THE IMPORTANCE OF PROTOTYPING FOR EDUCATION IN PRODUCT INNOVATION ENGINEERING

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Newsweek Magazine recently published a list of the 'world's best design programs'. The eye catching notion was the predominance towards active learning, and in particular the extensive use of prototyping in top design schools. This made us try to better understand why and in what way prototyping is important. In our previous research, we have been able to identify a number of important key factors enhancing innovation capability in design engineering programs. Among these key factors we have found prototyping as a means of increasing creativity, innovation and synthesis skills in product innovation engineering programs. This paper investigates prototyping functions as a means to building learning experiences by testing the beliefs of prototyping as a learning tool. The study reveals that an individual that collaborates integrates more of their colleagues' input into their own subsequent concepts. Vice versa colleagues also appreciate a more useful feedback to their creative thinking and prototyping efforts. Strengthening how and why prototyping practices differentially affect results can influence engineering education and engineering design practices. Past prototyping research is redundant to show more than scarce pedagogical comparisons to cognitive levels. Thus, we show traces of evidence between prototyping features and pre-existing knowledge creating frameworks.

Keywords: Prototyping, Engineering Education, Product Innovation.

1. INTRODUCTION

Innovation is characterized by breaking patterns; both by thinking differently and acting in new ways. A natural way to put across new innovative ideas is to communicate, share experiences and in collaboration with others build a thorough understanding of given ideas, concepts and range of feasible manifestations (i.e. prototypes). From a business perspective innovation literature [13, 26, 30, 32] tells that dedication to continuous learning and integration of prototyping activities is equally relevant as strategic implementation tactics to successfully build an organizational momentum. Shared learning and exchange of experiences across intra-organizational levels is seen as a way of assessing critical areas of improvement for the engineering role in industry [2].

Experimentation and prototyping consists of iterations of 'trial and error', directed by needs that sometimes may be difficult to distinguish. Past studies have shown that iterative trial and error is a significant feature in several aspects of product development; design [31, 33], technology integration [15] and manufacturing [2, 20]. Prototyping generates organizational capabilities as flexibility and 'requisite variety' become integral to products and processes, and also operates as an antidote against core rigidities through updates of new knowledge, and new methods for solving problems [19].

Research into Design — Supporting Sustainable Product Development. *Edited by* Amaresh Chakrabarti

ISBN: 978-981-08-7721-7

Innovation has repeatedly proven robust in correlation to adaptive or organic behavior [10]. However, innovation capability is founded in behavior that *produces new knowledge and new ideas* which is not the case with the adaptive behaviors. Based on Argyris and Schon's [3] influencing masterpieces on double loop learning, the challenge and redesign of existing knowledge can reproduce changes to framing consequences and underlying objectives. Confrontations to the status quo are matching the equivalent of innovation capability as it that relies on organic predispositions.

When looking at prototyping the actual design phase is associated with several iterative loops that confront existing prefabricated knowledge expressions. To achieve optimized learning iterations each occurring loop opens up for new opportunities where surprising elements can appear. To transform a learning optimum knowledge transitions between the learner and the facilitator is to embrace a repertoire of learner's actions of re-framing, listening, reflecting, engaging in dialogue, and trying again [27] From an agent-based view, individuals learn as part of a greater facilitating environment, and as part of an organizational learning environment [3]. Our view is that this hub facilitates elements and distinctive actions (e.g. prototyping) that is transferable between the relationship a single individual and a collaborative team. The learning progression in this somewhat chaotic and iterative process underpins an engineer's pragmatic skills [9] and functional knowledge [4] through adaptive and renegotiable conditions. Abernathy's dilemma [1] of establishing both innovation and efficiency simultaneously reappears in engineering education initiatives, where empowered graduates should be able to innovate as part of their natural skills [9]. Striving to incorporate 'both sides of the coin' could be seen as a response to industry's increasing market rivalry, where product attractiveness and time to market are vital factors that put emphasis on streamlining efficiency without losing quality. The trend towards simulation technologies in all design phases, from early concept to final implementation, is a way of streamlining full-size systems testing [20]. Here, individuals need to be utilized where practical knowledge gets incorporated to tangibles early on, avoiding waste and unnecessary slack in production. Today engineers need to embrace the importance of newness, creative manifestations and ultimately how prototypes are fundamental in producing improved products and processes.

