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Technical knowledge creation

Enabling tacit knowledge use

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Technical Knowledge Creation: Enabling Tacit Knowledge Use

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The paper investigates knowledge creation in nascent technical industries, a somewhat neglected empirical setting concerning knowledge creation. Frameworks on organizational learning and knowledge creation assume that knowledge creation depends on language creation and neglect the benefits involved by allowing elements of new product and process ideas to mature in a tacit form, whereas cognitive neuroscience data suggests that technical knowledge creation is largely nonlinguistic. The four case studies point to excessive reliance on group discussion, a need for more trial and error and that field tests and prototypes generate new learnings that save time and lowers subsequent risks. Technical knowledge creation in nascent high tech industries requires opportunities to work with and further develop knowledge in its tacit form. The paper refines frameworks on organizational learning and knowledge creation to better reflect the characteristics of technical knowledge creation. The paper adds prototypes as a necessary, but currently missing outcome option from interpreting processes in the 4I framework.

Keywords: Knowledge creation, Tacit knowledge, Organizational learning, Prototypes, Mirror neurons.

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INTRODUCTION

Knowledge creation requires collaboration (Tzortzaki & Mihiotis, 2014) and interaction (Vasantha et al., 2016), however, the role of language for technical knowledge creation is unclear. For Albert Einstein "*words seemed to play no role in his mechanism of thought, which instead relied on 'certain signs and more less clear images'* " (Hadamard, 1996: IX). Similarly, one of the founders of Apple (the technically talented Steve Wozniak) advises vigorously for working alone, not in teams or as part of committees when trying to create something revolutionary (Wozniak & Smith, 2006). Thus, Steve Wozniak, as well as Albert Einstein, seemingly support the notion that verbal group interaction in itself is insufficient to nurture the creativity needed to bring about new breakthroughs. Interestingly, they thereby contradict Crossan et al. (1999) and advice against any reliance on group dynamics and related language development. To introduce the 4I framework, Crossan et al. (1999) used another Apple founder (Steve Jobs) to exemplify how language development is essential for knowledge creation and argued that had Steve Jobs used other metaphors, much would have been different. Knowing what we know now, we might add that had Crossan et al. (1999) developed a case about Apple and investigated how technical knowledge creation takes place rather than inferring things about the company; some things might have looked different in the field of knowledge management. The account of Steve Wozniak is opposite to the story in Crossan et al. (1999) where Steve Job's metaphors gets a main role as driving forces of the knowledge creation in Apple. At the center of this misunderstanding lies the notion of knowledge creation as dependent on language creation.

Frameworks on knowledge creation and organizational learning reflect the assumption that knowledge creation hinges on language development and stress codification of tacit knowledge (Chomsky, 2006; Crossan & Berdrow, 2003; Crossan et al., 1999; Nonaka & Konno, 1998). However, empirical evidence suggests that tacit knowledge is an antecedent of innovation performance (Jisr & Maamari, 2017) and that brain processes required for technical knowledge creation are nonlinguistic (Amalric & Dehaene, 2016; Monti et al., 2012). It is necessary to understand the processes of technical knowledge creation and explore and revisit if they fit well with existing knowledge creation frameworks. Given that most frameworks on knowledge creation have neglected nascent high tech industries it is necessary to explore: how technical knowledge creation occurs in nascent technical industries?

The findings of this paper illustrate that technical knowledge creation in nascent high tech industries requires opportunities to work with and further develop knowledge in its tacit form rather than only forcing its codification. Codification and language development requires focused attention in other areas of the brain than those needed to evolve solutions for technical problems. Codification also requires time and resources not amply available in most high tech startups and thereby slows down technical development. The paper adapts the 4I framework (Crossan et al., 1999) by adding prototypes as an additional outcome option from interpreting processes in the 4I framework to make the framework more useful also for technical knowledge creation and reflect better the micro-processes previously neglected in knowledge creation theory (Foss et al., 2010). The design entails four case studies in which the conceptual background is applied and further refined. The findings enable technical knowledge creation to take place more efficiently by using prototypes that enable work with knowledge in a largely tacit form.

The paper sequence entails the conceptual background comprising perspectives from cognitive neuroscience, operations management, and product development that illustrate benefits of enabling the use of tacit knowledge. The analysis follows methods and case descriptions. Finally, discussion, conclusions, limitations, and suggestions for further research wrap up the paper.

