AC 2008-1264: TEACHING CONCEPT GENERATION METHODOLOGIES IN PRODUCT DEVELOPMENT COURSES AND SENIOR DESIGN PROJECTS

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Teaching Concept Generation Methodologies in Product Development Courses and Senior Design Projects

Abstract

Concept generation is a very important activity in product development projects and in the solution of open ended design problems. Following a structured and systematic approach is of particular importance to make sure that the entire space of possible solutions has been explored. Undergraduate and graduate product development courses in which a project-based learning strategy is used and senior design projects provide an excellent opportunity to teach concept generation methodologies and to have the students apply what they have learned in a practical context. Without this support, students tend to spend very little time generating possible solution concepts and end this activity with only a few design alternatives that are typically dominated by the previous background and knowledge of the team members. In this regard, it is not uncommon for students to conceive and focus on a couple of solution concepts as soon as the requirements have been identified, quickly select one of them, and proceed to the detailed design stage of the chosen concept. The problem is that if an inherently weak concept has been selected, even flawless execution of all the remaining steps in the product development process result in a poor and uncompetitive end result. In this paper, the approach followed by the authors to teach concept generation in sophomore level and graduate level product development courses as well as in senior design projects is presented. Examples extracted from projects carried out by students are used to illustrate the different steps of the methodology employed and the output corresponding to each step. Finally, a brief assessment of the results obtained is given followed by suggestions for possible improvements.

Introduction

Great emphasis is being placed in undergraduate education to prepare the students that have the necessary knowledge, skills, attitudes, and values, required to be successful in the practice of the profession in a highly competitive and global economy. One of the key competencies needed by many companies is the ability to work effectively in multidisciplinary teams that are designing new products or manufacturing processes. Among other things, this requires students that have a very good understanding of the design process and, in particular, of how to perform each of the tasks involved in it.

A very effective approach to teach product design and development is to use a project based learning strategy in which students have to immediately apply the concepts, methodologies and tools presented in the course to a project that has the key elements found in an industrial setting but that meets the severe time constraints found in an academic environment. At the present time some Senior Design Project and Capstone-type senior-level courses are following that particular approach (see for example Dutson et al.\textsuperscript{1}, Catalano et al.\textsuperscript{2}, and Muci-Küchler and Weaver\textsuperscript{3}). In addition, some of the freshman, sophomore and/or junior level design courses that are being incorporated into the curricula (see for example Starkey et al.\textsuperscript{4}, Newman and Amir\textsuperscript{5}, Wood et al.\textsuperscript{6}, and Muci-Küchler et al.\textsuperscript{7}) are also using a project based learning strategy.
The concept development phase of the product development process (PDP) starts with the task of identifying the customer requirements and ends when a product concept has been selected by the development team. All the activities carried out during this phase are of crucial importance for the success of the development effort. Once the needs from the customers and all the relevant stakeholders have been identified and proper target specifications for the product have been set, the next step is to generate product concepts. Although this is the most creative activity of the entire PDP, it requires following a structured and systematic approach to ensure that the entire space of possible solution concepts has been carefully explored. Otherwise, there is a very high risk that the “best” product concept is not envisioned and later selected. If the concept selected is weak, nothing can be done in the remaining phases of the PDP to make it a success.

Without proper guidance and training, most students do not pay enough attention and do not devote enough time to the activities of the concept development phase. Typically they only identify a relatively small sub-set of the customer requirements, do not select metrics that clearly reflect the customer needs that were identified, and fail to select adequate ideal and marginally acceptable target values for those metrics. Then, they proceed to generate a small number of possible solutions concepts during a couple of brainstorming sessions and finally, after some debate among the team members, they select one product concept and proceed to the detail design phase of the PDP. The classic failure mode in these types of situations is ultimately to see a competitor unveil an inherently superior concept resulting in the classic “why didn’t we think of that” response.