Prototypes allow ideas to merge in more comprehendible formats, and influence learning where existing and new technologies, routines and skills are integrated by problem-solving modes [24]. For engineers idea generation and prototyping could very well be merged together as it allows various methods to be worked 'hands-on'. In parallel to idea generation methods, prototyping by definition manifests lateral thinking where divergence and systematic thinking is matched up [13]. In this sense the capacity to design is an innate part of human intelligence, although, through genetics or education, certain individuals undoubtedly have a more developed ability than others [8].

In this paper we set out to put contextual relevance and depth to the arguments of prototyping importance for enhanced product innovation engineering practices by collaborative learning efforts [12]. The paper brings together several experiences that could motivate the fundamental use of prototyping as a collaborative mediator and supplement to already existing practices. Based on enriched insights, greater value propositions and overall curricula design of a prototyping course or activity, an overarching strive is to contribute with lessons learned from several industrial and academic applications.

1.1. Background

To portray the depth and richness in people's opinion concerning the importance of prototyping, our framing and intervening factors involves *innovation* [13, 16, 30], *product development* [31, 33], *engineering education* [9, 28], and *education for product innovation* [17]. Our previous research on education for product innovation identified five key factors in enhancing innovation capability in design engineering programs [12]. Prototyping was one of the five. Observing the predominance of prototyping activities as a fundamental part of the agenda of top design schools made us look closer, to better understand why and in what way prototyping is important in engineering design education. The prior study looked at identification and categorization of best practices within education in product innovation engineering. Results reflected various preconceptions of 'what is good practice' that still were verified against several distinguished professionals. This paper is partly a follow-up study, as it probes the academic and practitioners' use of prototyping, creating a hypothesis that unites a number of arguments for the importance of prototyping. This paper is outlined in four sections; 1) Introduction and theoretical justifications for the study, explaining prototyping essentials and its application in education; 2) Methodology, where we present our proposed hypothesis and explains actions taken, and unit of analysis; 3) Results, presenting the empirical data, and 4) Analysis, involving data synthesis, 'incubation' discussion and conclusions.

1.2. What is prototyping?

The fundamental use of prototyping as a mean for innovation is universally wide spread dispersedly width spread [11, 16, 26] but what constitutes a prototype and what purpose do they serve? The word *prototype* originates from the Greek [prototypos] meaning 'original, primitive' that today, depending on application area and discipline, constitutes a wide variety of meanings (e.g. Pathology 'virus'). Prototypes serve as a typical example, basis, or standard for other things of the same category. Prototype is a word that can mean something different to everyone. From a designer's point of view, the idea behind a prototype is generally defined as a representation of a design idea [24]. Notably, industrial designers use the label *model* when relating to what interaction designers consider a prototype, whereas engineering designers predominantly refer to prototypes. Prototypes externalize thoughts and make people talk, but the dialogues between people and prototypes is more important than creating a dialogue between people alone [8]. Depending on the type of design, prototyping can take on different forms and yet denote similarities in the final manufactured form.

Prototypes can be roughly categorized into two distinct formats: physical and analytical [31]. Physical prototypes are tangible approximations of the intended product, whereas analytical or 'virtual' [20] versions are more commonly used to create a detailed and mathematically correct model of a specific product component. Virtual prototypes are flexible and easily modified which facilitates accuracy when adjustments are made to vital data needed for predictions, and thus assures confidence in the modeling process [25]. In contrast to reliability forecasting, many traditional prototypes still carry an important role of illustrating and communicating functionality.

Prototypes serve several purposes: they function as guiding milestones; show tangible progression or demonstrative specific features; and enable systems integration, ensuring components and subsystems work together as planned [7]. Thus the activity of *prototyping* (working with prototypes) has a central role in all phases of a product development project (e.g. viability testing, sub-system functionality, proof of concept). Computer aided design puts technical skills into vital practice, as 3D simulations and CAD drawings allow iterations and new features to contingently influence concepts. With computer power constantly upgraded, the built-in testing capability of each virtual model has grown potentially. Organizations that engage in analytical use and modeling in their development work opens up for greater reliance and application of physical variants through various materialized feedback.

