reveals that even though definitions related to virtuality can differ, they always mention both the intensive use of ICTs and the geographical dispersion of the components of a team. Our case studies are characterized by both these two features.

The promises of virtuality to individuals and organizations are countless. Among others, several authors have mentioned that ICTs support: instantaneous information exchange overcoming geographical distance , costless stock of data and documents, improvements in the precision of knowledge replication and recombination, new and more effective routines to design new products and conduct problem solving activities both at individual and organizational level.

Virtualization is also expected to affect how individuals conduct knowledge-intense activities such as research and development projects. In particular ICTs are expected to transform how individuals and organizations create, transfer, store and apply knowledge [25]. For example knowledge storage at organizational level has been improved in degree and quality by electronic databases, knowledge repositories, and electronic bulleting boards [25]. By the same token, knowledge creation at organizational level has been dramatically modified by virtual design tools and other collaborative virtual technologies [10].

As already introduced, previous research has focused on the analysis of the impact of specific ICT tools, such as virtual simulation tools [16], enterprise resource planning (ERP) [17] or electronic data interchange [18]; but the literature has overlooked the overall impact of ICTs on knowledge creation processes. We intend instead to look at the overall impact of ICTs on the activities of a group and in particular on knowledge creation processes. Consistent with previous literature [26], we refer to ICTs or virtual tools as those electronic technologies used for information, data and knowledge processing and in particular to convert, store, protect, process, transmit, and retrieve information, data and knowledge from anywhere, anytime.

3. Theories on knowledge creation processes

The last two decades have witnessed the emergence of a variety of micro-theories of knowledge creation processes that opposed to the traditional epistemological studies on knowledge justification and to the macro-theories of scientific change [4]. The review of system and management science literature reveals at least five main frameworks associated with knowledge creation processes, i.e. the Shinayakana System Approach [27], the Nonaka model of knowledge creation [19], the Rational Theory of Intuition [28], the Gasson's OPEC Spiral (Objectives-Process-Expansion-Closure) [29] and the Motycka's EDIS Spiral (Enlightenment-Debate-Immersion-Selection) [30]. Although these theories differ in several important points, all of them are based on the premise that new knowledge is created through the continuous combination of contrasting cognitive resources and/or processes, such as the Polanyi's tacit versus explicit knowledge dichotomy adopted in the Nonaka's model.

Among all these theories on knowledge creation, the Nonaka's model represents without any doubts the most important one. Indeed, between the 1995 and 2004 Nonaka [19] and Nonaka and Takeuchi [31] were cited 1636 times [13]. We adopted the Nonaka's model for several reasons.

First, previous theoretical studies have adopted it to shed light on the potential improvements driven by virtual technologies on knowledge-based activities [25,32]. But, to the best of our knowledge, there are not previous empirical studies which validated these theoretical works. As a consequence this research will provide the first micro-level empirical indications useful to validate and extend the theoretical studies of Alavi and Leidner [25] and Junnarkar and Brown [32].

Second, in contrast with other theoretical models, each knowledge creation "mode" in Nonaka's model describes an organizational cognitive process which is associated with activities that are easy to observe (e.g. the internalization process is associated with the repetition of standardized processes or the combination mode with confront and integration of documents). This match between easy-to-observe activities and processes in the knowledge domain is very suitable for the conduction of an empirical analysis.

Finally, Nonaka's model has been extensively adopted to provide normative indications to managers and policy makers related to the development of organizational and environmental condition conductive of intensive knowledge based activities [25, 32, 44]. The adoption of Nonaka's model allows us to extend these indications, which were focused on traditional environments, in the context of highly virtualized organizations.