Although there are many good textbooks that can be used for product design and development courses (like the ones by Ulrich and Eppingger, Ullman, Eggert, and Otto and Wood, to name a few), faculty members teaching those courses benefit from having access to additional information and case studies that can help them to implement a meaningful learning experience for the students. The authors have used for several years a project based learning strategy in a sophomore-level product development course, a senior capstone design course sequence, and a graduate-level course in product planning and development. Muci-Küchler and Weaver and Muci-Küchler et al. already documented in detail the relevant aspects related to the tasks of identifying customer needs and of setting functional requirements and target specifications. This paper focuses on the concept generation task. The process followed, a brief assessment of the results obtained, and suggestions for future improvement are discussed using examples taken from projects carried out by students.

**Description of the Courses Considered**

The approach to teach concept generation discussed in this paper has been used for several years in a sophomore-level product development course, a senior capstone design course sequence, and a graduate-level course in product planning and development. This section provides information about those courses as well as a partial list of the products that have been considered in each one.

The sophomore-level product development course is offered every semester at South Dakota School of Mines and Technology (SDSM&T). It is a one-semester, four-credit course that is mandatory for all the students majoring in Mechanical Engineering. The course description provided in the undergraduate catalog is as follows:
“The course presents in a detailed fashion useful tools and structured methodologies that support the product development practice. Also, it attempts to develop in the students the necessary skills and attitudes required for successful product development in today’s competitive marketplace. The cornerstone is a semester-long project in which small teams of students plan, conceive, design, and prototype a simple physical product. Each student brings his/her own background to the team effort, and must learn to synthesize his/her perspective with those of the other students in the group to develop a marketable product. An introduction to manufacturing aspects that must be taken into consideration during product development is provided in the context of a mini-project.”

Typically each team proposes possible products for the semester-long project and selects one with the help of the instructor. However, one semester the instructor required all the teams to work on a product the he selected and asked them to adopt the framework of companies that were competing with each other to capture the target market. The main disadvantage of that approach is that the product chosen may not be appealing to some of the students and this, in turn, may have a negative impact in their level of motivation and performance. On the positive side, a common project allows each team to compare how well it did relative the other teams working under similar constraints.

The products considered in the sophomore-level course have included a flying toy, a vehicle undercarriage washer, a product for removing snow and ice from the windows of a car, a hand held aluminum can crusher, a wine bottle opener, and a concrete flatwork attachment.

The graduate-level product development course is a one-term, three-credit, mandatory course in the Master in Product Development Program (MPD) at the University of Detroit Mercy (UDM). The main goal of the course is to provide a fundamental understanding of all the key steps that are necessary in end-to-end product development and to gain the knowledge of and the ability to use various tools during each phase of the PDP. Typically the teams have nearly full latitude as to the actual product they will develop and the projects performed by the student teams have included an improved bicycle storage system, a bicycle carrier for a motor vehicle, a tool for cleaning gutters from the ground level, a vehicle trunk/cargo area grocery organizer, an improved aftermarket in-car entertainment system, an automatic fish feeder, and a doggie washer.

Capstone senior design course sequences spanning two consecutive semesters/terms are offered to Mechanical Engineering students at both SDSM&T and UDM. The projects that the authors have supervised have encompassed a wide variety of products, most of them falling into one of the following categories:

- Projects sponsored by a company or a local entrepreneur.
- Design competitions.
- Products tied to a funded research project.

An example of a project sponsored by a company was the development of a hard tonneau cover for the Ford Thunderbird that was carried out at UDM with the support of Ford Motor Co. An
example of a project sponsored by a local entrepreneur was the development of an advanced football training system that was carried out at SDSM&T.

In the case of the design competitions, the Center of Excellence for Advanced Manufacturing and Production (CAMP) of SDSM&T supports each year senior design teams that participate, among others, in the following events: Society of Automotive Engineers (SAE) Mini Baja West, Formula SAE, SAE Aero Design, SAE Zero Emission Snowmobile Challenge, American Society of Mechanical Engineers (ASME) Human Powered Vehicle, and the International Aerial Robotic Competition (IARC). One of the authors is the main advisor of several of those teams.

