USE OF CONCEIVE-DESIGN LEARNING ENVIRONMENTS TO PREPARE ENGINEERS FOR THE DEVELOPMENT OF COMPLEX AND HIGHLY INTEGRATED AERONAUTICAL SYSTEMS

Paulo Lourenção[1], Fernando Rosa[2], Otto Resende[3]

Affiliation [1] Engineering Specialization Program, Embraer
Affiliation [2] Excellence for Products and Clients, Embraer
Affiliation [3] Preliminary Studies, Embraer

ABSTRACT

Embraer, one of the largest aerospace companies in the world, was founded in 1969 to accomplish the vision of the Brazilian government to develop the capacity of designing and manufacturing Brazilian airplanes. Out of current 19,000+ employees distributed worldwide, the company has 5,900 engineers. In order to have recently graduated engineers prepared to tackle its future challenges, Embraer created the PEE – Engineering Specialization Program in partnership with ITA – Aeronautics Institute of Technology in 2001. PEE comprises a Technical Master's Program and has already prepared more than 1,400 alumni, graduated in 22 classes; out of them around 1,000 are currently Embraer employees. The main objective of PEE is to prepare future engineers to be specialists that will work in multidisciplinary teams, to accomplish the lifecycle design of complex and highly integrated systems. PEE has the duration of 18 months and consists of three phases. The first phase aims to provide the students with the fundamental knowledge on lifecycle design, covering topics from Marketing Analysis and Research & Technology, up to aspects related to operation, maintenance, and end-of-life disposal. In the second phase, the students select their area of specialization and Master Thesis topics related to one of the following tracks: a) Materials and Structures, b) Aircraft Systems and c) Manufacturing. In the third and last phase, multidisciplinary teams, organized by students coming from the three tracks, take part in a Conceive-Design project. Out of the innovations in teaching and learning methods that have been adopted, this paper presents results on: a) extensive use of visual communication tools and mock-ups in the "Design Room", to share created knowledge and technical data and b) involvement of current and former key Embraer specialists in mentoring the students.

KEYWORDS

Conceive-Design Experiences, Experiential Learning, Engineering Workspaces, Visual Communication, Mentoring, Standards: 5, 6, 7, 8.

INTRODUCTION

Embraer is one of the largest aerospace companies in the world and it was founded in 1969 to accomplish the vision of the Brazilian government to have, in the country, the capacity of designing and manufacturing airplanes. Out of more than 19,000 employees distributed worldwide, the company has 5,900 engineers dedicated to Research & Technology and Integrated Product Development.

In order to have recently graduated engineers prepared to tackle our current and future challenges, Embraer created the PEE – Engineering Specialization Program in partnership with ITA – Aeronautics Institute of Technology (www.ita.br – in Portuguese) in 2001. PEE comprises a Technical Master's Program and has already prepared more than 1,400 alumni, graduated in 22 classes, out of which, around 1,000 are current Embraer employees. Embraer, (2015). Due to regular turnover and the need to cope with new technologies, every year the company hires more than 100 engineers. The selection process of new engineers is crucial for success. In 2015, more than 5,900 candidates from the whole country applied for 40 positions in PEE. In addition to Technical Engineering Knowledge and English proficiency, the selection process comprised personal presentations, group dynamics and interviews involving ITA faculty, HR specialists, future managers and former PEE alumni.

The main objective of PEE is to prepare future engineers to be specialists in several departments of Embraer´s Vice-Presidency of Technology and Engineering. These engineers will be part of multidisciplinary teams, to accomplish the lifecycle design of complex and highly integrated systems, such as airplanes, its systems, manufacturing processes, suppliers, maintenance centers etc.

To address the objectives described above, this paper presents some theoretical aspects connected to the themes of designing systems of systems, the use of multidisciplinary teams in product development, knowledge management and the connection between PEE pedagogical approach and CDIO philosophy. In addition, it provides information about the Engineering Specialization Program and some results about the special arrangement of the "Design Room" and the important role of the "mentors" in the development of the young engineers' competencies. As a wrap up section, final comments and suggestions for future learning points are presented.

THEORETICAL ASPECTS

Systems of Systems

The starting point of educating engineers to work in the design of commercial aircraft is to provide them with the perspective that airplanes are systems of systems. Airplanes are independent complex systems that are connected to many other complex systems (other airplanes, airports, satellites, air traffic controllers, maintenance centers etc.), and that have to achieve some level of common performance, such as safety, scheduling, costs, etc.