Figure 1 presents this framework. As introduced before, knowledge creation is represented as the result of four sub-processes or "modes": socialization, internalization, externalization and combination. Socialization refers to the conversion of tacit knowledge into tacit knowledge through social interaction. "We use the term socialization to emphasize that tacit knowledge is exchanged through joint activities such as being together, spending time, living in the same environment rather than through written or verbal instructions" [34].The externalization mode relates to the expression of tacit knowledge and its translation into explicit forms that can be easily understood by others. People are able to externalize their tacit knowledge through dialogue and sharing of perspectives, often via allegories and figurative speaking [35]. Much of what Polanyi has called tacit knowledge is in fact expressible through metaphors [36,19]. The third mode, combination, refers to the creation of new explicit knowledge by merging, categorizing, reclassifying, and synthesizing existing explicit knowledge. Combination activities can be conducted through a wide group of processes such as

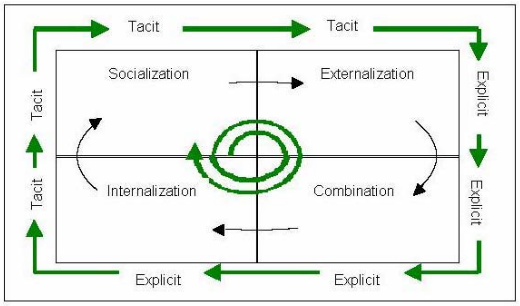

Fig. 1. The Nonaka Model of Knowledge Creation.

phone conversations, face-to-face meetings, writing, reading and exchanging written documents both in physical and virtual format.

The internalization mode allows the conversion of explicit knowledge into an organization's tacit knowledge at individual and group level. Knowledge can in fact be embedded in individual members, in the organization's rules, routines, cultures, structures and technologies [37]. The internalization mode relies on two different processes. First, explicit knowledge can be embodied in organization action and practice through the creation of formal routines and procedures. Second, the individual "embodiment" of explicit knowledge can be developed using guided simulations [31].

4. The research method

This work is part of a four-year research project designed to understand the impact of ICTs on innovation processes in the automotive sector. As part of this project, we have analyzed six different R&D projects and also conducted a wide survey on a population of 500 automotive first tier suppliers. For this particular study, because of its exploratory and descriptive nature, we adopt a multi-case study research method. Case study selection was driven by the need to analyze the use and contribution of ICTs to knowledge based activities in organizational contexts where these tools are extensively exploited. In particular, as explained below, we selected two projects with complementary technological and functional objectives in order to guarantee the generalization of the insights based upon our empirical analysis.

The two projects considered in our study were developed for an important European automotive company. It is a very well established and known firm with a global presence in different automotive sectors: industrial vehicles, sport cars, family vehicles, etc. The first project was the design and implementation of a hybrid propulsion system in a small industrial truck. We will refer to it as the "Eco Project." It lasted four years and involved a total of 16 engineers. Eleven of these engineers had recently completed their undergraduate degrees in mechanical and electrical engineering. They were hired by the company specifically for this project and enrolled in a long training project financed by the European Union. The project manager was a 55 year old engineer, an employee of the company with more than 25 years of work experience in automotive R&D projects. His activity was supported by a senior engineer, who had more than fifteen years of design experience in electric/electronic automotive components.

The second project, the "City Project", was the design of a small automotive city car that would compete with the Daimler Chrysler *Smart* model. The objective of this project was to develop a new city car with multiple propulsion systems, i.e. a fuel cell and a hybrid propulsion system. The main areas of technical focus for the project were: design of the structure, design of electrical, transmission and control systems, as well as the application of a fuel cell and hybrid propulsion systems already developed by the company in previous R&D projects. The "City Project" was a three-year project that involved 11 engineers with different specializations: mechanical, electricity systems, electronics, control systems, structural engineering, etc. The project manager was a mechanical engineer with a specialization in automatic systems and more than 25 years of experience in automotive R&D projects.

Qualitative and quantitative data were collected during three-week internship periods that one of the authors undertook in each of the R&D groups. Moreover, additional visits of two-three days, as well as phone interviews and e-mail exchanges with managers and engineers of each R&D group provided further information. At the end of the data gathering process, we spent approximately 80 days in on-the field activity and we completed 60 focused interviews and 28 open interviews.

