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Developing an Engineering Culture: The Use of Scientific Method as a Routine for Product Development

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***Abstract*—**The Product Development Process (PDP) is an already widely researched topic in several areas of knowledge, but new ways of teaching engineering request different approaches, such as using the scientific method in problem-solving. This paper proposes the development of a way of teaching the PDP using the Project-Based Learning (PBL) approach systematized in a routine of reasoning routine based on the scientific method, the Toyota Kata approach. The methodology used was action research conducted in a public university during a quarter, in two distinct classes of the undergraduate course in Materials Engineering of Federal University of Santa Catarina (UFSC), for testing this proposal. Students developed a product through the processes of the PDP Informative Design, Conceptual Design, and Detailed Design phases. As a result, the routine employed was capable to develop the Engineering Culture in the students, once they were able to progressively develop the practice of reasoning based on the scientific method in the search for solutions to solve the problems of product development.

***Keywords*—**Product development process, project-based learning, engineering, culture, routine.

I. Introduction

THE PDP is an already widely researched topic in several areas of knowledge, and today there are numerous methods, tools, and frameworks available to assist engineers and designers. It has long been believed that the teaching of PDP based on these technics was sufficient for the training of future designers [1], [2], but new insights in the teaching of engineering and product design point to the need to develop a different way of thinking the product development. Establishing a routine for the use of the scientific method in problem-solving (translated as an Engineering Culture) is a challenge because it consists of a change the way students think.

Habits develop as people respond repeatedly to a stable context, and thus form direct associations in memory between that response and changes in the performance context [3]. Solving different problems for the delivery of a project or a product can be considered as a way to exercise these habits. To this, the Toyota Kata approach can be used, which consists of a systematic routine that internalizes the scientific method (Engineering Culture) through experimentation in its participants. This approach is one of the techniques that can be used to drive and manage the PBL. Thus, this article aims to analyze the operationalization of PBL to perform the PDP through a scientific method systematic routine in the academic environment.

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II. Background

The PBL is an approach used to promote the problem solving process as it provides a concrete knowledge acquirement means in an active learning environment [4].

In teaching, the processes in which students ask their own questions, plan their research, analyze and express their own findings, and structure their own understanding, enable more effective and lasting learning [5]. According to Orlich et al. [6], providing the student the opportunity to question is important for him to express his opinions and propose solutions to problems. However, research-based instructions require a great interaction between environment, content, materials, teacher, and student. In this way, the results of teaching tend to be positive, bringing students to an active postural, with a better understanding and developing skills that help a better understand the nature of science [7], [8]. Five aspects are pointed out by Thomas [9] for the accomplishment of a successful PBL: (i) centralized teaching in the PBL; (ii) existence of a guiding question; (iii) the need for constructivist research, developing students' knowledge or skills; (iv) encouraging autonomy; and (v) realism, focusing on real problems. The PBL can be conducted through small cycles of experimentation, which require a systematic structure for its conduction and management. In this way, the routine of the Toyota Kata approach can be used to lead and manage the PBL by means of the elaboration and execution of the small cycles of experimentation for the proposed solutions, besides guaranteeing the record of the learning acquired in this course.

The Toyota Kata approach is a process improvement routine developed at the Toyota Company, which allows to navigate the territory of uncertainty by taking a small step at a time. The term Kata means "way of doing" and refers to the form or pattern that can be practiced to develop particular skills and a new mentality [10]. The goal is to develop well-trained mental circuits for systematic and scientific ways of developing solutions in dynamic and uncertain situations. The Toyota Kata approach is based on two concepts: Improvement Kata and Coaching Kata [10].

The Improvement Kata concept is intended to train and teach the whole organization, aiming at making continuous improvement a systematic ability. It consists of the following steps [10]:

1) Define what the challenge is. Before acting, the team must identify a challenge aligned in the direction of the organization's long-term vision.
2) Understand the current situation. Carefully, the team should analyze the facts and data of where/how they are now.
3) Establish the next target condition. A target condition describes a combination of attributes that one wants to achieve on a predetermined date. Achieving a target condition is a learning task because one is not fully aware of the obstacles one will face in reaching it.
4) Navigate from Current Condition to Target Condition. The Improvement Kata incorporates a systematic and iterative routine to navigate the unpredictable grey zone between these two conditions.

This systematic routine should be conducted through PDCA (Plan, Do, Check, Act) cycles of quick experiments. In this process, teams learn as they strive to reach their target condition and adapt based on what they are learning. A storyboard should be used to record the current condition, target condition, obstacles identified, and actions described each PDCA cycle accomplished (What do you plan?; What do you expect?; What happened?; and, What you have learned?).