1.3. Prototyping in Engineering Education

From an educational standpoint becoming an efficient engineer is rooted in the capability to design, and to use design thinking [8], which accounts for the creative expressions and the route to innovative practices [30, 32] Engineering design encompasses both artistic expression and science enabling improvement through learning of design methodologies and technologies [24]. Based on analysis and synthesis an engineer's decision making and design considerations need to incorporate a sense of fitness for purpose and also personal preferences [25]. *Integrated learning experiences* and *active learning* are building blocks (i.e. syllabus standards) in forming efficient engineers [9].

Engineering constitutes a profession that carries a tradition of varied externalization techniques (e.g. sketching, mock-ups, clay, CAD, 3D simulations) in the iterative product development processes, forming innovative solutions. In courses prototyping set-ups often involves teams that are required to perform more or less durable exercises or project assignments.

Modern engineering education builds on experimental learning, which can be seen as dualities between two perceived and translated knowledge categories: active *experimentation* and *reflective observation* [18]. Summarizing Kolb's ideas, active learners relate to testing beliefs through external methods and explanations in some way, whereas reflective observations involve examining and manipulating information introspectively. Active learners are experimentalists, and good in performing work in collaboration with others, whereas reflective learners are theoreticians, and like working by themselves or in micro format groups with just one other individual [11]. Indications say that engineers are more likely categorized as active learners [11], rather than reflective learners which correspond well into the role of an engineer, which is to engineer [9]. In our view, a learning perspective on prototyping departs from a need of reconfiguration and reinforcement of skills that can trigger students' innovative mindsets and their behavioral actions. The importance to succeed with individual skill building efforts is to learn how to facilitate such ones. Thus, forming individual creativity and application capability of pragmatic skills may ease the bridging between Abernathy's productivity dilemma [1] by being exceptionally well equipped and valuable to future employers and to society [11]. One key to bring about a reflective perspective and deepen the learning process for the individual would be to re-think and re-frame ongoing negotiating design processes. Understanding about the learning process, how it works from a practical viewpoint, may substantially increase the chances of developing and applying these abilities later in life [9, 11]. In framing the elements involved in our study a *Null hypothesis* [21] is used to state our hypotheses;

H0: prototyping is not perceived important as a collaborative learning tool for individual design practices

and alternative hypothesis stated as;

H1: prototyping is perceived important as a collaborative learning tool for individual design practices.

2. METHODOLOGY

The study was designed in three phases, making it flexible for durable changes of in-depth inquiries at later data collection stages. In total an estimate of 35 unique responses were collected. Triangulation of sources was a performed to increase content richness, depth, and accuracy corresponding to reliability level and thus transparency of the study.

Phase 1 originates from our previous study [12], where data is a conjunction with the data set retrieved from the structured questionnaire sent to senior university faculty (i.e. professors). However, data used in this study exclusively answers probing questions on prototyping importance, and main approaches to active learning. Two email reminders were sent out to each respondent. In total approximately 10 weeks elapsed from initiation to submission including both reminders. Founded in our previous study selected peers were targeted on either good reputation, indexing/rating or interesting ways of working with engineering students. Altogether a set of 20 distinguished engineering design institutes were contacted, four returned answers.

Phase 2 consisted of an experiment where the set-up was made over a social network (linkedin.com). The network consists of a multitude of sub groups where professionals share thoughts and experiences. Targeting individual sub groups respective population share a common interest that aligns with the