The main sources of qualitative and quantitative information were direct observations, interviews and official internal reports and documents of each project. Interviews were conducted following two different approaches: open interviews [38], which were done during the laboratories/ in plant visits or phone calls, and focused interviews [38] where the respondent was interviewed for about forty – fifty minutes using a specific, but flexible, set of questions. Moreover, we developed quasi-verbatim transcripts of all inteviews which were lately coded. In order to avoid bias caused by data collection, we developed a specific strategy of theoretical sampling. Based upon the plans of activities of both projects and the indications of project managers and of other members, we collected data of the activities of each task of each project.

During the development of case studies analyses we faced several methodological concerns. The first is related to the distinction between tacit and explicit knowledge[1]. To distinguish between tacit and explicit knowledge we developed a three step methodological approach based on previous empirical studies [42, 43, 12]. First, we looked for particular processes that are associated with the creation of tacit knowledge, such as intensive joint work related to experimental practices [36], or with the creation of explicit one, such as preparation of reports for internal and external uses [12]. Second, we integrated our interviews with questions that were previously adopted by [42] and [43] to distinguish between the exploitation of tacit and explicit knowledge sources. For example, we directly asked engineers if the knowledge driving a specific activity was available in codified form or, on the contrary, if it is was mainly based on tacit, non codified expertise [42]. By the same token, during the direct observations, we controlled for the use of manuals, online guides, which are sources of explicit knowledge, versus the exploitation of "*procedural habits as automatic processe*s" [43].

Finally, we looked for activities that were distinguished by previous studies as indicative of a specific knowledge creation mode, i.e. socialization, externalization, combination and internalization. For example, intense experimental collaboration between two or more individuals was identified as a socialization mode while repetition of guided organizational processes was classified as an internalization activity.

The comparison and triangulation between the aforementioned analyses allowed us to distinguish between tacit and explicit knowledge and to identify the four modes of Nonaka's model.

A second important methodological concern relates to the identification of the contributions that the various ICT tools (e.g. 3D- CAD, databases, workflow system) can provide to knowledge based processes. Our definition of ICTs includes all computer-mediated technologies used by individuals and groups in support of day to day activities. To address this identification issue we developed a two-step methodological strategy. First, we analyzed each relevant process/activity developed in the R&D projects, assessing the contribution of ICT tools through direct questions to designers and engineers as well as direct observations of their work. Then we reversed our data gathering path: we questioned designers and engineers about the contributions of each ICT tool to the development of the various project activities, its capabilities and main features, etc. Data triangulation between interviews indications, direct observations and internal reports of the project and the comparison between the results of the two step analysis provided a detailed description of ICTs contribution on each knowledge-based process that characterized an R&D project.

Another concern of our research agenda was "trustworthiness" [44, 12], i.e. external validity and reliability of the qualitative data gathered throughout the study. **External validity**, i.e. establishing the domain to which a study's findings can be generalized [45], was supported by: a) detailed description of the organizational and the environmental context of each project task object of our analysis b) interviews to a wide number of members of each R&D group, partners and suppliers involved in a specific task c) detailed description of the points of the empirical evidence representing the base for generalization. **Reliability**, i.e. demonstrating that the operation of this study can be repeated with the same results [45] was guaranteed by: a) purposive and theoretical sampling (e.g. timing of data collection, structure of interviews), b) data triangulation between on-site observations, open and direct interviews and official documents c) protecting the confidentiality of interviewees inside and outside each R&D group in order to prevent biased answers and d) a peer review of the results with a manager responsible of each R&D project considered. (Additional information concerning the research methodology can be provided upon request within the limits set by the confidentiality agreements signed with the participating organizations).