The Coaching Kata is the way in which the Kata Improvement routine is taught. The coach provides support to the learner, just as an experienced trainer influences the learner to practice a desired new behavior. The presence of the coach favors the practice of the path efficiently and effectively for the process of changing mentality and mastery of the new standard [11].

III. METHODOLOGY

The study was conducted through action research which seeks to link research with the academic practice, in order to make the research process a learning process for all participants (students and teacher). In this way, the problematic situation is interpreted from the point of view of the people involved [12], whose practical objective is the teaching for the students and scientific objective is to analyze the use the Toyota Kata approach to operationalize the PBL for teaching.

The research was conducted in a public university during a quarter, in two distinct classes of the undergraduate course in Materials Engineering of Mechanical Engineering Department of UFSC, with approximately 40 students each, who are in the 10th phase. The course has, in total, 15 phases. The study took place during the time reserved for the Project Methodology class, which are given on two days of the week (1h40/day) and proceed as follows: On the first day the coaching cycle is carried out with the formed work teams by the students; and on the second day, a lecture is given on a topic related to product development (e.g. QFD, selection techniques, creativity, functional modelling, among others). The objective of the class is to guide how to develop a new product, having as contents addressed: introduction and management of PDP; the model of reference for PDP, based on [13] that includes the presentation on the phases of Informational Project, Conceptual Project and Detailed Project. The class plan was established considering its time available (Fig. 1).

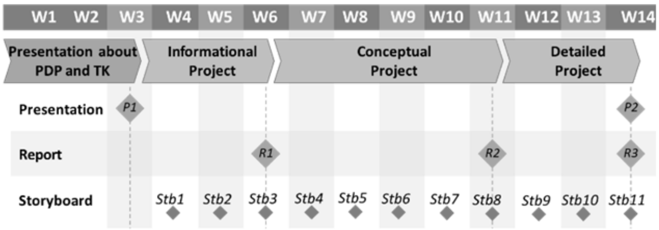

Fig. 1 Class plan

As illustrated in Fig. 1, the first 3 weeks were used for expository classes to explain/present: PBL logic and class rules; the fundamentals of the PDP, with the phases, the main stages and the exit of each one; and what is Toyota Kata's approach, including its concepts, usage logic and how to fill in the storyboard. The teachers set the dates for two presentations: the first, (occurs 3rd week) where the students should present their plans in the form of a delivery roadmap, and the second (occurs 14th week or at the end of the quarter), in which students should present the finished product completed until the detailed design phase. The delivery of three reports corresponding to the outputs of the PDP phases was also foreseen. The following items are requested in reports: Report 1 (R1), target customer, customer needs, and target specifications; R2, functional modeling, solution alternatives, and initial sketches; R3, product structure, material selection, macro manufacturing process planning, and cost definition. These reports are cumulative, so at the end of the process, students should submit all the information presented in the three phases of the project.

For the operationalization of this PBL, it was considered that the results of each phase of the PDP would configure a target condition for the iterations of the Toyota Kata approach. This enabled the students to clearly visualize the deliveries they were expected to make, as well as ensuring short experiment cycles to achieve these target conditions. However, to start the project, a delivery roadmap was requested to each team with the main deliveries that the students planned to carry out, as shown in Fig. 2.

The product development by Toyota Kata approach consisted of the description done by students about the current condition of the project (where is it?), its target condition (where it wants to go?) and the comparison between these conditions. This comparison allowed the identification of obstacles that must be overcome for that the target condition is reached. Each obstacle identified should be individually worked by students, who also describe what was planned and what is expected as a result of planned action. After performing the proposed action for the obstacle, the students describe what happened and their reflections on what they learned (PDCA cycle). In this process, the teacher assumes the role of the coach supporting the development of the project solutions and establishing the dates and content of the macro deliveries.

