Using Prototypes to Leverage Knowledge in Product Development: Examples from the Automotive Industry

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***Abstract*—This article is rooted in the automotive industry as starting point, and discusses the topic of leveraging tacit knowledge through prototypes. The aim of this study is to make the case of using reflective and affirmative prototypes for knowledge creating and transferal in the product development process. After providing an overview on learning and knowledge, the Socialization, Externalization, Combination and Internalization (SECI) model is discussed in detail, with a clear distinction between tacit and explicit knowledge. Based on this model, we propose a framework of using said reflective and affirmative prototypes in an external vs. internal learning/knowledge capturing and transferal setting. Rounded by two case examples from the automotive industry we end by identifying the emergent research questions and areas. Using prototypes and prototyping may hold a monumental potential to better capture and transfer knowledge in product development, thus leveraging existing integration events in engineering as a basis for knowledge transformation.**

Keywords—knowledge transfer; internal reflective prototypes; prototyping; tacit knowledge; integration events; product development; automotive engineering

I. Introduction and Background

In this paper, we argue for increased usage of reflective and affirmative prototypes for knowledge creating and transferal in the product development (PD) process. This paper attempts to make two literature contributions. The first is to provide a mapping of relevant literature on knowledge in PD. This section includes an overview of select topics, including organizational and individual knowledge, in addition to some current practices on knowledge transfer. A brief introduction to learning mechanisms is given, with integration events and knowledge owners as key aspects for lean product development in systems engineering. Furthermore, a synthesis on the Socialization, Externalization, Combination and Internalization (SECI) model [1] is presented, with its relation to tacit and explicit knowledge.

The second contribution is to provide a short overview of prototypes and prototyping, and their relation to knowledge transformation processes in PD. This paper proposes a model of four prototyping categories, with each aspect of the model briefly explained with examples. Examples on contextual internal, reflective prototypes from real-world settings are provided, and their relation to knowledge acquisition and transfer is emphasized. Lastly, the possibilities within said research space are presented, with a coarse mapping of interesting topics that need further investigation.

The automotive industry is subject to an immense pressure to develop new products ever faster due to steadily increasing competitive pressure. Being an industry in constant evolution, with increasing focus on both reducing lead times and emphasis on quality, a lot of research is targeting aspects of knowledge and the mechanisms of increased learning in new PD. For example, knowledge-based development has been established as a viable method [2] for extracting the base points of Toyota's PD process [3]. In this paper, we will focus onto knowledge, its creation and its transfer in a PD organization.