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CONCEPTUAL BACKGROUND

"*Knowledge creation is concerned with the development of new organizational knowledge in the firm.*" (Nielsen, 2006; 62). Firms "*rely on internal knowledge sharing and creation to develop new products, production processes, marketing strategies, and management practices*" (Costa & Monteiro, 2016; 215). The 4I framework (Crossan & Berdrow, 2003; Crossan et al., 1999; Crossan et al., 2011) and the SECI model (Nonaka & Konno, 1998) are examples of frameworks within organizational learning and knowledge management that equals knowledge creation with language development. These frameworks thereby neglect nonlinguistic aspects of technical knowledge creation. The SECI model has much in common with previous work (e.g., Hedlund, 1994), emphasizes verbal group interaction and centers on transformations of knowledge back and forth from tacit to explicit knowledge using the four modes socialization, externalization, combination, and internalization. The emphasis of tacit knowledge should sit well with the nonlinguistic nature of technical knowledge creation, and the framework does include notions of using visuals as part of externalization. However, the notion of frequent knowledge transformation back and forth from tacit to explicit knowledge fits poorly with technical knowledge creation and receives criticism (e.g., Gourlay, 2006; Tsoukas, 2003). It begs the question if it makes sense to outline a knowledge creation process where advanced technical knowledge, as a default needs to be made explicit? This aspect of the SECI-model does not sit well with the nonlinguistic nature of technical knowledge creation and seems somewhat naive. On the other hand, the SECI model entails an exciting distinction between different components of tacit knowledge. The cognitive component of tacit knowledge concerns belief systems and mental models, whereas the technical component resembles know-how (Jisr & Maamari, 2017; Nonaka & Konno, 1998). This distinction is useful in that much creative potential likely exists for companies when mixing existing know-how with new mental models since this approach brings new perspectives and thereby possibly new applications for the existing know-how. New ideas are often merely new perspectives (Miesing et al., 2007) that are particularly likely to form when existing know-how (the technical component of tacit knowledge) collides, or combines with, new mental models (the cognitive component of tacit knowledge) (Søberg, 2011). Companies can use and exploit this destinction as inspiration to maximize the availability of different mental models and different levels of know-how and thereby increase diversity in project groups following the notion that diversity is often benefits creativity (Beeby & Booth, 2000). However, providing opportunities for people to recombine existing knowledge in group settings is insufficient to nurture radical ideas. It is interesting that the two modes of the SECI model that emphasize verbal or codified group interaction (externalization and combination) are suitable for creation of incremental product ideas rather than novel ones. Only the modes not focusing on verbal group interaction (internalization and socialization) are useful for creating novel product ideas (Schulze & Hoegl, 2008). Similarly, Jisr and Maamari (2017) find that tacit knowledge is an antecedent of innovation performance.

Language is also a key part of the 4I framework (Crossan & Berdrow, 2003; Crossan et al., 1999; Crossan et al., 2011). The 4I framework focuses on strategic renewal and has been heavily used also for research on product development (Akgün et al., 2007; Bstieler & Hemmert, 2010; Holmqvist, 2004; Reid & De Brentani, 2004; Schulze et al., 2013). It comprises the four processes intuiting, interpreting, integrating, and lastly institutionalizing (Crossan & Berdrow, 2003; Crossan et al., 1999). Crossan et al. (1999) acknowledge that intuiting is largely a preverbal process and paraphrase Watson (1969) on the point that forcing the sub-conscious process of intuiting to be conscious may prevent it from happening. However, Crossan et al. (1999) stress only linguistic elements such as imagery, metaphors, language, and conversation/dialogue as outcomes from the intuiting and interpreting processes of the 4I framework.

Product development requires technical knowledge that entails a good grasp of math and spatial understanding. These knowledge domains are largely non-linguistic. We know this from functional magnetic resonance imaging (fMRI) which has enabled mapping of which parts of the brain are active during different activities. During activities related to math or spatial thinking that are often essential for technical knowledge creation and product development, other parts of the brain are more active than those related to language (Amalric & Dehaene, 2016; Monti et al., 2012). It thereby seems inadequate to follow the normative tenets of the 4I framework, and force people prematurely to put in words their technical ideas.