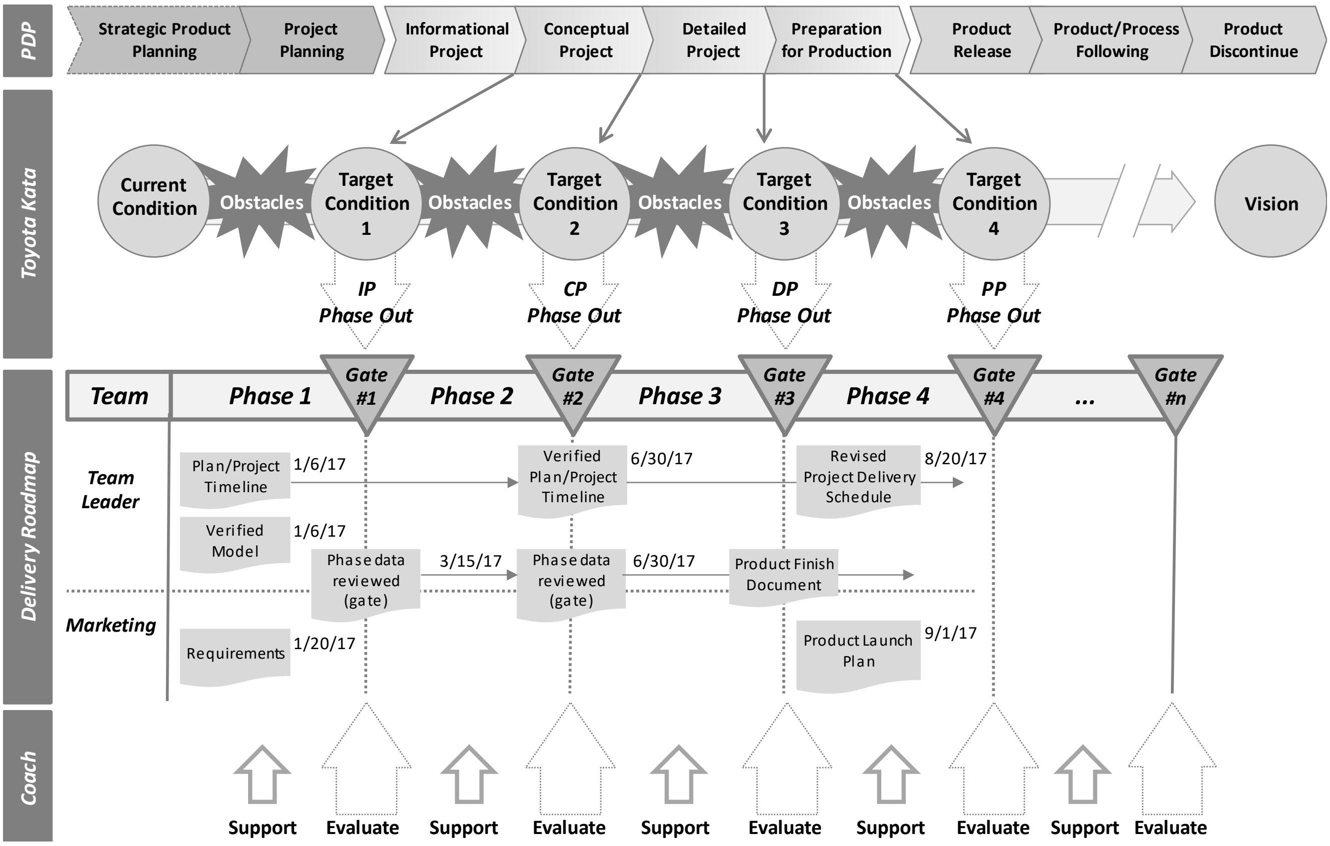

Fig. 2 PBL structure

TABLE I
STUDENT'S STORYBOARD

Project: Bottle Holder		**Challenge:** Target specifications	
Current condition - Unknown of competitors - Unknown target customer - Life cycle not defined - Customer requirements not determined - Non-determined product requirements	**Target Condition** - Niche of known competitors - Target customer defined - Product life cycle defined - client requirements determined - Product requirements determined	**What you plan?** 1- Search in physical stores of sporting goods and on the Internet products that are the same or similar to what we want to manufacture. 2- Define target customer that the product will attend	**What is expected?** 1- Define which are the national and international competitors that manufacture products that are the same or similar to what we want to produce. 2 - Define what type of customer we want to reach, their revenue and race habits
Obstacles ~~1- Unknown of competitors~~ 2- Unknown target customer 3- Unknown of the product life cycle 4- Indeterminacy of product requirement 5- Indeterminacy of customer requirement		**What happened?** 1- It has been seen that in Brazil there are no products that are the same or similar to what we want to produce. In the USA, there are several models of bottle holder during races and physical exercises.	**What you have learned?** 1- It was defined that our product will serve the national market. It will be an accessible and innovative product in Brazil. We will use the products of American competitors as inspiration for developing our own bottle holder.

IV. RESULTS

Initially, each group produced their delivery roadmap and filled out their Stb1 (Storyboard 1) according to this information. Following, there was the coaching round in which the teacher checked the storyboard and endorsed the continuation of the work. The students performed the actions for a week and presented again the storyboard in the class dedicated to the coaching round. In this new cycle, in addition to describing what happened and what they learned, the planning for the following week was recorded and the team described what they hope to achieve by developing this planning (see example in Table I). This storyboard is analyzed by the coach, who provides feedback to the student. The focus of the feedback given by the coach is not for the outcome of the project achieved by the student, but for the complete execution of the system, the description of the current condition and target condition, the obstacles identified, the recorded planning and what is expected with this planning. The goal is for the student to exercise scientific thinking (Engineering Culture). That is, regardless of the tool used or the steps are taken to carry out the project, the result expected by the coach is the correct scientific method.