5. Results

ICTs were intensively adopted in both R&D groups. According to our interviews, virtual technologies have replaced most of the traditional practices (e.g. paper based designs, physical prototyping) related to design activities for three main reasons. First, virtual technologies can improve "*the detail and precision of design activities*". For example, three dimensional computer aided design (3D-CAD) technologies allow to design with extreme precision "*microscopic details of the attaches of structural parts… with a precision that was almost impossible with paper based sketches*". Second, ICTs, and in particular CAD technologies, help designers to look at a particular components with multiple and complementary viewpoints. For example, designers are able to select with a specific color the electricity system of a component, with another color its structural parts, and with a third color its hydraulic system. Finally, ICTs allow designers to easily exploit designs of other documents previously developed inside the organization. This feature has consistently reduced the time consumption associated with design working practices. Indeed, the work of the past can be exploited just with a "paste and copy".

5.1 Socialization

Previous empirical evidence [10, 46] suggested that CAD tools provide a virtual environment where designers can intensively work at the same time on the design of a new component and develop experiments through virtual

[1] Consistent with existing literature [39, 40, 19] the understanding of *tacit knowledge* in the context of our empirical study will be: *knowledge that is not and can not be easily codified in documental form, which is difficult to express with completeness through words and/or that is grounded on personal and/or group experience.* Examples of tacit knowledge are: knowledge associated with long period of co-working and sharing of experiences such as that acquired by apprentices in craftsmen laboratories [19] or aesthetic considerations related to product shapes [41].

simulation. Since these activities are indicators of the socialization mode [19, 12, 35], we focused our attention on collaborative design practices.

The direct observation of more than 250 hours of working activities of designers involved in both projects showed that ICTs support *virtual* socialization modes both between designers located in the same physical location and between geographically dispersed individuals. In particular, collaborative 3D-CAD systems allow two or more designers to work at the same time on the same design of a component and, if necessary, internet-based messenger systems can support simultaneous conversations. We provide two instances of how ICTs can be exploited in support of virtual socialization processes.

The first example relates to the collaborative effort of four designers designing the structural attaches of the engine of the ECO project. They worked together at the same time on the same virtual prototype. We noted that one engineer would consistently be manipulating the virtual prototype, while others would just look at the colleague's actions and provided him/her comments and suggestions. When we directly questioned designers about their use of virtual tools, one of them stated: "*we use [3-D] CAD applications as virtual cameras where it is possible to work together […] design new things […] understand how things can be matched through iterative simulations […] and* ***how*** *others do the same thing…".*

By the same token, when the senior engineer of the ECO project was required to move to another geographically separate unit of the company (for reasons unrelated to the project), three designers continued to interact with him exploiting both the collaborative CAD functionality and electronic voice/instant messengers. In particular the senior manager was able to visualize in real time the designs (of the additional brake system) prepared by the young engineers of the remote center and correct them in real time. Likewise, the collaborative CAD tool enabled young engineers to see in real time **how** the senior designer was modifying their sketch, and directly interacted with him to "correct" some of his modifications. Finally, voice/instant messenger allowed them to freely speak during all these activities.

We recognized this activity to represent a *virtual* socialization mode. Indeed, such kind of collaborative practice is analogous to the "traditional", i.e. non virtual, socialization modes identified in previous empirical studies on new product development [12,35]. Moreover, according to the interviews, both the knowledge sources and the newly generated knowledge are mainly at tacit level. The knowledge source of these experimental practices is tacit because" *it's based mainly on our previous design experience*" (Interview PG) or "*it's a mixture of practical experience and a mess of things I am not sure how I know*" (Interview SP). The knowledge created during this task is also mainly tacit because it refers to experiences related to highly specific technological contexts and cannot be easily codified. Indeed, it is "*…is too specific and complex, there is no way to explain it …it's not a competency constraint [of the other colleagues] … it's just that it's almost impossible to use words for it...you have to see it for a long time*" (Interview, year 3).