Enabling Use of Tacit Knowledge

Following the notion that, "*learning processes can be compared to production processes*" (Crossan et al., 1999: 535), it is relevant to consider elements from operations management. Despite the data-driven nature of many operations management approaches, including statistical process control, the field of operations management includes tools that enable the use of tacit knowledge (Ferdows, 2006). To limit wasteful overproduction Henry Ford would decrease the space available for work in progress between workstations and the Kanban system at Toyota had the same purpose (Goldratt, 2008). However, a key benefit of some implementations of the line layout type is the lack of (need for) verbal communication. Lean production promotes visual management and at-a-glance transparency, which enables the sharing of key information without lengthy verbal elaboration. For instance, in lean production adjacent processes as well as the early and late steps of transformation processes are often located nearby each other to allow problems to be obviously identifiable without lengthy communication. Locating process steps closer together following lean production best practices (Bicheno & Holweg, 2009; Slack & Lewis, 2015) enables more tacit knowledge transfers

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across different process steps. Colocation makes it possible for nearby operators to have a look at what is wrong. If not co-located, operators at the place of the breakdown would likely have to call other operators and try to explain the problem. The colocation of process steps enables the use of the collective experience of different operators to diagnose and solve problems faster. Such ways to allow for the use of tacit knowledge in its tacit form is often faster. Decisions as to when to put new knowledge and ideas in the technical realm into natural language have similarities to decisions concerning, when is it the right time to standardize as part of operations improvement. One reason is that in the context of product development, language is kind of a standard, a tool for sharing thoughts and ideas, but not a bespoke one. When using natural language to describe ideas, there are limits to how many new words one can invent for the occasion while remaining understandable for others. Language induces constraints as does standardization in operations improvement. Premature standardization can introduce limitations that restrict subsequent improvements and long-term innovation. Consider for instance the essential lean tool 5S, which is short for the five steps that each starts with the letter s: Sort, Set (in order), Shine, Standardize, and Sustain. Notice that standardization is only introduced as the fourth of the five steps because 5S implicitly acknowledges the costs of premature standardization. Although standardization is often essential for operations improvement, it should not take place before the right standard is available. Similarly, language use forces (hopefully) informed choices about which elements of the richness of knowledge to reduce away to arrive at something others can understand using words. However, if this tool is applied prematurely, the result is often ideas that are less novel (Schulze & Hoegl, 2006, 2008).

Novel technical ideas need time to mature in a tacit form. Tacit and explicit knowledge does work the other type of knowledge can not (Cook & Brown, 1999), which reflects that it is often difficult, costly, or overly time-consuming to convert tacit knowledge into explicit knowledge and contingencies need consideration before this is done (Ferdows, 2006). Rather than attempting to convert tacit knowledge into explicit knowledge, it is sometimes sufficient and faster to enable the use of tacit knowledge in its tacit form or gradually externalize only a part of it using language. Incremental ideas rather than radically new ones result when people are not ready or unable to formulate their ideas (Dahl & Moreau, 2002; Goldenberg et al., 1999; Koberg et al., 2003; Schulze & Hoegl, 2006, 2008).

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METHODOLOGY

This study aims to develop insights and understanding in a particular area. A case study is a relevant research strategy when exploring complex real-life phenomena (Yin, 2009) and studying "how things work" (Stake, 2010). The knowledge creation literature has neglected the micro-processes inside firms (Foss et al., 2010) and these are best studied using the case study approach (Merriam, 1998). In line with the abductive approach the conceptual background and the cases coevolved in the process of “walking back and forth” between the two (Alvesson & Sköldberg, 1994; Alvesson & Sköldberg, 2000; Dubois & Gadde, 2002, 2014).

The case selection criteria favored leading industrial companies in relatively fast-paced or emerging technological fields, willing to provide good access. The focus on choosing leading well-performing companies was made to increase the likelihood of best practice identification. The emphasis on fast-paced somewhat emerging technological fields was made to complement previous research empirically biased towards cases of big existing industrial companies only. Good access was necessary for this research and therefore included in the case selection criteria.

The data collection entailed semi-structured manager interviews alongside observation and informal talks with lower-level employees. The empirical data were analyzed primarily using the patternmatching logic (Yin, 2009). The interviews were digitally recorded and transcribed, and findings received informant feedback.