As examples of products tied to a research project, currently at SDSM&T one senior design team is working in the development of a lower extremity protective armor for US ground troops and another team is developing a device to measure the momentum imparted to a structure by a blast. Also, at the present time one senior design team is working on mobile robotic architectures for military applications at UDM.

**Overview of the Product Development Process Used**

The first aspect that needs to be considered while teaching product design and development using a project based learning strategy is to define the process that the students are expected to follow as well as the different tasks that need to be completed in each step. In this regard, the anticipated level of complexity of the products that will be selected for the projects is a very important factor that needs to be taken into account. In product development courses that last one semester, only relatively simple products can be considered. However, for senior design project or capstone-type course sequences lasting two semesters, the products selected can have a higher level of complexity. Regardless of the products that are eventually chosen, the PDP used needs to expose the students to all the key activities corresponding to the conceptual design phase. If the products have a relatively high level of complexity, the process followed needs to include activities in which the basic principles of systems architecting and systems engineering are applied.

The authors typically use as a framework the PDP for products of low to moderate complexity proposed by Ulrich and Eppinger that is shown in Figure 1. The mission statement is used as the starting point for the development effort and the phases and activities covered depend on the duration and level of the course. For courses lasting one semester, the time constrain only allows to perform most of the activities of the concept development phase presented in Figure 2 and to manufacture and test a comprehensive proof-of-concept physical prototype. For senior design projects, activities related to the system-level design phase are included if warranted by the product under consideration, the detail design is performed, and a product prototype (i.e., an alpha prototype) is built and tested.

The relevant details of the approach used by the authors for the tasks of identifying customer needs and establishing target specifications are given in Muci-Küchler and Weaver and Muci-Küchler et al., respectively. As can be seen in those references, the outcomes of the activities performed for those tasks include the key elements of the “House of Quality” that is employed by many companies as part of their “Quality Function Deployment” (QFD) process. In what
follows, only the concept generation task will be considered and some of the steps of the methodology used will be illustrated using examples taken from students projects.

Figure 1. Phases of the generic PDP proposed by Ulrich and Eppinger

Background Information about the Case Study

Before proceeding, it is important to give some background information about the project that will be used as a case study in this paper. The project was performed by students taking a one-semester sophomore-level product development course. The 73 students enrolled in the class were divided into eight teams: four teams of ten students each, two teams of nine students each, one team of eight students, and one team of seven students. Although the author’s experience has been that for this type of courses having teams with more than five students is not a good option, with only one instructor and one teaching assistant assigned to the section it was not possible to work with and manage more than eight teams. To “kick-off” the project, the students were given the mission statement presented in Table 1 during the first week of classes. Also, the teams were told that they were going to work as if they were “companies competing against each other for the product market” and, consequently, should not share information about the project. Finally, the role of the instructor in the context of the project was clarified. The instructor was going to
act only as a “product development consultant” that had “no specific knowledge” about the product that the teams had to develop.

Table 2 presents a comprehensive list of customer needs for the “GI Joe® Super Flyer Project” that was compiled from progress reports provided by the teams. The next to last column in the table gives the importance rating assigned to each need using a 1 to 5 scale in which the higher the number the more important the need. The last column in the table gives the classification of each need according to the “Kano Model” of customer satisfaction. The list of customer needs is a key input and provides the context for the concept generation task. If all the relevant customer requirements are not identified and understood, the concepts that are generated may not be what the customers are looking for and the rest of the development effort will only result in a product that is not competitive.

At this point it is important to note that while two teams did an excellent job in the tasks of identifying customer needs and setting target specifications for the product, some teams failed to perform at an adequate level. The graph presented in Figure 3 shows the number of needs and the number of metrics reported by each team. The highest number of needs identified by a team was 68 (Team 4) and the lowest was 27 (Team 1), which correspond to a ratio of about 2.5 to 1. As will be seen later, the product concept selected by the team that identified the lowest number of needs was weak and less attractive when compared to the concepts chosen by the other teams.