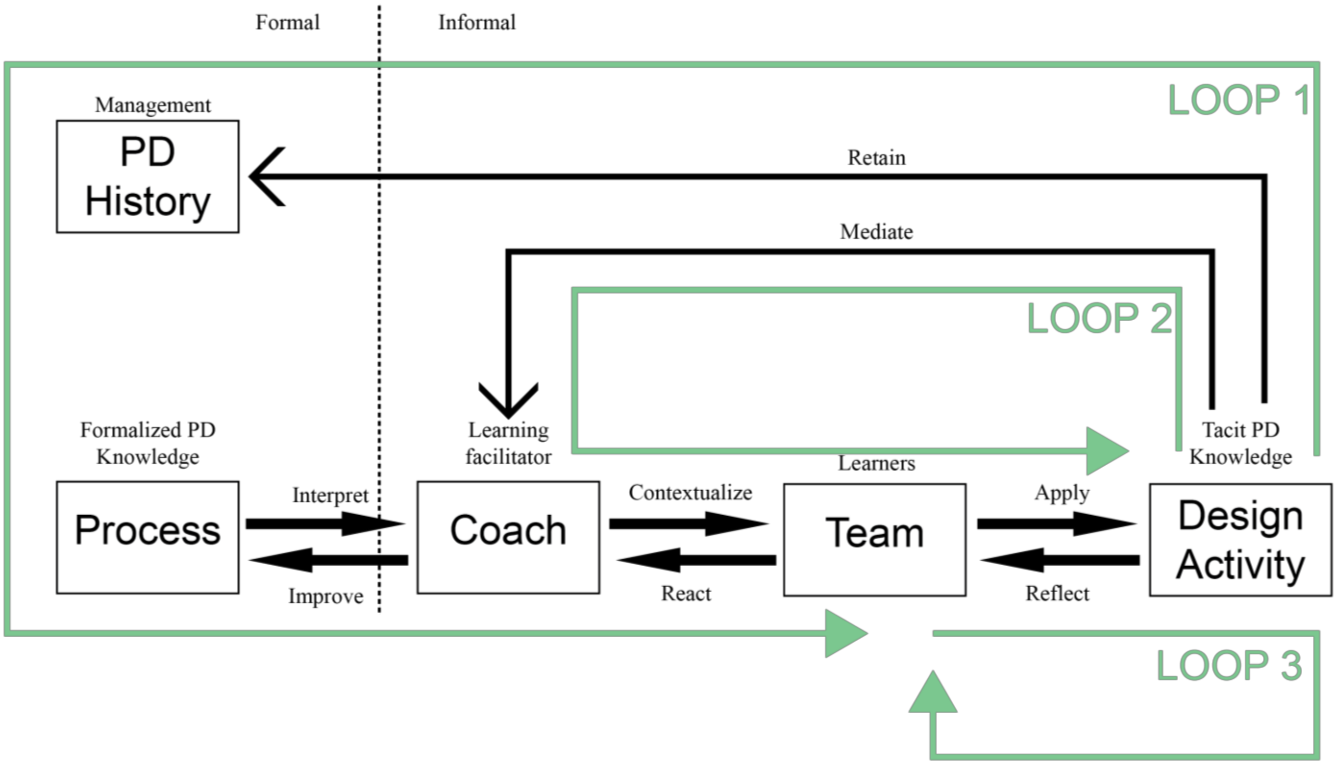

Fig. 1 - Learning Mechanisms in Product Development, adopted from [11].

In the automotive industry, making mistakes may cost you dearly. With (relatively) low cycle times, the costs of making mistakes in the later stages of PD are immense, having major implications further down the value stream. Also, automakers cannot develop knowledge from scratch every time they start new projects. Thus they aim to keep a large base of standardization of parts and processes within a product-technology platform to ease the burden on the PD team(s). Hence, managing and controlling the knowledge within the company becomes an important issue.

For our research, we have access to several industrial liaisons, including a multinational automotive tier 1/2 supplier company. Many of our insights and proposed discussion points are gathered from case-examples, semi-structured interviews and conversations with said liaisons [4].

II. Theory: Knowledge in Product Development

There are numerous definitions of knowledge provided in the literature [5]. Wisdom and knowledge are differentiated by [6], defining wisdom as evaluated understanding ("know-why") and knowledge as application of data and information ("know-how"). Reference [7] argues that knowledge can be divided into individual and organizational knowledge. Organizational knowledge is defined as the sum of what is learned, perceived, experienced or discovered (by individuals) during a project (in the organization). Individual knowledge has three main categories; experience-based, information-based and personal knowledge [8]. Interactions of individuals are the main ingredient of organizational knowledge, and that this knowledge exists between (and not within) individuals [9].

A. *Defining Integration Events and Knowledge Owners*

Most companies use a stage gate process in PD. However, stage gate is an investment-based governance process. Hence there is a call for more event-driven approaches for improved organizational learning as this aspect becomes increasingly important in competitive consumer businesses. One of the more recent practices is the use of so-called 'integration events' [10]. These events are reported to ensure better insights and information while preserving other know-hows, providing a basis for transforming project knowledge into organizational learning. Integration events are 'learning cycle gates' where informal knowledge is formalized (made explicit), and formal knowledge is interpreted. When these events are systematically applied, they become learning loops [11]. Hence, the key to organizational learning is in the mutual exchange of knowledge between the individuals and the organization.

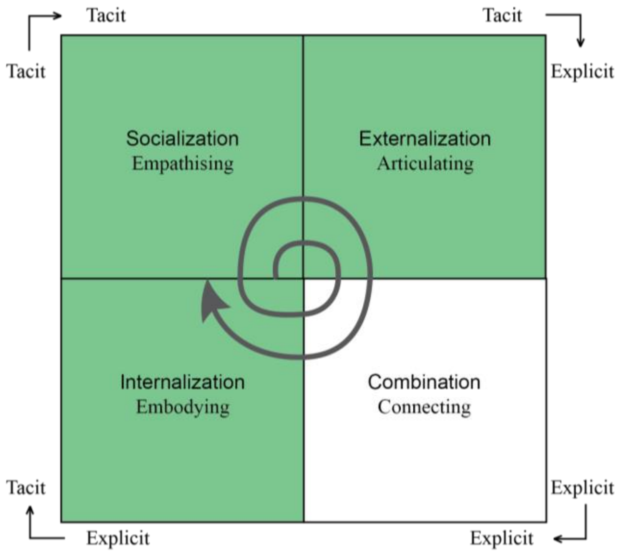

Fig. 2 The SECI model, with highlighted areas of interest [1].