CASE DESCRIPTIONS

Intellifusion

Intellifusion, based in Shenzhen, China and founded in 2015, provides visual intelligence solutions, that is, solutions that analyze video material through the use of deep learning algorithms. The number of employees (170) is growing fast, and 75% of the employees work with R&D at the time of writing of this paper. Unlike similar companies, the company already generates a good cash flow from different applications, including surveillance systems with face recognition for crime reduction.

The technology developed by the company is relevant to many applications. One example is that the company won a competition to help the border police identify sick people at the border. With globalization, it has become increasingly important to identify people that are spreading diseases such as SARS. For this purpose, efforts are made to identify any sick people crossing the borders for instance between Hong Kong and China. People with fever are detected using infrared cameras that trigger temperature alarms. However, most often, this solution generates false alarms because objects like tea bottles and cell phones are usually warmer than human foreheads, and the system is unable to distinguish between objects and humans. Therefore, the existing solution would be particularly suitable for use at the airport, where people are not allowed to bring tea, and cell phones are just turned on after landing and not yet warm. However, in the context of land borders, the system would generate a lot of false alarms, wasting much time and irritating everyone involved. Therefore, the company provides a solution which only generates an alarm when the high-temperature object from the video is confirmed (simultaneously) to be above a human forehead or neck. Spending time with customers to understand their problems helps to find new application areas of the technology. A challenge for the company is that customers are often unable to specify what they want, as illustrated with the following quote:

> "*this is a very high skill, to read the customers and deliver something that is good enough for your business to continue. That is a piece of art*" (Interview).

So far, the solutions delivered by the company have included cameras as well as algorithms because the customer's existing cameras are not currently useful. It is expensive for the customer to buy new cameras, and the benefits of using this technology often increase with the number of cameras which are part of the system. It is also inefficient to transfer all video material from every camera to a back office for analysis. It is better and more convenient to use cameras with embedded algorithms on a chip which can pre-analyze the video material and only send back key information. However, a problem with existing chips is that they cannot be updated. Over time, as one learns, it is vital to update different algorithms. It would be beneficial to have a chip that is flexible enough to allow for new updates to the algorithm. Therefore, the company is developing a chip that can be integrated into existing cameras and allow continuous updates while reducing energy consumption to 2-5% of that of existing solutions. The goal is to become the Intel of the visual intelligence industry by providing the advanced chips that enable wider application of this technology.

However, the chip development represents a new approach for the company. It is faster to fine-tune algorithms in the field than to test everything beforehand. However, chip development (as

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hardware) is different from software development in that iterations are much more costly and take longer. It necessitates the company to consider every possibility and design everything right before starting the manufacture of a new chip because it will be worthwhile to put much effort into increasing the likelihood the developed chip works already the first time.
Interviews revealed that too many resources go into for instance assessment interviews for new employees approaching formal employment. A manager described the ongoing mutual adjustment in the company on this matter in the following manner:

> "*Sometimes I will ask people in such a meeting: "what do you contribute to this interview*"?" (Interview).

Also, often there is too much talk at meetings; it would be more efficient instead to give someone the task to research on an issue and come up with solutions, as opposed to solving everything by verbal discussion.

Medical aids

The company is a leader in medical aids. It has recently started using additive manufacturing (AM) for prototyping and tooling. The motivation to adopt additive manufacturing for prototyping and tooling is a reduction in concept to launch time, faster iteration and experimentation. The prototyping and tooling department in the company now regularly develops prototypes of new products and some fixtures using 3D printing. The prototyping manager notes that:

> "*Additive manufacturing allows having a better feel of the tool before ordering aluminum parts, which can be made using that tool. The delivery times are 3-4 weeks to order the tools. However, with AM, you have seen a 3D version of what you order*" (Interview, 11.11.2016).

Having seen 3D versions of the tools before ordering them reduces the risk of ordering a tool that does not fit the requirements. The more iterations of ordered tools needed, the more time it requires and reductions in the product development lead time from the current level of around two years are welcome in the company. A key enabler for the company to efficiently use AM is allowing people to experiment and try out different things. A manager explains that:

> "*If machines are kept in different places in the premises, and it is known that the company has those machines, it will encourage people to experiment*" (Interview, 11.11.2016).

One project in the company required the development of a holder for a smartphone that is used for testing out a new product with patients. They can take a picture exactly when something happens with the product; this is updated in the cloud, so the company has real-time data on the use of the new product. More than 100 holders were needed. These were produced with AM partly to advertise what could be done with the technologies to create awareness and share knowledge within the company.