This particular project was selected to illustrate the concept generation methodology because it corresponds to one of the very few instances in which the authors had so many student teams developing the same product and under the same constraints. When only one team is working on a project, it is relatively difficult to determine how effective that team was while performing each task of the PDP. The assessments made tend to be subjective since they are mostly based on the instructor’s perception of how well the team did. Also, it must be kept in mind that, as is the case in other courses, not all students have the same level of interest to engage in the learning process.

Approach Used to Teach Concept Generation

When teaching the concept generation task, the authors typically present the process proposed by Ulrich and Eppinger\(^8\) which involves the following five steps:

1. Clarify the problem.
2. Search externally.
3. Search internally.
4. Explore systematically.
5. Reflect on the results and the process.

Minor modifications and adjustments are made regarding the activities associated with some of those steps. Instructionally, PowerPoint presentations are used during the lectures to cover each topic and case studies and/or short in-class exercises are employed to illustrate how the ideas presented can be used in a practical context. Then, the teams are asked to apply what they have learned in class to their product development project. To make sure that feedback can be given to
the students in a timely fashion, progress reports are requested at key milestones and/or meetings are held between the instructor and each team during out-of-class time.

In the next sections, each of the steps of the concept generation methodology mentioned above is considered in turn and some final comments are provided.

Table 1. Mission Statement for the “GI Joe® Super Flyer Project”