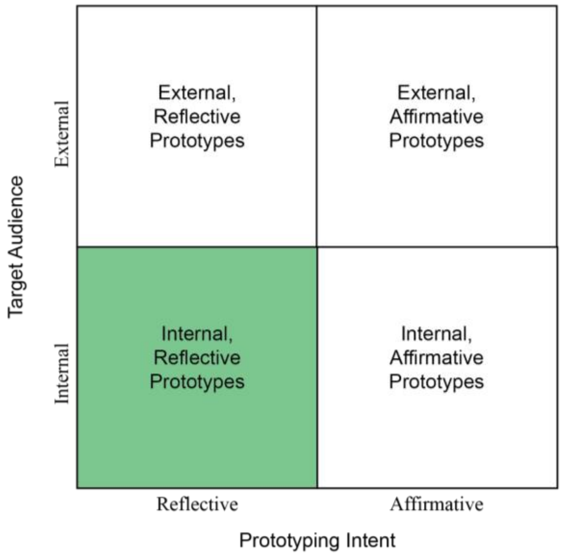

Fig. 3 A proposed model of four prototyping categories.

As a catalyst for this exchange of knowledge, many companies deploy key experts or learning facilitators. These are engineers and so-called 'knowledge owners' within each project, providing organizational grounding, previous insights and know-how for the PD team. For example, Toyota is well-known for using functional managers to employ existing knowledge within projects, and chief engineers to challenge the existing standard by being the customer representative [3]. As a result of being part of the development team, these knowledge owners gain insights and experience – thus contributing to organizational learning as long as they are part of the ongoing projects. In (Fig. 1), adapted from [11] and [12], three different types of learning loops within the PD knowledge acquisition processes are illustrated.

B. *Tacit and Explicit Knowledge in PD*

Closely linked to organizational knowledge, is the differentiation between tacit and explicit knowledge. Explicit (i.e. formal) knowledge, learning loop one, includes information-based, fact-based [13] learnings that are summarized in knowledge artifacts [14]. An example of knowledge artifacts within the automotive industry is the use of A3s, described by [3] and [15]. Tacit (i.e. informal) knowledge, learning loops two and three, is the know-how, the craft, the skill and learnings of the product engineering individuals [16]. Tacit knowledge is hard to formalize and to make explicit, as this kind of knowledge is stored within interactions, experiences, instances and discoveries. We argue that one key dimension of tacit knowledge is the interactions with (and use of) objects and experiences in the product engineering processes, often referred to as prototypes in one form or another.

C. *The SECI-model and Transfer of Knowledge in PD*

In [1], the prevalent model for dynamic knowledge creation has been proposed. Here, the SECI process (Fig. 2) is presented, explaining the enhancement of knowledge creation through conversion of tacit and explicit knowledge. The SECI process spirals through four stages, including socialization, externalization, combination and internalization. The model further proposes certain knowledge assets as facilitators of knowledge creation. Knowledge assets are categorized as experiential, conceptual, systemic and routine. This model has gained major traction, and a study by [17] concludes conceptual knowledge assets (i.e. early stage PD insights) to have the most effect on knowledge creation.

The socialization (tacit-to-tacit), internalization (explicit-to-tacit) and externalization (tacit-to-explicit) stages of the SECI process describe the setting of tacit knowledge creation and transfer in development teams and organizations. Socialization in the context of transferring tacit knowledge includes creating a work environment which encourages understanding of skills and expertise through practice and demonstrations, while internalization includes conducting experiments, sharing results, and facilitating prototyping as a means of knowledge acquisition [1]. The study conducted in [17] concludes conceptual knowledge assets to be the most efficient tool in facilitating internalization and externalization. Conceptual knowledge assets are defined as "knowledge articulated through images, symbols and language" [1] – and although not explicitly identified in the definition – it can be argued that prototyping is encompassed by the term conceptual knowledge assets.

D. *A Proposed Model of Prototyping Categories*

In general, prototypes are defined as "An approximation of the product along one or more dimensions of interest" [18], thus including both physical and non-physical models, e.g. sketches, mathematical models simulations, test components, and fully functional preproduction versions of the concept [19]. Further, prototyping is defined as the process of developing such an approximation of the product [18].