It is worth nothing that during the interviews several designers have pointed out that the adoption of virtual technologies has driven to an increase of the degree of the tacitness of the knowledge associated with design processes. Two main reasons can explain this fact. First, virtual design tools allow costless and almost instantaneous simulations. As a consequence, when compared with traditional design tools, the virtual ones support the development of a higher number of design attempts per unit of time and in turn the acquisition of more experiential tacit knowledge associated with such practices. Second, virtual design tools have increased the degree of precision and detail of design sketches and the development of virtual tri-dimensional effects. This leads designers to developing a deeper understanding of the problems related to each technological solution, the spatial and technological interdependences between different components and their possible combination. For example, a designer suggested: " *3D [CAD] pushes us to understand and think things in a different way… problems enter in my mind now and I can see them in a different way…it's difficult to say…like when you play with videogames and you start dreaming about them... with a pen and a paper you do not understand anything relevant…*"

In conclusion, just like artisans working in the same factory share and create new tacit knowledge related to working practices [39], ICTs create a *virtual* 'ba' [235,47,48,33] i.e. a shared context that provides a platform for advancing individual and collective knowledge [49] through shared simulations and experimentation, and where meaning emerges involving the tacit dimension of knowing [50].

5.2 Externalization

We did not find any significant contribution of ICTs to the externalization processes of the ECO and the City Car projects. According to the interviews, the conversion of tacit knowledge into explicit is generally done in order to prepare documents- such as internal and official reports, or a manual, or a collection of best practices- and to provide indications to inexperienced colleagues.

Engineers in both the ECO and the City Car projects noted explicitly that the contribution of ICTs is not relevant for externalization. The tacit knowledge they have to convert in explicit form was mostly related to the experience and knowledge they acquired during experimental practices. During an interview, a designer of the ECO group declared "*we do not have tools that help us convert our experience in documents… translating experience in explicit form… it is very difficult … requires a lot of effort … and the only thing we can do is using our minds and then to write …"* (Interview, year 4). The interviews of the designers of the Car project confirmed this insight. The usual way to externalize tacit knowledge and to create new one at explicit level in the City Car project team was discussing and hand-writing during brief informal meetings and lately preparing small reports with the results of the discussions. Although the reports were generated with a word processor, the experience and process was not very different than what would have been associated with using a very sophisticated typewriter.

5.3 Combination

As presented in Table 1, ICTs supported combination in both R&D groups. They allow and leverage in unique ways individuals as they gather, analyze and re-elaborate explicit knowledge from sources that are internal and external to the R&D group and create new explicit knowledge. For example, during the preliminary phases of the ECO project, designers acquired a wide set of European environmental norms (e.g. 70/156/CEE, 80/1268/CEE, Standards EURO III, IV and V) and internal documents related to similar projects already developed inside the company. They then recombined and summarized these documents in a new review report that was posted in the project database. Similarly, structural designers of the City Car project collected the European and national norms of crash test requirements and prepared a summary for their colleagues.

When compared with traditional working tools (e.g. paper based documents), ICTs have dramatically improved the combination capabilities of an organization. Indeed, ICTs allow a group to: a) easily acquire useful knowledge from a wider number of sources through the Internet and the company intranet, b) to compare and triangulate important data in order to guarantee the creation of new trustworthy documents, c) to select and easily recombine important parts of documents previously acquired, d) to post the new documents in electronic database for further use.

5.4 Internalization

ICTs provide a significant contribution to internalization processes in two main ways. The first is individual (guided) simulation and experimentation through virtual design tools (i.e. 3-D CAD software, structural design software, electrical component design software). For example, during the preliminary phases of the ECO project, three designers started individual work to prepare different preliminary designs for the batteries' layout and to simulate different consumption/charging temporal trajectories in urban, non urban and mixed routes. Designers were guided by on-line virtual indications provided by software demos or small videos that allowed them to internalize working practices related to virtual experimentation. According to the interviews, these on-line virtual tutorials helped them to better understand and absorb working practices related to the design practices or to develop a simulation of a consumption-charge battery history.