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Forensic operations

At the forensic laboratory of the university, DNA samples are tested as part of criminal investigations as well as paternity tests. The laboratory gets some samples from the police, i.e., around 40,000 cases of for example cotton swabs. Most of the samples will go into small plastic containers. Throughout the process, it is essential that the samples be placed accurately during pipetting, and the pipette tips go into the intended containers. During movement of samples, it is vital that each sample is placed correctly. For example, if the attached lid on one plastic container is located on top of the plastic container next to it, the robot, handling the samples will hit it, resulting in contamination. The automation department working with the forensic laboratory realized that placeholders manufactured using AM could address the above problem. The process of having fixtures and placeholders printed with a service provider and having those sent back took almost one week for one revision, and it required explaining to the service provider how to do it which spilled over in multiple iterations to get the placeholders printed as per requirements. Hence, the laboratory brought 3D printers.

Having own 3D printers resulted in a steep learning curve as indicated in the following quote:

> "*We learn with every print. We also get more ideas for things to do. We learn from the mistakes. We break filaments. We get skewed stuff. You get to learn to know the material a lot better and choose the materials accordingly.*" (Interview, 10.11.2016).

Also, a key benefit is that they no longer have to explain the requirements to an external service provider. Instead, when getting an idea, they can just go ahead and print it without explaining the idea to others. This speeds up the development of the processes and improvements.

Industrial conglomerate

The company manufactures various industrial products that it gradually has diversified into over the years. In recent years the company has started using 3D printers for creating prototypes and tools for the production. The expenses are allocated to the respective departments using the 3D printers based on the material costs.

The product development time is usually around two years. 3D printing can help the company to realize its potential. According to a 3D printing manager in the company the biggest potential for improving the development processes of the company is related to changing the current practice that entails extensive documentation and thinking instead of enacting good ideas as illustrated in the following quote:

> "*I think the biggest potential for the overall development process is less discussing, more acting. It is hard to put that into words or into sentences. That is what I see has become one of the major issues in product development today. Not only in our little factory, but in many places. It seems like there is no one ready to take a risk or one that has the experience, or the guts to make decisions and go by them. The trial and error politic has been buried alive more or less. Today it is not trial and error; it is thinking, thinking, thinking, thinking, thinking, thinking, thinking and suggesting and thinking…*
>
> *The processes of documenting everything has been overly accepted. You spent more time documenting things that might not be relevant than in fact doing good work. But again how to put that in a sentence I cannot tell.*" (Interview 15.6.2017).

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ANALYSIS

The 4I framework serves as the conceptual starting point for the analysis. Therefore, Table 1 outlines empirical elements from the cases captured, and not captured, by the 4I framework processes. Each point mentioned in Table 1 starts with the case name to clarify the empirical origin. Rather than including everything, the empirical items serve as illustrative examples, and subsequently, the emphasis will be on some of the elements not captured by the 4I framework, to amend these aspects of the 4I framework. The focus will, in particular, be on the interpreting process.

Insert Table 1 about here

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Empirical elements captured by the 4I framework

The 4I framework captures a lot of relevant empirical elements from the cases. As part of the development of solutions for the police forces, Intellifusion visits the police at the border. In line with the intuiting process, these visits inspire and initiate preverbal recognitions of patterns and opportunities for application of Intellifusion's technology to help the customers.

In line with the normative tenets of the 4I framework, the industrial conglomerate spent much time documenting and thinking through as part of their development projects, which has similarities with the existing contents of the interpreting process in the 4I framework. Interestingly the company experience related shortcomings and they perceive a need for more iterative trial and error approaches to speed things up.

Regarding examples of the integrating process, Intellifusion experiences as part of their rapid growth a need for more rules that can ensure efficiency in the organization. Examples thereof are rules for how to conduct the review held for each newly recruited employee after three months. The review outcome determines whether the employee can stay on with the company. Currently, too many people in the company wish to attend these meetings which make them challenging to schedule and the aggregated amount of time spent by everyone involved seems excessive. Limiting the number of people taking part in such meetings and collecting further information from others beforehand seems a viable option regarding the procedures and systems of the company, and the related needed mutual adjustments are going on.

In the industrial conglomerate, materials costs of 3D printing are paid by the departments using the 3D printer. This rule seemingly works well since it ensures that financing the facility is part of the running business of the company instead of relying on repeated individual case allocations and decisions by upper management.