Taking a broad perspective, we propose that prototypes and prototyping may be divided in a two-by-two metric (Fig. 3). On the first axis, the intent (of the prototype) can be split into two sub-categories; "reflective" and "affirmative". On the second axis, inspired by [20], the target audience is split into "internal" and "external". By using this two-by-two metric, we map four different prototyping categories. These four are:

Fig. 4 An early wooden prototype of the 'X1 Experimental Vehicle'.

1) External, affirmative prototypes: These prototypes display an approximation of a nearly finished pre-production model, and are typically the prototypes presented for validation or showcasing purposes, or namely alpha/beta prototypes [21]. Both appearance and relative functionality is high, and these prototypes are often used for marketing or external validation (e.g. New Car Assessment Programme (NCAP) tests) etc.

2) Internal, affirmative prototypes: These prototypes are focused in terms of function, and can be subject to function, reliability and manufacturability testing. Examples of these prototypes are the combination of subsystems, fatigue testing of a conceptual prototype or a project milestone to validate the progression of the team. These prototypes are rarely shown to external audiences.

3) External, reflective prototypes: These prototypes are often concepts displayed to external sources for feedback in early stage development. The response and reaction gathered from observing a user interacting with a prototype expressing the basic functionality of a concept can provide useful insights and be a time-saver.

4) Internal, reflective prototypes: These are the prototypes the PD team uses to learn internally and conceptualize their ideas. Internal reflective prototypes are learning tools. Their purpose is conceptualizing ideas, and might focus on certain functionalities or suggest appearance of a product concept [22]. Internal, reflective prototypes are used for learning, enabling experiences and insights through interactions. Generally, these prototypes are low fidelity [20], and often thrown out after the projects are finished.

The insights, experiences, interactions and learnings, created by means of the internal, reflective prototypes lay the foundation for the tacit knowledge accumulated within the PD team. How this knowledge is captured, stored and utilized, however, is not well described in the literature.

Fig. 5 Finished 'X1 Experimental Vehicle' at Stanford University.

In [23], Simon identifies a gap between professional knowledge and real world practice. The foundation of a "science of design" is drawn up, applying methods of optimization from statistical decision theory. He thus lays the basis for a scientific approach of treating knowledge.

This is criticized in [24] by Schön for its presumption of technical rationality. He argues instead that the real challenge lies not in the treatment of well-formed/modeled requirements, but in the extraction of these, often unknown, requirements from real-world situations. The practical unknown unknowns are the core challenge. In [25], he thus proposes reflective iteration rounds as the learning tool with the biggest potential. Schön also points out that creation/translation of explicit knowledge, is a major difficulty. Together, Simon and Schön thus represent the knowledge creation spiral in the SECI model.

III. Examples: Knowledge Transfered from Prototypes

In the following sections, we attempt to exemplify the internal, reflective prototypes by providing findings from two case studies. Both cases come from an automotive concept setting at Stanford University, with the prior being the development of a multi-modular vehicular research platform, and the latter being a dynamic hunter-gatherer approach [26] to the future autonomous driving experience.

A. *Case I: Real Industry Case with Reference*

Collaborative efforts between the Dynamic Design Laboratory [27] and Product Realization Laboratory [28] at Stanford University to create a steer-by-wire prototype. This project, later dubbed as the 'P1', was an electric vehicle with independent rear-wheel drive, and also independent left and right steering mechanisms. This car was first done as a one-off to test steering mechanism redundancy, independent torque control, maximize handling performance and minimize tire wear, but the project was later extended in another project, dubbed the 'X1'.

As the P1 was first built as a research vehicle, the team had several insights as to how to improve this setup for further

Fig. 6 Early prototype on increasing autonomous car passenger comfort.

testing when building the X1. Hence, the X1 was built to be modular, rather than fixed, with different testing modules and systems fitting together on a single test platform. During the early stages of the X1 project (Fig. 5), the team discovered that simple design decisions on single aspects of the car altered a vast amount of other aspects, making the planning of everything (i.e. in SECI-terms: both externalization and internalization) before building a prototype a very difficult task. Indeed, a CAD process failed utterly. As a result, the team planned the car structure (with modules, their relations and critical functions) in physical mock-up prototypes, using wood (Fig. 5) for convenience and learning speed. This way, they could iterate rapid designs, reflect, and gain new insights on the systems and their relations to each other in a short amount of time.