<table>
<thead>
<tr>
<th>Product Description</th>
<th>Safe, resistant, and attractive flying toy capable to transport a crew of at least two GI Joe toy soldiers whose individual heights do not exceed approximately four inches.</th>
</tr>
</thead>
</table>
| **Key Business Goals**                                                              | **Short Term:**  
|                                                                                      | • Comprehensive physical prototype ready by “MM/DD/YYYY.”  
|                                                                                      | • Make the most effective and efficient use of the material and facilities available on campus to build the comprehensive physical prototype.  
|                                                                                      | • Keep any out of pocket expenses to a minimum.  
|                                                                                      | • The selling price of the product should be at the most 80 dollars.  
| **Long Term (given only as an example – don’t apply to the course):**                | • Introduce the product to the US market in “MM/YYYY.”  
|                                                                                      | • Start exporting the product to other countries in “MM/YYYY.”  
|                                                                                      | • Capture 15% of the US market for flying toys by the end of “YYYY.”  
|                                                                                      | • Have a profit margin of at least 25% of the product cost. |
| **Primary Market**                                                                   | Middle class boys who are 7 to 12 years old. |
| **Secondary Markets**                                                                | Upper class boys who are 7 to 12 years old. |
| **Assumptions**                                                                      | • The toy is safe.  
|                                                                                      | • The toy gets the attention of the children in the target market.  
|                                                                                      | • The toy can be used with GI Joe toy soldiers whose individual heights do not exceed approximately four inches.  
|                                                                                      | • The toy can fly both in open and in closed areas, indoors or outdoors.  
|                                                                                      | • The toy is strong enough to resist impacts due to landing without being damaged.  
|                                                                                      | • The toy can transport during its flight a crew of two or more GI Joe toy soldiers. |
| **Constraints**                                                                      | • If some assembly is needed, it must be simple enough so that a single child can assemble the product without any help.  
|                                                                                      | • A single child must be capable of launching the toy.  
|                                                                                      | • Once the toy starts to fly, it must not be controlled by any external means.  
|                                                                                      | • Besides any energy provided by the child, the only source of energy that the toy can have must come from standard batteries. |
| **Stakeholders**                                                                     | • Children in the target market.  
|                                                                                      | • Parents of the children in the target market.  
|                                                                                      | • Toy stores.  
|                                                                                      | • Department stores.  
|                                                                                      | • Distribution Centers.  
|                                                                                      | • Customer Service Department.  
|                                                                                      | • Sales Department.  
|                                                                                      | • Legal Department.  
<p>|                                                                                      | • Production. |</p>
<table>
<thead>
<tr>
<th>Primary Need</th>
<th>#</th>
<th>Secondary Need</th>
<th>Imp.</th>
<th>Kano Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>The SF has good flight characteristics.</td>
<td>1</td>
<td>The SF flies indoors.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>The SF flies outdoors.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>The SF can perform stunts.</td>
<td>4</td>
<td>Exciting</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>The SF is easy to launch (a single child).</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>The SF flies fast.</td>
<td>3</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>The SF flies an appropriate amount of time.</td>
<td>4</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>The SF flies an appropriate distance.</td>
<td>4</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>The SF can land on a solid or liquid surface.</td>
<td>2</td>
<td>Exciting</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>The SF allows the user to control flight height.</td>
<td>3</td>
<td>Exciting</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>The SF allows the user to control flight time.</td>
<td>3</td>
<td>Exciting</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>The SF allows the user to control flight distance.</td>
<td>4</td>
<td>Exciting</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>The SF allows the user to control flight direction.</td>
<td>2</td>
<td>Exciting</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>The SF lands near its launch point.</td>
<td>4</td>
<td>Performance</td>
</tr>
<tr>
<td>The SF is attractive.</td>
<td>14</td>
<td>The SF has an attractive color scheme.</td>
<td>4</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>The SF has an attractive shape.</td>
<td>4</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>The SF has an attractive size.</td>
<td>5</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>The SF can be customized by the user.</td>
<td>1</td>
<td>Exciting</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>The SF has symmetric decoration.</td>
<td>2</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>The SF can be painted.</td>
<td>2</td>
<td>Exciting</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>The SF looks realistic.</td>
<td>4</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>The SF looks futuristic.</td>
<td>3</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>The SF is educational.</td>
<td>2</td>
<td>Exciting</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>The SF has attractive packaging.</td>
<td>4</td>
<td>Performance</td>
</tr>
<tr>
<td>The SF is durable.</td>
<td>24</td>
<td>The SF does not break upon landing.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>The SF does not break during launch.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>The SF has a warranty.</td>
<td>5</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>The SF does not have parts that break off easily.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>The SF is easily maintained.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>The SF is made from durable material.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td>The SF is safe and meets Government Regulations.</td>
<td>30</td>
<td>The SF is free of parts that could pinch a child.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>The SF is nontoxic.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>The SF is not corrosive.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>The SF is not flammable.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>The SF is not explosive.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>The SF is not radioactive.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>The SF contains no lead paint.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>The SF has no electrical, mechanical or thermal hazards.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>The SF has no sharp edges.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>The SF contains no parts for a child to choke on.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>The SF operates at a reasonable noise level.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>41</td>
<td>The SF has slow descent.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>The SF does not damage the walls.</td>
<td>5</td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>The SF has controlled flight.</td>
<td>5</td>
<td>Basic</td>
</tr>
</tbody>
</table>
The SF is realistic. 4 Performance
The SF is interactive. 4 Performance
The SF is imaginative. 4 Performance
The SF has moving parts. 4 Performance
The SF has detachable parts. 4 Performance
The SF has interchangeable parts. 4 Exciting
The SF has a landing mechanism. 2 Exciting
The SF has storage area(s). 4 Performance
The SF glows in the dark. 2 Exciting
The SF is capable of land as well as air travel. 3 Exciting
The SF has radar to detect enemies. 2 Exciting
The SF throws smoke during takeoff. 1 Exciting
The SF ejects the GI Joes® when it loses control. 3 Exciting
The SF holds the child’s interest. 5 Basic
The SF is transformable. 2 Exciting
The SF has lights. 4 Performance
The SF has decals. 4 Performance
The SF has sounds. 4 Performance
The SF is remote controlled. 3 Exciting
The SF has guns/missiles. 4 Performance
The SF is easily assembled. 5 Basic
The SF is compact/easily transported. 4 Performance
The SF has a small number of parts. 3 Performance
The SF is easy to use. 5 Basic
The SF needs no batteries. 2 Performance
The SF is lightweight. 3 Performance
The SF is economically priced. 4 Basic
The SF can use standard batteries. 5 Basic
The SF is capable of carrying two GI Joes®. 5 Basic
The SF flies independently once launched. 5 Basic
The SF is appropriate for 7-12 year olds. 5 Basic