Empirical elements not captured by the 4I framework

When studying the empirical elements not captured by the 4I framework concerning the interpreting process, some common denominators seem to be in place. Intellifusion mentions the benefits of field testing while the forensic operations, as well as the medical aids company, experience benefits from 3D printing. The forensic operations experienced benefits from internal 3D printing and prototyping in that it is not required to explain to third parties how to make the models. Without explaining anybody, they can just go ahead and do them on their own. Also, the industrial conglomerate reports benefits of acting and prototyping rather than only thinking. Prototypes seem a relevant complementary outcome from the interpreting process so far only conceptualized as a process that using linguistic elements forwards preverbal notions to a stage where they can be shared with a broader audience.

The industrial conglomerate case pointed to drawbacks of excessive documenting. The Intellifusion case pointed to the advantages of not documenting every aspect of new developments beforehand, but instead to put in the field, test, and iteratively refine new products.

When speed is of the essence relying on excessive documentation efforts may often be too slow and often also unnecessarily costly in the sense that the return on investment in documentation investments depends on the extent to which the documented knowledge is going to be used again in the future. In environments where knowledge fastly becomes obsolete, the documentation will likely be less worthwhile. However, within the same company, Intellifusion software development caters to rapid iterative field testing without much upfront documentation, whereas the hardware chip development necessitates more upfront documentation given that each iteration of a chip takes a long time and is much more costly. Hence, the relevance and requirements for documentation, in this case, differs much across two areas of the company, and the decision does not lend itself to industry-wide generalizations.

DISCUSSION

Many big industrial companies possess old and continuously refined knowledge that constitute their core capabilities. This knowledge is more likely available in a documented form than the knowledge and capabilities of technological companies in fast-changing emerging fields. The excessive focus on "the old" industries bias the knowledge management frameworks and underlying assumptions (Boisot & Child, 1999; Crossan & Berdrow, 2003; Crossan et al., 1999; Hedlund, 1994; Nonaka & Konno, 1998), and normative tenets to fit those companies in particular. Characteristics of emerging technological fields are poorly reflected in the existing knowledge management frameworks because previous knowledge creation research has primarily studied such existing big industrial enterprises. These frameworks assume that most knowledge can be codified and shared verbally. The implicit codification recommendation in existing theory may fit poorly in fast-changing technological fields. Here, ideas need to be developed fast, and there is often no time for the codification of every aspect of these ideas; thus, knowledge becomes outdated so rapidly that it makes less sense to attempt codification of everything. However, a closer look than the aggregate industrial level needs to be applied.

Previous studies have confirmed the importance of tacit knowledge for innovation performance in the service sector (Jisr & Maamari, 2017) and likely tacit knowledge is even more critical in technical oriented high tech industries. The findings of this paper speak to the benefits of utilizing prototypes in relation to technical knowledge creation as it allows working with knowledge in a tacit form, which is particularly relevant when working within nonlinguistic knowledge domains related to technical knowledge creation.

While doing a case study in a software company – an agile knowledge-intensive environment, Israilidis and Jackson (2012) suggested not using asynchronous tools in knowledge creation. While investigating knowledge creation in a consulting firm and an oil exploration company Aarrestad et al. (2015) also include the use of artifacts like prototypes in their framework. Their framework pinpoints conducive social processes and drivers for knowledge creation, but do not provide a knowledge process model with feedback loops, etc. Hence it seems more relevant to update existing frameworks with recent insights rather than suggesting entirely new frameworks. In line with this thinking, and in order avoid fragmentation of the field, the findings of the present paper are used to

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amend shortcomings of an existing framework (the 4I framework) rather than suggesting an entirely new framework. The suggestion in this paper to include prototypes in interpreting processes in the 4I framework can be seen as an example of defining and refining the role of artifacts (i.e., prototypes) in relation to specified knowledge processes, as suggested by (Mariano & Awazu, 2017; Mariano et al., 2016).