The coach focuses on conceptual errors, such as (a) when the team describes what it expects to diverge from the planned activity; or, (b) when the team plans something but cannot express the reason for such planning (e.g. application of tools without justification). The evolution of students is also analyzed through the descriptions of their learning. The following excerpts are related to some examples of apprenticeships registered by the teams:

- "We have learned that market research is important in order to better understand customers and know their main needs and wishes".
- "A single customer's need/desire can mean more than one requirement for the product, just as a big number of needs/desires can be translated into a single requirement".
- "We learned the importance of verifying information and storing it in a clear way to establish the relationship of customer needs with engineering requirements. We have also learned how to correlate product requirements with their specifications through tools such as Mudge Diagram and QFD".
- "We have learned that creating innovative solutions with similar products on the market is difficult, as this 'model product' unconsciously ends up limiting the creativity of the group. This activity has shown great difficulty since the creativity aspect is little worked and explored during graduation. Thus, it was possible to perceive the importance of exercising group work by generating many ideas without judging them in the first instance".
- "Throughout development, we noted the development of the team regarding how to conduct the PDP phases. In that, the routine of planning the next steps in short cycles stimulated the gathering of information, updating, and control of the decision making."

In order to analyze students' progress in the problem-solving system, the teachers evaluated the completion of the teams' storyboards in addition to the learning records made by the students themselves. This analysis enabled teachers to direct actions focused on the most fragile points related to the knowledge presented by the students, both in relation to the learning of the product development and on the systematics of scientific thinking to solve the problems encountered. These results are presented in Table II.

TABLE II
EVALUATION OF STORYBOARDS PERFORMED IN ONE OF THE CLASSES

#	Item	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8	Total
1	"What happened" isn't correctly described	3	0	3	1	2	2	2	3	16
2	"What we learned" isn't correctly described	2	2	2	1	2	2	1	1	13
3	No planning for next cycle	2	1	3	2	2	1	2	0	13
4	"What we learned" is "what happened"	1	3	1	0	1	1	1	0	8
5	"What you expect" is an action plan	1	0	0	1	0	1	0	0	3
6	Obstacles don't reflect the gap between CC and TC	1	0	0	0	1	0	0	0	2
7	Planned doesn't match obstacles	2	0	0	0	0	0	0	0	2
8	"What we learned" doesn't match planned actions	0	1	0	0	0	1	0	0	2
9	"What you expect" isn't correctly described	0	0	0	0	0	0	0	1	1
10	"What you expect" doesn't match the planned actions	0	1	0	0	0	0	0	0	1
	Accumulated	12	8	9	5	8	8	6	5	61

In the results presented in Table II the item # 1 is about the lack of information in the "what happened" field. In which students are concerned to describe how they did the action and not the results obtained. Item # 3 is disregarded in cycle 8 because it is the last. Both problems have demanded a greater explanation in the introduction to their mitigation in future classes. In it, it is possible to observe the development of the students in relation to the learning of the use of the Toyota Kata approach. Even using the structure with 11 storyboards it was possible to perform only 8 coaching cycles with students (due to non-school days). However, it is possible to notice the tendency in the reduction of mistakes made by the students during this period.

V. CONCLUSION

According to the execution of the classes, it was observed that it is possible to operationalize the PBL in a scientific method routine to perform the PDP in the academic class. The use of the Toyota Kata approach has proven to be promising, providing standardized support for driving and managing product and student development. In this way, the students developed a routine for solving Product Development problems with the scientific method. This development is accompanied by the evaluation of the storyboards by the coaches.

This approach also helped to evidence students' perceptions of the importance of using the scientific method for problem-solving. We also observe that each experiment has an evolution in the form of teaching, and the teacher is able to identify the weaknesses of his students' knowledge, thus being able to act specifically on the necessary key themes. Most of the students who participated in this research had great difficulty in describing what they learned and often recorded only the results of their actions. This draws attention to the form of teaching currently practiced, in which the training of students is constantly based on the repetition of actions, techniques, tools, etc. that do not stimulate reasoning based on the scientific method for the resolution of the problems of engineering (Engineering Culture). In the research carried out in this study, it was possible to observe that with the course of the classes the students were able to identify their mistakes and learning from their own experiences. This has contributed to a gradual improvement in the execution of classroom activities, as well as the students' own perception of how to deal with the problems (obstacles) that appear throughout the activities that make up product development.

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