As pointed out by Altfeld (2010) the design and development of new aircraft comprises many complexities such as volumetric (size), systems, design, customization, process, and multicultural aspects among others. The aircraft itself is composed by several different systems such as structures, flight controls, hydromechanical systems, electrical systems, avionics, cabin and so on. Consequently, it will require the competencies of professionals from many engineering areas such as Mechanical, Electrical, Materials, and Production Engineering among others.

To cope with this multidisciplinary approach, the engineers and others specialists are organized in teams called "Integrated Product Development Team" (IPT). These teams are composed by representatives of all appropriate functional disciplines such as customers, program management, engineering, manufacturing, test, logistics, and suppliers among others. Once such a team is organized, the specialist must know that his role changes from being a member of a particular department, who focuses in a given discipline, to a team member who focuses on the product and its associated processes.

Multidisciplinary Teams for Product Development

According to Ulrich & Eppinger (2008), to be competitive, companies depend on the ability of creating new products that meet customer needs and that can be produced at low costs. Firms that aim to create these products have to realize that this challenge requires the creation of cross-functional teams, involving people from Marketing, Design and Manufacturing areas among others. The challenge is to emphasize that the team must work toward a common goal.

In order to create product development teams that are effective, the way the specialists are recruited, selected, trained and organized is a critical success factor. There are some challenges to be taken into account (Ulrich & Eppinger, 2008): trade-off analyses, technology dynamics, complexity, time pressure and economics. Other aspects to be taken into consideration are creativity, satisfaction of societal and individual needs, team diversity and team spirit.

In the front-end process, **concept development**, emphasis is given on the following activities: identification of customer needs, establishing target specification, concept generation, concept selection and setting final specification (Ulrich & Eppinger, 2008). During this phase, other aspects are economic analysis, benchmarking with competitive products and building models and prototypes.

According to Altfeld (2010), the rationale behind the effectiveness of multifunctional teams is to assure that the “right decisions” are made with participation of the most important stakeholders: engineering, manufacturing as well as customers, suppliers and certification authorities. Those stakeholders should be represented jointly in **the design and development processes,** and be encouraged to actively influence them.

Lean Product Development

In the end of the 80s, the MIT unleashed a worldwide study searching for answers for the loss of competitiveness and market share by the American manufacturers of the automotive industry. After a huge number of visits in different countries and factories, the IMVP – International Motor and Vehicle Program (Womack, Jones, & Roos, 1990) - realized particular characteristics in some Japanese companies, for instance Honda and Toyota. The way of doing more quality in less time and less cost comparing to the mass production found in American and European companies was considered lean by one of the IMVP members and the term is used until our days. In the brief words of Taichii Ohno, manager at Toyota and recognized as the founder of the TPS - Toyota Production System, "all we are doing is looking at the timeline from the moment the customer gives us an order to the point when we collect the cash. And we are reducing that timeline by removing the non-value added waste" (Ohno, 1988 cited in Liker, 2004).

In addition to the observations made in the manufacturing environment, a great difference was noted in the product development process. One important and general finding about launching of a new product, comparing the Japanese versus American and European companies, stated that the Japanese manufacturer would need approximately 1,7 million engineering hours over 46 months against 3 million engineering hours during 60 months for Occidental manufactures. Twice more expensive and one third longer lead-time. Through further investigations devoted to this topic, the authors selected four relevant differences between the designing methods: (1) leadership, (2) team work, (3) communication and (4) simultaneous work. In a brief explanation, the technical leader, Shusa - Chief Engineer - had true power over the whole team during all project phases and, according to Sobek, Ward & Liker (1998), "must demonstrate both exemplary technical expertise and fluency in synthesizing technical knowledge into clever, innovative designs". The team under Shusa's command work together during the whole project and over continuous problem solving and decisions based on visual knowledge. They make it possible, for different technical groups, to develop concurrent solutions and to integrate through decisions taken in the last possible moment, aiming to cause few rework and construct a perfect final solution. (Morgan & Liker, 2006).

The Obeya Structure can be seen in the Figure 1.