B. *Case II: ME310 Product Innovation Renault Prototype*

During the mechanical engineering course of ME310 [11] at Stanford University, a team working with Renault had the challenge of redefining the future autonomous driving experience, especially regarding passenger trust towards the vehicle. In (Fig. 6), we see an explorative prototype made by the team. The prototype is a plate, mounted in the passenger foot well to represent pre-queuing braking motion by small actuation in fully autonomous vehicles. The prototype was used as an initial road test within the development team, and lead to a new insight; that is, the interaction with the prototype facilitated increased passenger comfort. The insight is not captured within the prototype (the object), but rather within the interaction with the object. It is worth noting that the development team had a hard time understanding the cause of increased level of passenger comfort.

IV. Research Potential of using Prototypes in Knowledge capturing and transferring

There is certainly a need for further exploring the transfer of insight, learning and knowledge, especially through the use of physical tests and prototypes. The product developers and engineers of tomorrow will need a broad understanding of systems, enabling improved problem-defining (rather than problem-solving) skills, as the challenge in PD as a whole is to both define and solve problems. An experiment conducted in [29] focuses on the role of prototyping in the detection of design anomalies in a course of engineering students. When presented with initial examples containing certain bad features, some groups were made aware of the bad features, while others were not. The study concludes that certain bad features were excluded in the students own initial prototypes (i.e. before testing), while other bad features predominantly were not excluded until after the initial prototypes were tested. As stated in [29], there is a call for more research on understanding the students' preliminary selection of concepts, their understanding of systems, and the effect on both as a result of physical testing.

It is with respect to these insights that we define future research areas – and possibly fields. The research space of tacit knowledge transfer within PD is one promising focus. We would like to especially encourage exploring how prototypes (and prototyping) can be used as a catalyst for the tacit knowledge transfer. If the insights, experiences, learnings and interactions with prototypes accumulate tacit knowledge in the PD processes, how can one facilitate the PD process in such a way that most of the tacit knowledge is transferred – both internally (socialization), but also within the organization (externalization and internalization)? The ambiguous nature of tacit knowledge poses some challenges, especially regarding the capture of this knowledge, as this externalization is very difficult to automate.

After raising the question on how to accumulate (more) tacit knowledge, one can also argue that we need more understanding on how to capture the knowledge. How can the organization internalize the tacit knowledge, making it usable for others, and how can it be externalized back in the PD process when needed? We see a need to explore the importance of the human aspect of this tacit knowledge. How do human interactions influence the accumulation and transfer of tacit knowledge, and can we alter this for the benefit of the PD process? Can tacit knowledge be transferred by interactions with (other's) prototypes, or can you transfer the same insights through pictures? Are there instances, events or arenas that leverage the transfer of tacit knowledge, and how can we better design the PD processes for this purpose? Can we use objects (prototypes) as tacit knowledge artifacts, and can we use these to alter the learning or the PD team? If we find ways of accumulating, capturing and transferring tacit knowledge, how do we employ these methods and practices with minimum effort?

Ultimately, we are questioning whether there are there methods that can work for a) better internalization, and b) better externalization of tacit knowledge? How do we capture experiences, interactions and insights, and how do we store these? Can we use artifacts like pictures, video and text for capturing this knowledge? Are there prototypes that are better for capturing said knowledge, and if so, what are their properties? Are there any systematic tools that can be used for capturing and leveraging tacit knowledge? These are all questions that need attention in coming research.

V. CONCLUSION

The purpose of this article has been to propose a new research space, including prototypes and their use and impact on knowledge acquisition and transfer within PD organizations. This paper aims at taking a comprehensive view on the different kinds of knowledge provided in the literature, and bringing this into the context of engineering design. Individual knowledge and organizational knowledge have been differentiated, and some current knowledge capturing practices in the automotive industry have been briefly discussed.

A model on prototyping categories is proposed, mapped in a two-by-two metric in (Fig. 3). These categories are briefly presented, with the four categories being *external, affirmative* prototypes, *internal, affirmative* prototypes, *external, reflective* prototypes and *internal, reflective* prototypes. Two small case studies have been presented, with emphasis on prototypes and their effects on developing knowledge.

Lastly, this paper has attempted to map future opportunities within said research space. The need for a better understanding of how to deal with tacit knowledge – both within the PD team and the knowledge value stream of system engineering organizations – is evident. The use of prototypes in relation to tacit knowledge transfer is of particular interest. We expect their deployment to lead to more event-driven and thus leaner PD processes. This is a call for more research towards the use of prototypes and prototyping, especially covering the socialization aspects of knowledge transfer in engineering design.

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