Step 1: Clarify the Problem

The goal of this step is to decompose the design problem into simpler sub-problems and to select the critical sub-problems that the team will address first. To start this step, the teams are asked to carefully review the mission statement for the project, the list of customer needs, and the target specifications for the product. These are the “upstream influences” that will drive the concept generation as well as the concept selection tasks of the PDP. Thus, it is crucial that each team member has a very good understanding of what the product has to do.

The best approach to decompose the design problem into sub-problems depends on the type of product being developed. Although different alternatives can be conceived and used to do the decomposition, three approaches that are frequently employed are a functional decomposition, decomposition by key customer needs, and decomposition by sequence of user actions. The first
is very useful in the case of technical products. The second can be conveniently applied when the physical form of the product, and not its working principles, is the primary concern. The third is useful when considering products with very simple technical functions that involve a lot of user interaction. As can be expected, there are products in which more than one of the options stated above can be employed.

![Number of Needs and Metrics Identified by the Teams](image)

Figure 3. Comparison of the number of needs and metrics identified by the eight teams

Since in the courses that the authors teach the products selected for the project always have some technical aspects, the teams are asked to perform a functional decomposition first. Then, they are asked to decide if one or both of the other two approaches presented in class (i.e., decomposition by key customer needs and decomposition by sequence of user actions) can be a good alternative for the product that is being developed. If that is the case, the team is asked to use the additional decomposition strategy or strategies to identify sub-problems.

Once the decomposition using all the applicable options has been completed, the teams are asked to compile in a single list all the different sub-problems that were identified. In most cases, the number of items that are present in the list is relatively large. Thus, it becomes impractical for the team members to focus on all the sub-problems at the same time. Under these circumstances, the students are asked to review the list and to carefully choose the critical sub-problems that will be addressed first. The students are told that they should avoid selecting more than five or six critical sub-problems. Also, generic guidelines are provided to the students to help them decide which sub-problems could be selected as the critical ones. They are told that sub-problems that meet the following criteria could be critical sub-problems:

- Sub-problems that have a strong impact on the overall size, shape or weight of the product.
- Sub-problems that have a strong impact on the overall performance of the product.
- Sub-problems whose solution will severely constrain the space of possible design alternatives for other sub-problems.
- Sub-problems that present a substantial technical challenge or that may require an innovative solution.
- Sub-problems related to the most important customer needs.

This is consistent with Maier and Rechtin’s system architecting heuristic which suggests “do the hard parts first.”

Our experience has shown that students usually require a lot of guidance during this step of the process. In particular, they struggle when trying to do the functional decomposition for their product unless they had the opportunity to practice that decomposition strategy in class. For that purpose, we usually do an exercise during a class session that involves an existing product, such as a coffee maker or a lawnmower, with which most students are familiar. To begin the exercise, we show a picture of the product to the students and ask them to identify the material, energy and signal inputs and outputs and we write their answers on the board. Then we use that information to draw a “black-box” diagram like the one shown in Figure 4. Next, we request the students to mention, in solution neutral terms (another problematic concept to convey), the different functions that they think the product has to do in order to convert the inputs into the outputs and we compile a list with their answers on the board. Then, we request the participation of the students to prepare a functional decomposition diagram like the one presented in Figure 5. Finally, we show a functional decomposition diagram for the same product that we prepared before doing the exercise and we start a discussion regarding the similarities and differences between the two and use that opportunity to stress the fact that there is no “unique” or “correct” answer – and that the ultimate measure of “correctness” is how useful the decomposition is in understanding the problem and facilitating systematic exploration of the design space.