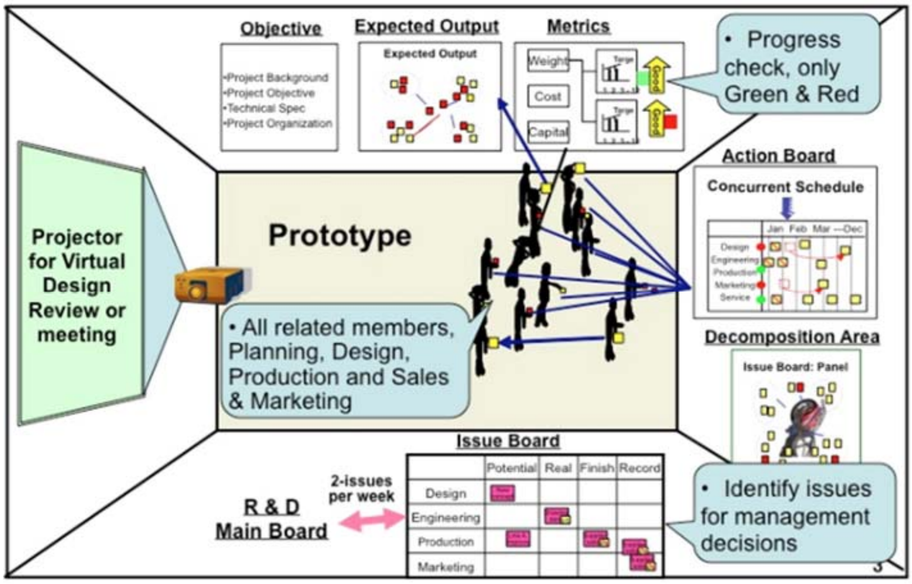

Figure 1. The Obeya Structure (Tanaka, Horikiri & Flynn, 2010)

To understand the origin of Obeya, it is important to know that one of Toyota's great success in sales and public appreciation is the Toyota Prius, the first fuel-electric hybrid car to be mass produced and introduced in the end of 1997. For Liker & Morgan (2006) it is not only a success as a product but also as an extraordinary development process. In the beginning of the project Toyota's highest-level executives took an atypical decision of choosing a CE-Chief Engineer who was not creating a career in that direction. As Uchiyamada did not feel he was qualified for the CE role and the coming decisions in the project, the first action was to be surrounded by a cross-functional team of experts in a big room, obeya in Japanese. In his own words, it is a place where "the chief engineer gathers the team of people responsible for that project. That is where simultaneous engineering can be even more effectively implemented by all the key people coming together in this area." (Morgan & Liker, 2006).

In Ward’s (2007) opinion, "almost all defective projects result from not having the right knowledge in the right place in the right time. Therefore, usable knowledge is the basic value created during development." In a complete description, Ward states the learning cycle as the left side of the Figure 2.

Knowledge Management

Surprisingly, the authors of this paper have identified a similar diagram in an Andragogy reference. One of the core adult learning principles is “problem centered” among other five not mentioned in this text. Kolb (1984) (cited in Knowles, Holton III & Swanson, 2005) defines learning as "the process whereby knowledge is created through transformation of experience”. In his Experiential Learning theory, Kolb suggests a four-step cycle as shown in Figure 2 in the right side. One of Kolb’s suggestions for the stage “Observations and reflections” is discussion in small groups (Knowles, Holton & Swanson, 2005).