Table 1. Research design set-up

Set-up	Data collection method	Population	Sample
Phase 1	Structured questionnaire (Univ.)	20 international universities	4 answers (1India/1USA/2EU)
Phase 2	Experiment (social network)	Sub groups 5500/860	14 (12+2) participants
Phase 3a	Structured interview (Students)	KTH 28/UiD 30	15 (10+5) answers
Phase 3b	Structured interview (Lecturers)	KTH 2/UiD 1	2 (1+1) answers

beneficial assumptions of 'community of practice' [6]. Discussions are the most common way of sharing knowledge between peers although discussion formats varies in depth and frequency. Two sub groups were selected based on 1) contextual relevance (i.e. design research, design education) 2) and depth and frequency in discussion threads. At time of experiment, targeted sub groups had over 5.500 and 860 users registered respectively. Execution was made by posting the following main open-ended question in both forums; *what is the importance of prototyping?* In total the response rate was relatively high compared to other posting threads in one of the two forums. Data was presented based on postings, in chronological order. Narratives (i.e. storytelling) were used to present perspectives on prototyping from the network discussions.

Phase 3a involved students represented at two Product Innovation Engineering (PIEp) nodes [17], working in Integrated Product Development and Design project courses at the Royal Institute of Technology and Umea Institute of Design. Informal questioning was addressing the use, and post-use reflections on distinctive prototyping experiences by randomly sampled students.

Phase 3b opened up each project course to respective course lecturer to comment on prototyping ongoing application and shared experiences on the students' projects. Unit of analysis was made on two different levels: First, we looked for keywords, where content analysis was performed using example extractions and matching between cross tabulated data. We refer this step to the individual (primary) level. Then we tested our hypotheses based on collected data, which after was post-elaborated from a knowledge-based perspective.

3. RESULTS

This section involves extracts from the data collection where institutes such as the Dschool at Stanford University and the Institute of Design in Umea, Sweden (UiD), emphasize prototyping, hands-on experiments and the ability to very quickly visualize ideas. From our investigation the phase 1 interviews suggest prototyping design schools to be perceived as '*essential for all our final year major projects*'. Students start experiencing and building design and prototyping skills early in their education, when entering the program a number of skills are practiced already from the first year: e.g. visualization, rapid prototyping and modeling. *'These are used as preparatory courses for their prototyping skills'* in this process computer based skills are developed through courses that enable computerized techniques, e.g. CAD modeling.

Below is an extraction from phase 2 and some of the most intriguing answers brought forward to establish depth and perspective on the subject; *'what is importance of prototyping?'* By one of the initial respondents, prototyping was described as part of a cyclic triangle as it involved communication, evaluation and learning methodology. *'Externalizing models, we not only evaluate the accuracy of our initial model, but we communicate it directly to others. This creates collaborative learning opportunities that may draw from the divergent perspectives of others'.* Another respondent posed that process refinements had influenced his experiences and perception of prototypes, as to now being a natural part of most of the respondent's iterative work; *'ranging from simple mock-ups to advanced models, prototypes allow the best way to test human interaction to speed up the development process by providing evidence, reduce overall project cost and risk and make it more likely that a design will meet a customer's need'.*

The collective knowledge is grouped together as project teams are set up, which was referred as a unique way to capitalize on each other's ideas. This incorporated core development know-how as part of the ongoing learning process where a number of iterations were perceived as dependent on team functionality. *'That would usually mean as many as five or six iterative samples to get to the final sample ready to send off to the customer. Of course we would constantly fight the tendency of designers and sample makers to want to do it all by themselves but when our group functioned as a true team, magic happened.' Another respondent argued: 'I believe that prototypes are a more democratic way of communicating ideas. Some people are better at making the conceptual jump from a picture to the actual device or product.'* In relation to early communicative advantages, intended output considerations establish efficiency through systematic use, especially if requested knowledge is integrated in the development work-flow, or as another respondent stated; *'The role of prototyping at our company is we arrive with sample mock ups, flows depending on the inputs, discussions with the user…or we can say domain experts. It has helped us a lot in freezing things like functionality before going to actual development.'*

'These days I tend to see the prototypes/simulations as iterations starting at low detail and the detail gradually building up as decisions get made and more inputs come into the process.'

'. . . prototyping has to be technically credible with a strong and solid file to demonstrate what type of risks and opportunities the concept could provoke. To me it is the professional proof of a vision and a strategic tool for top company's management to decide how to orientate future programs in order to make good healthy business.'