Proposed inclusion of prototypes in the 4I framework

Using prototypes and similar models have many benefits (Bogers & Horst, 2014; Braitenberg, 1984; Clark & Wheelwright, 1995; Iansiti, 1998; Leonard Barton, 1995; Schrage, 2013). A prototype is a physical or non-physical approximation of a product along one or more dimensions of interest. A broad notion of prototyping including field tests as illustrated in Intellifusion is applied in this paper. Prototypes help to frame design problems and explore various possibilities related to the design (Elverum & Welo, 2015). "*Prototypes unlock cognitive association mechanisms related to visualisation, prior experience, and interpersonal communication in ways that favor iterative learning between peers in the product development community… Prototyping has been portrayed as an excellent activity to share inner thoughts*" (Berglund & Leifer, 2013: 2). Prototypes illustrate things difficult to explain, and they embody tacit knowledge. Prototypes pinpoint shortcomings of ideas faster than deliberation can do and provide form and focus on which to build further conscious deliberation. Prototyping allows sharing of ideas without necessarily including words, but it still allows other people to grasp critical elements.

Table 2 illustrates the amendments to the 4I framework where the interpreting process also includes prototypes as an additional outcome option.

Insert Table 2 about here

Frameworks on organizational learning and knowledge management should nurture novel ideas as well as incremental ones. The suggested inclusion of prototypes as an additional outcome option from interpreting processes in the 4I framework enables the use of tacit knowledge. Facilitating use of tacit knowledge nurtures novel ideas as opposed to incremental ideas (Schulze & Hoegl, 2008).

One could imagine prototypes used in other parts of the 4I framework, but it seems particularly relevant as an outcome option from the interpreting process. This placement of prototypes enables the framework to reflect better technical knowledge creation and its nonlinguistic characteristics, that necessitates an emphasis on working with knowledge in a largely tacit form, as opposed to only expressed in words and language.

When building a prototype, the maker may not be aware of everything, but the result will often reveal learning the maker was unaware of, and unique aspects of the idea will likely be more accessible to others when a prototype is present instead of only words.

Product development as strategic renewal

The 4I framework has previously been used in the context of product development (Akgün et al., 2007; Bstieler & Hemmert, 2010; Holmqvist, 2004; Reid & De Brentani, 2004; Schulze et al., 2013), however, the adaptation of the 4I framework proposed in this paper further enables such application of the 4I framework. Crossan et al. (1999) outline product development (as focal to the

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SECI model) and strategic renewal (as focal to the 4I framework) as separate things, however, this is a misconception given that product development needs to be an integrated part of strategic renewal in many firms. If a framework for strategic renewal is not embracing product development, it will have little relevance in many firms that continuously need to innovate. The proposed inclusion of prototypes as an outcome of interpreting processes makes more relevant the 4I framework as an integrated framework of strategic renewal including product development. Product development and the resulting strategic renewal depend on technical knowledge which is often most efficiently refined using prototypes because it caters well to the ineffable and nonlinguistic characteristics of technical knowledge creation.

MANAGERIAL IMPLICATIONS,

Practitioners need a more fine-grained look at knowledge creation and organizational learning than that available in theory, and managers should critically reflect the requirements for their particular situations. Since language use focuses energy in other areas of the brain than those required for technical advances, such as math, spatial thinking, and so on, it is relevant to use prototypes as part of technical knowledge creation in firms. Therefore prototypes are proposed as an additional outcome option for interpreting processes in the 4I framework. Although this outcome will be relevant under multiple circumstances, it will be particularly relevant for organizational learning and knowledge creation in contexts that require strong technical knowledge such as product development. Practitioners applying the 4I framework will likely be able to advance better and more novel ideas and potentially innovate in more radical ways when also considering prototypes as an outcome option from interpreting processes in the 4I framework, since it enables better use of - and development of tacit knowledge. Hence, we recommend adapting the 4I framework by including prototypes within interpreting processes.

CONCLUSIONS

While introducing new conceptual links between operations management, product development, cognitive neuroscience, knowledge management and organizational learning, this paper has exposed gaps in existing frameworks on knowledge management and organizational learning and questioned the assumption that knowledge creation hinges on language development and verbal group interaction as it pertains to technical knowledge creation. The paper has taken steps to reconnect the field of knowledge creation with firm micro-processes that it has neglected (Foss et al., 2010). Technical development in fast evolving emerging fields often necessitates the use of tacit knowledge in its tacit form. Tools relevant to this end such as prototypes, therefore, needs to be available and reflected in these processes and frameworks. As opposed to using language only to enable productive interaction, prototypes are often relevant and are therefore inserted in the 4I framework as an additional outcome option from interpreting processes, as outlined in Table 2.