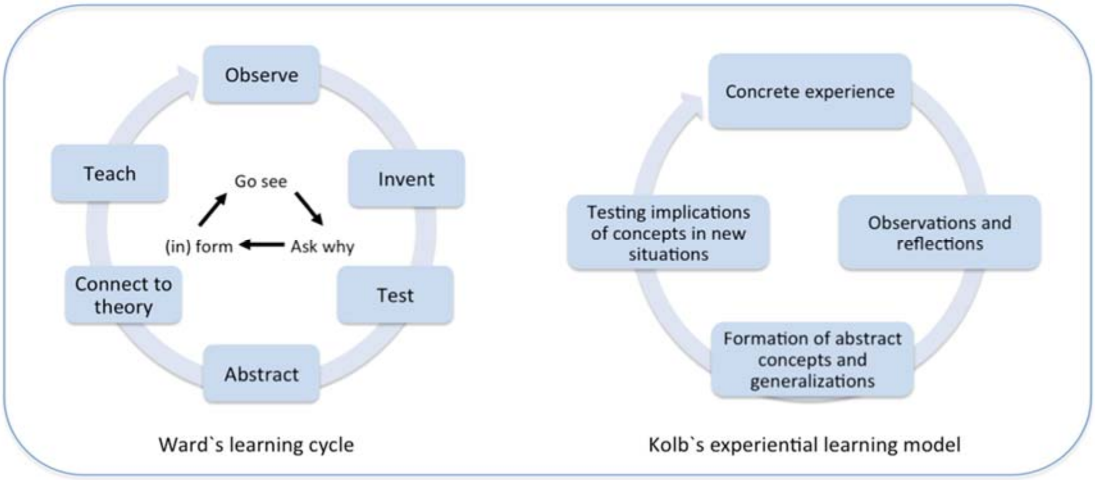

Figure 2. Ward’s and Kolb’s learning models

One of the important aspects discussed in this paper is the crucial role experienced engineers have in the education of the future workforce, acting as mentors, helping the students to cope with their conceive-design challenge. Nonaka & Nishiguchi (2001) discuss the concept of **Ba**. Ba refers to a physical, virtual and mental space, shared by two or more individuals. According to those Authors, social relationships established among those individuals have a strong influence on the scale and knowledge creation.

Nonaka & Nishigushi (2001) describe a model of knowledge creation, based on a spiraling process of conversions of tacit and explicit knowledge, involving the four stages of socialization, externalization, combination and internalization. **Socialization** refers to process of transferring tacit knowledge among individuals by means of joint activities in the same environment. **Externalization** is another very important process where the tacit knowledge is expressed by concepts, diagrams models or prototypes that can be understood by others. **Combination** is the process of converting explicit knowledge in more complex and systematic explicit knowledge through elaboration of documents, for example. Finally **Internalization**, which is the process of embodying explicit knowledge into tacit knowledge, or “learning by doing”.

The last and essential point to be addressed in this paper in the importance of social relationships in organizations (Nonaka & Nishigushi, 2001), presented in the chapter “Bringing Care into Knowledge Creation”. They state that care can help organizational knowledge development. Employees, who help each other, are accessible and have high degrees of kindness characterize high care organizations. In these organizations, individuals are supported by a social network, which make possible the process of sharing tacit knowledge with other employees.

CDIO Standards and Syllabus

The objective of PEE is to prepare engineers to work in Integrated Product Development processes, organized in multidisciplinary teams, to emulate the Front-end phases: Conceptual and Preliminary Designs. Although not adopting the CDIO Standards “formally”, since 2004 the group in charge the coordination of PEE Program have been using the CDIO model as a reference model to guide the improvements that have been implemented. With respect to CDIO Standards, the results presented in this paper are related to Standard 5, Design-implement experiences and Standard 6 Engineering workspaces, particularly in the way the ideas of Morgan & Liker (2006) related to obeya have been implemented. Standard 7 is also followed in an indirect manner since the students develop their conceive-design and interpersonal skills working together in the same room with the participation of ITA faculty and Embraer current and formers specialists, composing a group of 20+ mentors. The way the Conceive-Design projects are planned, organized and managed is in consonance with Standard 8 (active learning).

With respect to CDIO Syllabus v 2.0, PEE focuses on the following items. In terms of Personal and Professional Skills (2), special emphasis is given on Problem Solving and on System Thinking. Moving to Interpersonal Skills (3), PEE focus on Team Work and on Communications skills. Finally, on Conceive-Design Project (4), the most important competencies addressed are 4.2 (Enterprise and Business Context), 4.3 (Conceiving & System Engineering) and 4.4 (Designing). Although implementation is not completely covered by PEE, mainly because the problem presented to the students is the development of a new aircraft (vehicle, suppliers, production line, tests, maintenance, etc.), emphasis is given on experimental prototypes (interiors, wind tunnel models, etc.).

ENGINEERING SPECIALIZATION PROGRAM (PEE)

PEE has the approximate duration of 18 months and consists of three phases. Figure 3 presents the general structure. **Phase 1** aims to provide the students with the fundamental knowledge on lifecycle design, covering topics from marketing analysis and research & technology, through product (airframe and aircraft systems) and manufacturing processes, up to aspects related to operation, maintenance, and end-of-life disposal.