Another point that the students often need help with is the decomposition by key customer needs. They are told to review the list of customer needs and extract the most important ones as the sub-problems. Typically only needs with an importance rating of 5 (and sometimes also some with an importance rating of 4) are considered.
In the case of the “GI Joe® Super Flyer Project,” the product under consideration was such that a functional decomposition and a decomposition by key customer needs were worth pursuing. As an exercise, the teams were also asked to perform a decomposition by sequence of user actions although that particular approach was not going to be a very useful option in this case (though as a final sanity check, it never hurts to explore this decomposition for a given concept to make sure there are no obvious deficiencies or oversights relating to how the product will be used).

Although some teams apparently prepared functional decomposition diagrams by trying to closely imitate the example presented in the textbook, others tried to apply what they learned during the lectures and the in-class exercise in the context of the project. Figure 6 shows the diagram prepared by one of those teams.

Regarding the critical sub-problems chosen by the teams working on the “GI Joe® Super Flyer Project,” three teams selected six, three teams selected five, and two teams selected four. Table 3 provides a summary of the different critical sub-problems that the teams decided to consider. It is interesting to note that only the three critical sub-problems highlighted in the table were common to all the teams. Also, one team selected “implementation of ejection seating” as a critical sub-problem which implies that the toy must have that particular feature and that is too restrictive for the product under consideration. It is worth noting that clearly certain needs (like retaining the
action figures) are critically important (likely importance level 5), but the authors feel that some such needs do not meet the aforementioned criteria for the critical sub-problems.

![Functional decomposition diagram prepared by Team 2](image)

**Figure 6. Functional decomposition diagram prepared by Team 2**

**Table 3. Critical sub-problems selected by the teams working on the “GI Joe® Super Flyer Project”**

<table>
<thead>
<tr>
<th>Critical Sub-Problem</th>
<th># of Teams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch / take-off</td>
<td>8</td>
</tr>
<tr>
<td>Land safely / landing</td>
<td>8</td>
</tr>
<tr>
<td>Maintain flight / create lift</td>
<td>8</td>
</tr>
<tr>
<td>Aerial maneuvers / perform stunts</td>
<td>4</td>
</tr>
<tr>
<td>Has an attractive shape</td>
<td>3</td>
</tr>
<tr>
<td>Flight path/pattern</td>
<td>1</td>
</tr>
<tr>
<td>User selectable flight path</td>
<td>1</td>
</tr>
<tr>
<td>Simulate crash (suddenly stop flight)</td>
<td>1</td>
</tr>
<tr>
<td>Contain GI Joe® figures</td>
<td>1</td>
</tr>
<tr>
<td>Retain GI Joe® figures</td>
<td>1</td>
</tr>
<tr>
<td>Carry GI Joe® figures and cargo</td>
<td>1</td>
</tr>
<tr>
<td>Implementation of ejection seating</td>
<td>1</td>
</tr>
<tr>
<td>Has movable parts</td>
<td>1</td>
</tr>
<tr>
<td>Flight design</td>
<td>1</td>
</tr>
<tr>
<td>Safety</td>
<td>1</td>
</tr>
</tbody>
</table>
Having identified the critical sub-problems, the next step is to begin the search, first externally then internally, for possible solutions to these problems.

**Step 2: Search Externally**

The goal of this step is to identify existing solutions or possible solution concepts for each of the critical sub-problems from sources external to the team. The students are requested to search patents, examine existing products (particularly the ones that team considered during the competitive benchmarking), and review the literature. Also, they are encouraged to talk with experts (for example, faculty members whose expertise is related to one of the sub-problems under consideration) and with the lead users that they were able to identify while conducting interviews to find the customer requirements.

We suggest to the teams that they assign specific search tasks among their members and that each student documents his/her findings using formats like the ones shown in Table 4 and Table 5. In this fashion, each team member can conveniently share the information that he/she found with the rest of the team.

While lecturing about this topic, we emphasize to the students that the importance of searching patents is twofold. First, they are an excellent source of ideas. Second, they cannot use a solution concept that has been patented unless they reach an agreement that allows them to do so.