In case the reader disliked the metaphors used in this paper, perhaps the message still came across that relying on metaphors alone when conveying silent ideas is not sufficient, particularly not for technical knowledge domains.

LIMITATIONS AND FURTHER RESEARCH

Wipawayangkool and Teng (2016; 205) “recommend that researchers determine further whether the effect of knowledge internalization on knowledge sharing depends on sharing mechanisms."

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Following this insight and given the findings of the present paper, it seems relevant that such further studies take prototypes into account as a relevant sharing mechanism.

Research within the field of cognitive neuroscience has discovered the existence of mirror neuron systems (Fogassi et al., 2005; Gallese et al., 1996; Gazzola et al., 2007; Keysers et al., 2003; Kilner et al., 2009; Kohler et al., 2002; Rizzolatti & Craighero, 2004). According to Gazzola et al. (2007: 1674) "In humans and monkeys the mirror neuron system transforms seen actions into our inner representation of these actions." Put simply, the observer's brain activities suggest the observer is also undertaking similar activities as the observed. This system is interesting to consider concerning the use of prototypes since a physical or nonphysical model is closer to action than words are. So possibly prototypes bring about other reactions in the minds of the people prototyping and others involved than just expressing the idea only through words. However, further research is required to test this.

Within product development, there is a vast body of knowledge on prototyping and rapid prototyping and more recently on the use of AM for prototyping. However, there is limited discussion of the impact of AM on organizational learning, knowledge management, and finally on product development outcomes. There will be possibilities for empirical research to develop models and test the above relationships.

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Table 1:

Some empirical elements from the cases captured, and not captured, by the 4I framework processes

4I Framework processes	**Empirical elements captured by the 4I framework**	**Empirical elements not captured by the 4I framework**
Intuiting	Intellifusion: visiting customers like the border police provides new experience and insights for solutions the customers need.	
Interpreting	Intellifusion: much talk at meetings. Industrial conglomerate: extensive thinking through, and documentation concerning product development.	Intellifusion: field tests generate new learnings. Giving people tasks and time to experiment to make solutions is often a faster way to the solution than discussions in a meeting. Medical aids: Prototyping reduces the risk of specifying and ordering the wrong tool. Forensic operations: internal 3D printing ability decreases the need to explain ideas and requirements to others and increases and speeds up the creative output. Industrial conglomerate: too much thinking, too little doing. More trial and error is needed.
Integrating	Intellifusion: Rapid growth necessitates the creation of robust processes and rules that can ensure efficiency in the organization. E.g., rules for how many/few people need to attend reviews of new employees; Processes/rules for how to conduct meetings. The ongoing mutual adjustment entails questioning of the current procedures (or lack thereof).	
Institutionalizing	Industrial conglomerate: materials costs of 3D printing are paid by the departments using the 3D printer.	

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Table 2:

Adaptation of Learning/Renewal in Organizations: Four Processes through Three Levels
(Source: adaptation from Crossan et al. (1999))

Level	Process	Inputs/Outcomes
Individual	Intuiting	Experiences Images Metaphors
	Interpreting	Language Cognitive map Conversation/dialogue/prototypes
Group	Integrating	Shared understandings Mutual adjustment Interactive systems
Organization	Institutionalizing	Routines Diagnostic systems Rules and procedures

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Personal knowledge creation is suitable for those managers and knowledge workers who wish to dig deep for answers, not just rely on external props, but rather believe in placing value on intangibles, not just on tangibles.Â The technical dimension may encompass learning technical knowledge from non-verbal observation. An example given revolves around the master craftsman who has a high level of expertise but struggles to articulate this. Therefore, an apprentice chef may have to learn his craft by observational procedures. Organizational knowledge creation as part of the knowledge management process. Discussion of unstructured work environments and the role of IT.Â Knowledge Creation. The ability to create new knowledge is often at the heart of the organization's competitive advantage. Sometimes this issue is not treated as part of knowledge management since it borders and overlaps with innovation management (Wellman 2009). Medical Controls. Patient Management. Technical support. Clinical support department.Â Knowledge Creation. One of the most serious complications in orthopedics and trauma surgery is infection in the field of inset implants. The rehabilitation of the focus of infection and the reconstruction of function is the daily challenge faced by the staff of Septic / Reconstructive Department. the interdisciplinary coordination of the various necessary diagnoses and therapeutic interventions is essential for treatment to be successful.