In **Phase 2**, the students select their area of specialization and Master´s thesis topics related to one of the following tracks: a) materials and structures, b) aircraft systems and c) manufacturing. In the last phase, **Phase 3**, multidisciplinary teams, organized by students coming from the three tracks, take part in a Conceive-Design project.

Phase 3 of PEE is a Conceive-Design exercise applied to an aircraft. It is not limited to complying with a prescribed technical specification, but might involve market research, technical specification generation and business case construction. The conceive-design challenge is presented to the students in a broad sense, usually requiring them to generate value to the aircraft client (for instance, through competitive price and operational efficiency targets) and to the Embraer stakeholders (for instance, through profit margin and market share targets) by addressing a given market niche. The niche is chosen from one of the business areas of Embraer: Commercial, Executive or Defense. It should be stressed that the most important Phase 3 result is neither the aircraft characteristics nor its business case, but rather the learning in the technical multidisciplinary design integration and in the social-technical design process.

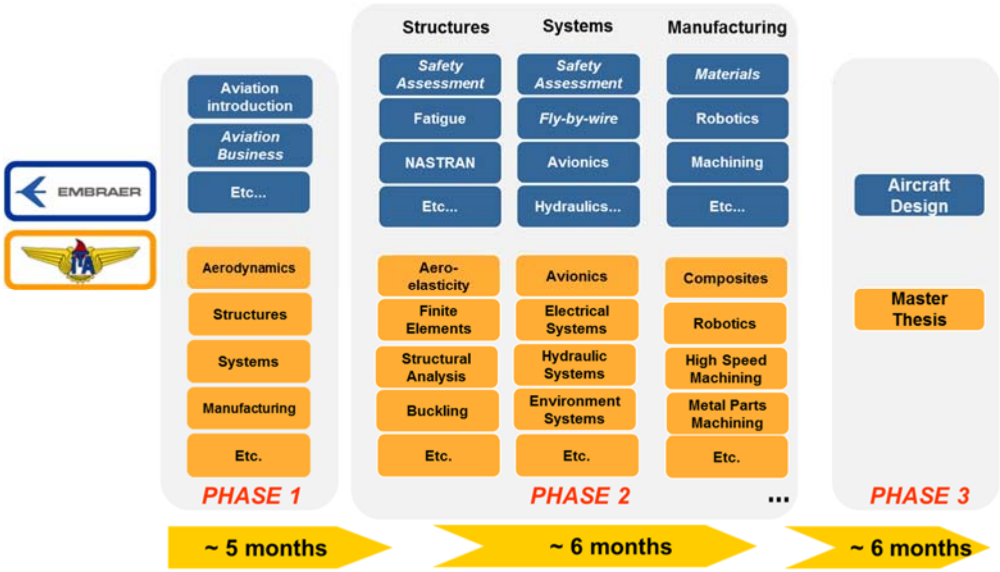

Figure 3. General structure of the Engineering Specialization Program (PEE)

The duration of Phase 3 is approximately 6 months. The student class is normally divided in two teams by the PEE management and each team is encouraged to present and defend, in a technical and business sense, a different solution to the challenge. This provides a healthy competition between the teams, although they still may share technical knowledge and information sources. After the teams have been defined, they become self organized and the teams have full autonomy to choose technical solution alternatives. Each entire team is co-localized to simulate the real engineering environment they would be facing in a real Embraer engineering project.

A group of integration and multidisciplinary mentors from several Embraer technology areas helps the PEE teams. Although there are regular weekly meetings involving all the students and mentors, they and other Embraer specialists are available all the time. Since 2012, some “Lean Product Development” concepts and methods were implemented, aiming in Phase 3 to help the students in the learning process and to be in accordance with Embraer’s new development practices. Some ideas taken into consideration are: a) developing towering technical competence, b) build in learning and continuous improvement, c) establish customer-driven value, d) front load the product development processes to explore alternative solutions, and e) extensive use of simple and visual communication tools for organizational learning.

Intermediate Phase 3 design results are presented to a team of Embraer technical specialists and managers, and the Final Presentation is done to an audience that includes Embraer high-level technical management.