Moreover, newly hired designers of the ECO and the City Car projects discovered they had to follow rather strict organizational procedures. For example, the introduction of a new CAD sketch in the company database had a mandatory completion of a small on-line form, while the modification of a sketch posted in the project database required the creation both of a copy of the old file and another of the new one. Since these rules were mainly managed through ICT applications, following them through the use of virtual tools allowed designers to embody into action and daily practice the explicit knowledge represented by organizational procedures. According to the interviews, while "old" working processes (e.g. paper based workflows) could be easily eluded, ICT tools (e.g. workflow software) constrain employees to respect organizational procedures with more precision and consequently to acquire the organization's *forma mentis*. Indeed, when questioned about the impact of ICT-enabled routines on organization culture, a designer suggested: "*the workflow system is really boring… but it does work on me… after a long period of repeating a specific task, I start to do it without thinking… it's just how **we** do things*" (bold added by the authors) (Interview, year 1).

6. Discussion

The empirical evidence associated with the ECO and the City Car projects points to several ways through which ICT tools can contribute to knowledge creation processes associated with firms' innovation activities. As reported in Table 1, the group of virtual tools exploited in such activities comprehends very common technologies such as e-mail or company databases, as well as design-specific applications such as structural design programs or 3-D CAD tools.

Both case studies show that the combination of these tools creates a *virtual dimension* that covers the day-to-day working practice of designers and engineers. In other words, all virtual tools available today on a designer's desktop offer a virtual space where an individual can create new designs, collaborate with other colleagues in experimental practices, acquire, share and create new documents, etc.

Our study corroborates part of previous theoretical and empirical researches on the impact of ICTs to firms' knowledge based activities. ICTs increase the speed and the precision of information transmitted between geographically dispersed individuals [10], increase the amount of knowledge that can be stored in company databases [51], improve the easiness of knowledge replication processes [52] and provide new and more effective problem solving techniques, often exploiting virtual simulations. This last result contrasts the findings of [14] which pointed out the indispensable role of traditional working practices, such as paper sketching, in problem solving efforts of an important civil engineering design company. We propose two main explanations associated with this different result. First, civil engineering design may require a lower level of precision when compared with modern high tech automotive mechanical artifacts (an hybrid engine). For example, the average tolerance level in a civil engineering project is around half a centimeter, while in the automotive sector is less than half a millimeter. Second, the aesthetic success of the body of a car is based on the design of details that are very difficult to represent through paper-based sketches. On the contrary, virtual design tools can be very useful in representing tri-dimensional effects of a car.

A very important result of this study relates to the ability of ICTs to support the exploitation and creation of new knowledge both at tacit and explicit level. In particular, both case studies show that collaborative 3D-CAD tools create a *virtual medium* where designers can develop collaborative simulations that, grounded on the tacit sources of individual designer experiences, generate new tacit knowledge associated with the new collaborative experimentations. In this context, two important insights seem worth noting. First, several designers have suggested that virtual collaborative design tools *enhance the degree of tacitness* associated with design practices. Since these tools support an higher number of simulations per unit of time and have increased the precision of design practices through the generation of multi-dimensional representations, the new tacit knowledge associated with experimentations done through these tools is consequently more rich and even more difficult to express in explicit form. Second, the contemporary use of 3D-CAD and internet-based instant messengers allows geographically dispersed individuals to conduct virtual socialization processes. This is a very important result since previous literature [19,31] has relegated socialization processes to traditional face to face contacts.

Both case studies show that ICT-based knowledge creation processes can occur not only in the first quadrant of the Nonaka's model but at least in other two knowledge creation modes, i.e. combination and internalization. In particular, four software or ICT-based services, i.e. e-mails, communities of practice, shared databases, and the Internet, contributed to the combination mode of the ECO and the City car projects. As already suggested by previous studies [55,9], these tools have increased the availability of useful sources of explicit knowledge overcoming temporal and spatial constrains. We found that ICTs can support internalization mode in at least three ways. First, they can provide online manuals and courses in replacement of the traditional paper based ones. Second, they can support the exact repetition of organization processes through workflow systems. Finally, they can support guided experimental practices through tutorials of virtual design tools. These last two virtual processes, when compared with traditional working practices, are seen to be more effective. Indeed, workflow systems and on line tutorials can guide step by step individual activities, avoid doing mistakes and provide continuous assistance for the development of a specific task. This uninterrupted online assistance helps consequently individuals to acquire and internalize the explicit knowledge associated with organization routines and/or design rules supporting in turn the development of a unique organizational culture.