Phase 3a tells about lessons learned from a full year academic team based project course in Integrated product development, where in the early stages students commented: *'Prototyping, well, the ones that have been taking the Design and Product Realization courses know what to do by now — we don't think so much we just do'.*

The other student group is mainly from the Machine Design program and thus, equipped with less experience in working with prototypes. There are two main prototype categories that students have been working with, function and design. Earlier in the project the two types were not separated. As time went along it was necessary for the students to take precautions by separating the two and more focus on functional prototypes. In terms of format, 2D representations are the dominant contributor especially in early phases. '*Sketching allows freedom and provides less time on task compared to 3D modeling when we are in the phase of communicating quick and dirty ideas'*. Applying a systematic and collaborative rapid prototyping exercise, OMB (Open Mega Brainstorm) 3D models were by students recollected as a highly appreciated early phase activity. For this exercise it was open to use all kinds of materials (cardboard, tape, plastic cones, metal springs, colorful paper, rope, feathers, rubber pieces, etc.).

Notably, all students were divided in groups that had the same basic materials with one group responsible for each purposeful function metaphor description. Based on what the students could find that could work well to put forward conceptual ideas in the shape of a 3D prototype. At this occasion restriction in time forced the students to finish and be ready to present their mini group prototypes after just five minutes. Function metaphors were used to make the prototyping both playful and valuable for the students that interpreted the presentations from the mini groups.

At UiD, third year design students considered prototyping as '…*a natural ingredient in the design loops taking the projects forward each week'*. Each week students made preparations for team examination exercises were interpretation between various materials and focus areas were considered to *"allow for quick materializing of specific features…this week we for instance will use clay to get user feedback on their ideal shaped grip"*. *'Part of the process is to come up with ideas how to make others input worthwhile, making the greatest contribution to the ongoing design processes'.* Prototyping importance carries several dimensions, whereas communication was perceived as process oriented by one of the design students: *With prototyping exercises it does not take long until it becomes an integrated part of continuous work…you simply start consider it as a way of expression'.*

In statements from phase 3b, the examining lecturer pointed out that; '*In this process you get the material talk-back that carries an equally important role as the prototyping activity itself…you process your experiences and you benefit from others' viewpoints.* Stated from another perspective where functional prototypes account for the physical output by the end of the course: *'Part of the process of establishing a functional prototype is to repeatedly try over and over again and by doing so establishing confidence in acting out, materializing bits and pieces, and in the end realizing ideas'.*

4. ANALYSIS

4.1. Concluding remarks

In this section we try to put forward elements of proof that can confirm or disconfirm either of the opposing hypotheses. In Table 2, keywords have been synthesized into clusters, and enumerated in

Table 2. Prototyping keywords.

Phase 1	Phase 2	Phase 3a & 3b
1- Visualization	1-Visualization and evaluation	1-Evaluation, process
2- Learning	2-Communication, evaluation and learning	2-Experience levels
3- Evaluation, integration of skills	3-Evaluation	2-Communication, Learning
4- Performance, evaluation, efficiency	4-Communication, increase value spiral, and speed	4-Learning, feedback
	5-Communication and visualization	5-Learning, feature emphasis
	6-Communication, evaluation and learning	6-Visualization
	7-Communication and collaborative design	7-Visualization
	8-Visualization	8-Communication
	9-Visualization	9-Learning, iteration speed
	10-Communication, democracy	10-Communication, Visualization
	11-Communication and visualization	11-Evaluation, learning
	12-Communication and visualization	12-Evaluation, efficiency
		13-Visulization
		14-Learning
		15-Collaborative design
		16-Communication
		17-Visualization, evaluation

relation to individual responses. The three categories (i.e. Phase 1, Phase 2, and Phase 3a & 3b) are separated due to distinction in time (i.e. phase of data collection) and distinct data collection method used in our study.