RESULTS

In the context of this paper, it is important to take into consideration some aspects: the design on a new airplane may last 5-6 years, the aircraft manufacturer will have to support the airline for 20 years and the end of life has to be carefully considered in the front-end process. Since the scope is the education of future engineers through conceive-design projects, the following product development phases are used by PEE: Strategic planning of new products, planning, customer needs, product specification, conceptual design, preliminary design, detail design, manufacturing preparation, testing, product launching, customer support, and end of life. The big challenge in preparing future engineers to work effectively on the development of a new aircraft depends on the creation of an education environment that emulates these processes with an adequate level of fidelity for them to understand the “rules of the game”.

Obeya System

The first attempt of introducing the obeya system for the PEE design-conceive phase was based on the hypothesis that the team leaders (students) were in the same shoes of Takechi Uchiyamada: no experience in leading a complex development process such as the one they would face in the moment they were selected or, in PEE’s case, elected as the chief engineer. This hypothesis was clearly confirmed after the first class and the coordination of PEE stated the obeya system as the process of managing the Phase 3. One of the very first perceptive results were that the rooms got very different solutions in visualization and people organization, clearly attributed to the different leaders and formation of the teams. Other important result that may be kept analyzing the last six teams is that, qualitatively speaking, it seems that the developing time decreases. Even with the timeline being the same or slightly different, from class to class, the results improve in quality and depth of the engineering solutions presented by the students. In Figure 4 it is possible to see some examples of different results: (1) Integration Board; (2) mock-up of the landing gear bay; (3) mentors and students interacting with the visual knowledge; (4) systems integration mock-up.

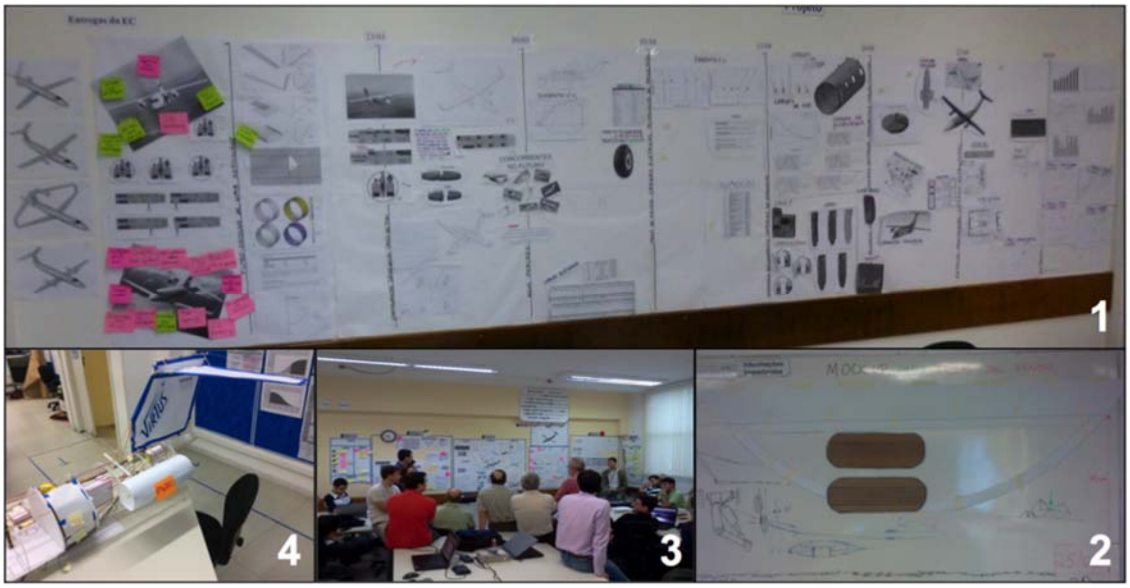

Figure 4: Obeya system examples

Mentors

Phase 3 mentors are senior technical specialists coming from different specific areas of aircraft design and project management, such as: aeronautics, structures, systems, manufacturing, maintenance, market intelligence, project planning, human factors, logistics, certification, etc. Most of them are “volunteers” from the Embraer’s workforce, but some are retired Embraer employees or external specialists. Figure 5 presents a group mentors. The number of mentors may vary during Phase 3 classes, but is usually around 20. The number of students varies from 20 to 30, per design team. This represents ratios student/mentor of 2 to 1, depending on the size of the class.