Collectively, the observations of our research point out several important insights for both practitioners and scholars. First, they expand early attempts to recognize the ability of ICTs to support tacit knowledge exchanges [41], an aspect of strategic importance for organizations [53]. Current literature of management of information system [9, 32] and innovation management [51,1] has associated the contribution of virtual technologies only with explicit knowledge processes.

Among other dimensions, the possibility to transfer and develop new tacit knowledge using virtual technologies can resolve the dilemma of knowledge replication versus imitation [55]. Organizations often rely on externalization – by generating documents – to allow other groups inside the same company to exploit tacit knowledge; but this codified knowledge also becomes more likely to be appropriated by competitors [55,56]. Our work suggests that virtual technologies may allow a bypass of externalization in assuring a wide dissemination of relevant tacit knowledge within a firm, even between geographically dispersed units, thus limiting the risk of competitors' replication or learning.

This result opens new important perspectives of research and managerial practice since previous studies [53] have prescribed as best policy in support of the geographical diversification of firms' R&D activities the mobilization of personnel because tacit-to tacit communication is considered of strategic importance for the successful conduction of R&D projects. Our study suggests that virtual technologies can support knowledge-based process at tacit level between distant individuals and consequently these tools can reduce the organizational and financial costs associated with geographical diversification of R&D by avoiding the need of personnel transfer.

A second important insight for practitioners relates to the impact of design tutorials and workflow systems on the internalization mode. The improvements of internalization processes driven by these virtual tools suggest they should be widely adopted and used in contexts that require both the development of a more homogeneous organization culture and the reduction of individual mistakes in design activities or procedural works.

Finally, it is important to note that we did not find any relevant contribution of ICTs to the externalization mode. Our observations confirm that the conversion of tacit into explicit knowledge was mainly based on individual efforts and that ICTs did not supported such activity in a meaningful way. However, this result needs further empirical examination in order to acquire more data necessary for adequate generalizations.

7. Conclusion

By understanding the changes associated with the virtualization of organizational knowledge creation in the context of innovation activities, this study represents a point of connection the system science research, the management of information systems and innovation management literatures. It demonstrates how the implementation and intensive use of several virtual technologies can lead to the creation of a multi-tool virtual medium that has the potential to modify and improve knowledge creation processes both at individual and organizational level. The recognition and description of the multiple ways through which virtual technologies can improve knowledge creation processes, both at tacit and explicit level, has pointed out the need to radically change our understanding of the strategic and organizational potential offered by these technologies to contemporary firms.

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PREVALENT MODE	PROCESSES	ICT APPLICATION
Socialization	a) Cooperative design between designers located in the same office. b) Cooperative design between geographically dispersed designers.	a) Virtual Design Tools (e.g. 2D/ 3D-CAD), structural design software, design software for electricity components (DSEC) b) Virtual Design Tools (e.g. 2D/ 3D-CAD, structural design software, design software for electricity components (DSEC)
Externalization	a) Preparation of internal detailed technical reports b) Preparation of external detailed technical reports	a) Word Editor b) Word editor
Combination	a) Exchange and re-elaboration of documents acquired inside the R&D Org. b) Exchange and re-elaboration of documents acquired outside the R&D Org. c) Development of a project's database, etc. d) Grouping, synthesizing and re-organizing technical reports	a) E-mail, Internet, virtual communities of specialists b) E- mail, Internet, virtual communities of specialist c) Project Database d) Project Database, e-mails Corporate Databases, Text Editor.
Internalization	a)[2] Finding and reading procedures/manuals b) Simulating and experimenting alone (learning by doing) c) Respect of organizational procedures	a) Corporate Databases b) Virtual Design Tools, structural design software, design software for electricity components (DSEC) c) Workflow systems

Table 1: Processes and related contribution of ICT-tool in each Nonaka's mode.

[2] Alphabetical letters provide the correspondence between activities and the ICT tools adopted in supporting each of them.