Phase 1 and 3a and 3b involved similar phrasing and clustered keywords as the phase 2 experiment. Conversations seem to be a key ingredient when probing problems at hand, awakening a set of questions, without not necessarily providing any straight answers. Kelly's basic prototyping assumption begins in this end…*'start conversations that answer the questions'* [17]. Practitioners also brought forward the essential in embracing an open mind and allow one to *'play in sandbox and learn'* and *'rush to the prototype — fail fast'*. Collaborative efforts was considered a combination of capitalizing on peers' knowledge through modes of repetition and experiential learning, manifested in statements as; '*how to make others' input worthwhile'* . Based on the tabulated data an overall tendency to incorporate elements of learning (i.e. communication, visualization and evaluation) makes the null hypothesis to be discarded. In turn *prototyping is perceived important as a collaborative learning tool for individual design practices.*

4.2. Incubation

The interrelation of individual and collective knowledge is proposed to be a generative source of accumulated successes, where stories and externalized means (e.g. prototypes) carry meaning to a specific group of people [6]. In this process inter-functional communication and co-ordination depend heavily upon the effectiveness of non-articulated translation and integrative procedures. Thus, prototyping allow re-appropriation and important means to ensure the integration of sticky information [14]. Given that prototyping should be perceived as a mean to interact, and an activity where a bundle of specific value creating meanings are attached, the enriching depth that prototyping allows must not be neglected or by any way disregarded as less important. Prototyping meets the requirements of lateral thinking, or rather creative and in many aspects functional communication. Perceiving prototyping at a meta-cognitive level the externalization process follows Nonaka's SECI arguments [22]: 'While tacit knowledge held by individuals may lie at the heart of the knowledge creating process, realizing the practical benefits of that knowledge centers on its externalization' [23]. Several key words stand out that are also well aligned with this knowledge spiral assumption:

- working together, utilizing each other experiences and perspectives, integration and synthesis - socializing
- sketching, 2D and 3D representations, utilizing support instruments (e.g. SLS machines), rapid prototyping, functional and design features, numerous iteration, mental models, visualization - externalizing
- sensitive for recipients level of understanding, user need, correlation between output-input, verification, usability of content, delivery format or mode - communicating
- imagine, reconfigure, redesign thinking, reflection, pause, influencing decision making, sense making - internalizing

Our study emphasizes the need for incentives towards lateral thinking and innovative dispositions through variation in prototyping practices in engineering education. Learning methods have always changed throughout time, thus it is not the method as such, but how it is facilitated that needs to be reconsidered. Thus, to prototype the actual methods in which learning is manifested (e.g. set-up variations) would be a way to perpetual reconfiguration of existing beliefs. Prototyping activities facilitates in-depth learning, still learning methods should be flexible and balance along the axis of a duality optimum where on one hand; learning disposition shifts from more practical action based individuals embracing all sorts of prototyping challenges, and on the other hand; more theoretical, reflective individuals may need moments for thoughts to fully appreciate and incorporate the practical approaches involved with prototyping.

This paper set out to link industrial and academic practices with ambitions to create a better understanding for educational efforts involving prototyping as a learning tool and mean to communicate. Through modes of communication, visualization and evaluation collaborative activities play pragmatically important roles in both industry and academia. Our hypotheses show that prototyping is perceived important as a collaborative learning tool for individual design practices. This opens up for more in-depth reasoning and questioning as to what extent individual learning is reassured and assessed through team-based prototyping, but this is beyond the scope of this paper. Our final remark concerns educational implementation of future prototyping activities, where versatile approaches can bridge individual creative and innovative predispositions and collaborative settings.