Figure 5. Group of mentors on phase 3 of PEE

The purpose of the mentors is to help the students choose and refine their technical and business solutions to the Phase 3 Conceive-Design challenge. This is typically done by indicating technical alternatives, information sources or methods and by critically questioning the student design decisions. It should be noted that the students keep the autonomy to choose their solutions; they are not bound to the mentors´ suggestions or preferences. This allows Phase 3 to be open to new ideas from a younger set of engineers, instead of just applying the

Embraer technical “state of the art” solutions as represented by the mentors´ experience. The students are required, nevertheless, to justify their choices. The mentors care that the students really understand their technical choices, and are not just defining them arbitrarily.

Since aircraft design can be considered as a big trade-off exercise among several disciplines and requirements, mentors from different areas might sometimes suggest conflicting solutions. This reflects the real social-technical environment that the students would be facing in a real engineering project. Although agreement between the mentors is usually reached, based on their own expertise and experience, there is an Integration Mentor who can be called in to intervene and suggest a technical solution, if needed.

Positive results have been observed via focus groups organized by the coordination of PEE six months and one year after graduation, with former students from PEE classes. Common expressions are: “*I did like the integration between us and the mentors*”, or “*most of the people helped us very much”.* Post-Morten meetings with mentors, to reflect on Phase 3 and to collect strengths and opportunities of improvement, are also in place. It has been observed by the coordination of the program the enthusiasm of mentors, who usually ask: “*When the next Phase 3 will take place? You can count on me*”.

FINAL COMMENTS AND SUGGESTIONS FOR FUTURE LEARNING

Out the observation of the last six classes of PEE, some important aspects could be observed. The first point refers to the conceive-design experience represented by Phase 3 of PEE, when young engineers learn from their mentors not only by spoken words or written documents, but also through active learning, via group discussions, debates and feedback from the mentors. While young engineers prepare charts of trade-off analyses and present their conclusions to the mentors, listening to their comments, they learn via externalization.

The preparation and execution of Preliminary Design Review presentation (PDR), shown to the mentors and the board of the company, to demonstrate that their projects are technically feasible, consist on conclusion of a truly integrated learning experience. In addition to the development of technical knowledge and systems skills, the young engineers also improve personal and interpersonal skills in the context of the company.

It is important to remark that the students and mentors are highly committed to their tasks in Phase 3, and their interaction has a very positive effect on the motivation and enthusiasm of both of them. The level of care developed between mentors (experienced employees) and students (young engineers) in the PEE program is a very important success factor that leads to social-technical integration as well as development of competences by the trainees.

The engineering workspace represented by the obeya system and its various parts, not only shows the knowledge acquired, but also guide the students to construct the rationale that support their decisions. Observed time reduction and improvement in technical quality of the projects presented by the students appear to be a consequence of the implementation of obeya system and increasing use of mock-ups and simulations during the conceive-design experience. The lean development system is vaster than the obeya and its full application takes time and constant energy. PEE succeeded in implementing the visual management and the use of mock-ups and will keep doing it, but there are other fronts to be addressed, to increase the results in the learning process.

A suggestion for future work is to design and implement an evaluation scheme to measure the impact of PEE program on the real work performed by the engineers after their graduation and hiring by the company. The idea is to collect data from alumni, their respective supervisors and peers to evaluate quality improvement, rework reduction and other measures of individual or collective performance, which could be attributed to the program.

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BIOGRAPHICAL INFORMATION

Paulo T. M. Lourencao, Dr. Sc. is the Technical Coordinator of the Engineering Specialization Program of Embraer. He has experience in the areas of Experimental Aerodynamics, Dynamics and Control of Aerospace Vehicles, and Advanced Training of Engineers. He is responsible for selecting and educating young engineers to become product development specialists for Embraer.

Fernando Rosa, M.Sc. is an internal Lean Consultant for Embraer specially devoted for the product development teams and processes. Besides his collaboration concerning continuous improvement topics among the current employees, he is also a mentor in the Engineering Specialization Program for lean product and process development concepts and paradigms.

Otto Resende is a product development engineer at the preliminary design group of Embraer. He has participated in the design and preliminary design of several Embraer aircraft in the area of aeronautical engineering. He has also participated as a Phase 3 aeronautics and integration mentor in several PEE classes.

Corresponding author

Dr. Paulo T. M Lourenção
Embraer S.A.
2170 Avenida Brigadeiro Faria Lima
S.J.Campos, São Paulo, Brazil, 12227-901
55-12-3927-8794
paulo.lourencao@embraer.com.br