REFERENCES & ESSENTIAL BIBLIOGRAPHY

1. Abernathy, W. J. *The Productivity Dilemma: Roadblock to Innovation in the Automobile Industry*. The Johns Hopkins University Press, London, 1978.
2. Adler, P., *Shared Learning, Management Science* 36: 938–957, 1990.
3. Argyris, C., and Schon, D. *Organizational learning: A theory of action perspective*, Reading, Mass: Addison Wesley, 1978.
4. Baillie, C. and Moore, I., *Effective Learning and Teaching in Engineering*, New York: Routledge Falmer, 2004.
5. Brown, J. S. and Duguid, P., Organizational learning and communities of practice: Toward a unified view of working, learning and innovation. *Organization Science*, Vol. 2, pp. 40–57, 1991.
6. Cook, S. D. N. and Brown, J. S., Bridging Epistemologies: The Generative Dance Between Organizational Knowledge and Organizational Knowing, *Organization Science*, Vol. 10, No. 4, pp. 381–400, July–August, 1999
7. Chua, C. K., Leong, K. F. and Lim, C. S., *Rapid prototyping principles and applications*. Singapore: World Scientific Publishing Co. Pte. Ltd, 2003.
8. Cross, N., Christiaans, H., and Dorst, K., Design Expertise Amongst Student Designers, *Journal of Art and Design Education*, Vol. 13, No. 1, pp. 39–56, 1994.
9. Crawley, E. F., Malmqvist, J., Östlund, S. and Brodeur D. R., *Rethinking Engineering Education: The CDIO approach*, New York: Springer, 2007.
10. Damanpour, F., Organizational innovation: A meta-analysis of effects of determinants and moderators. *Academy of Management Journal*, Vol. 34, pp. 555–590, 1991.
11. Felder, R. M., Learning and Teaching Styles in Engineering Education. *Journal of Engineering Education*, Vol. 78, No. 7, pp. 674–681, 1988.

12. Grimheden, M., Berglund, A., Larsson, A. and Nilsson, F., Education for Product Innovation — An Investigation of 'Good Practices', *submitted for journal publ.*, 2011.
13. von Hippel, E. *The sources of Innovation*. Oxford University Press, 1988.
14. von Hippel, E., 'Sticky Information' and the locus of Problem-Solving, *Management Science*, Vol. 40, No. 4, pp. 429–439, 1994.
15. Iansiti, M., *Technology Integration: Making Critical Choices in a Turbulent World*, Boston (MA): Harvard Business School Press, 1997.
16. Kelley, T., *The Ten Faces of Innovation*. New York: Doubleday, 2005.
17. Kelly, T., op. cit., ref. 20, p.14.
18. KoIb, D. A., *Experiential Learning: Experience as the Source of Learning and Development*, Prentice-Hall, Englewood Cliffs, N.J., 1984.
19. Leonard-Barton, D., *Wellsprings of Knowledge — Building and Sustaining the Sources of Innovation*, Boston (MA): HBS Press, 1995.
20. Liou, F. W., *Rapid Prototyping and Engineering Applications — A Toolbox for Prototype Development*, Boca Raton, FL, USA: CRC Press, Taylor and Francis Group, 2008.
21. Mann, P. S., *Statistics for Business and Economics*, New York: John Wiley & Sons, 1999.
22. Nonaka, I., A dynamic theory of organizational knowledge creation, *Organizational Science*, Vol. 5, No. 1, pp. 14–37, 1994.
23. Nonaka, I., op. cit., ref. 27, p. 20.
24. Petroski, H., *Invention by Design — How Engineers Get from Thought to Thing*, Cambridge (MA): Cambridge University Press, 1996.
25. Pisano, G., *The Development Factory*, Cambridge (MA): Harvard Business School Press, 1996.
26. Schrage, M. *Serious play: How the world's best companies simulate to innovate*. Boston: Harvard Business School Press, 1999.
27. Schon, D. *The Reflective Practitioner, How Professionals Think in Action*, London: Temple Smith, 1983.
28. Sheppard, S. D. and R. Jenison, Examples of Freshmen Design Education, *International Journal of Engineering Education*. Vol. 13, No. 4, pp. 248–261, 1997.
29. Stenmark, D., Leverage Tacit Organizational Knowledge, *Journal of Management Information Systems*, Vol. 5, No. 3, pp. 9–24, 2001.
30. Tidd, J., Bessant, J. and Pavitt, K., *Managing Innovation: Integrating Technological, Market and Organizational Change*. 2nd ed. Chichester: Wiley, 2002.
31. Ulrich, K. T. and Eppinger, S. D., *Product Design and Development*. 4th edition. Singapore: Mc Graw Hill, 2007.
32. Utterback, J. M., *Mastering the Dynamics of Innovation*. Boston, MA: Harvard Business School Press, 1994.
33. Wheelwright, S. C., and Clark, K. B., *Revolutionizing Product Development — Quantum Leaps in Speed, Efficiency, and Quality*. New York: The Free Press, 1992.