In the case of competition projects such as SAE Mini Baja, we suggest that the students explore the solution concepts that other teams have successfully used in the past. Also, if other teams at the same institution have worked in the same project during previous years, we ask the team to review the documentation left by those teams, examine in detail the products that they built, and consider any suggestions for improvements that those teams made after the competition.

**Step 3: Search Internally**

In the internal search the team members use all the information that they have gathered together with their own creativity to propose solution concepts for each one of the critical sub-problems. The goal is to come up with as many solution concepts as possible without making judgments about the feasibility of the ideas that are being generated.

To start this step, we ask that the students work individually and try to generate as many solution concepts as possible for each of the critical sub-problems. We suggest that for each sub-problem the team members set a minimum number of concepts that each student is expected to conceive. Once this activity is completed, the team members are asked to work together reviewing all the ideas generated by each student and trying to propose as many additional solution concepts as they can. It has been our experience that this combination of individual and team work tends to produce the best results.

During the lectures we cover the basic aspects of TRIZ (Theory of Inventive Problem Solving) and explain to the students that this tool could be useful to generate possible solution concepts.
We typically request that the teams try to generate at least one solution concept based on this approach. In general, the feedback that we have received from the students is that for them going over the inventive principles has been more useful to generate ideas than using the “contradiction table.”

Once the team has compiled potential concepts addressing each of the various critical sub-problems, it is time to explore how these various solution fragments might be combined into a comprehensive concept.

### Table 4. Format to document the results of the patent search for a critical sub-problem

<table>
<thead>
<tr>
<th>Patent Number</th>
<th>Relevant Figure(s)</th>
<th>Useful Solution Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>6471158</td>
<td><img src="Figure_taken_from_the_patent.png" alt="Figure taken from the patent" /></td>
<td>This patent relates to vertical takeoff and landing of an aircraft.</td>
</tr>
</tbody>
</table>

### Table 5. Format to document possible solutions for a critical sub-problem obtained from the analysis of existing products

<table>
<thead>
<tr>
<th>Product</th>
<th>Relevant Figure(s)</th>
<th>Useful Solution Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATK Helicopter (Lanard Toys, Inc)</td>
<td><img src="http://www.coojoes.com" alt="ATK Helicopter" /></td>
<td>Transparent cockpit and easy placement of GI Joes.</td>
</tr>
</tbody>
</table>

**Step 4: Explore Systematically**

The two main tools that we use for this step are the concept classification tree and the concept combination table. Information about the use of these tools can be found in several references (see for example Ulrich and Eppinger⁸).

First the teams are asked to prepare a concept classification tree for each critical sub-problem using the results of the previous step. Then the students are requested to examine those concept classification trees and “prune” the solution concepts that are clearly unfeasible or that are poor
alternatives when compared with the others. Next, all the concepts that were not removed are input into the concept combination table.

Once the concept combination table has been prepared, it is used by the team members working first individually and then as a group to generate as many product concepts as possible. Figure 7 presents some the product concepts that were envisioned by one of the teams working on the “GI Joe® Super Flyer Project.” As can be seen from the figure, this team did a good job at exploring many alternatives for the product being developed. It is very interesting to compare the concepts that this team generated against the final concepts selected by the other teams which are shown in Figure 8. It is evident that, with the exception of the shape and accessories, the product ideas found in Figure 8 are either similar or variant designs of the concepts presented in Figure 7.

One point that catches the attention while looking at Figure 8 is the different concepts that were eventually selected by the teams. A similar situation was found in a senior design project course sequence in which all the teams were working in the development of the same product as if they were companies competing with each other (see Muci-Küchler and Weaver3).

**Step 5: Reflect on the Results and the Process**

The purpose of this activity is to have the teams review all the previous steps of the methodology and their corresponding results to identify any deficiencies and weaknesses. The team should not proceed to the next task of the PDP unless all the team members are confident that the space of possible solution concepts has been carefully explored and that a good number of competitive and feasible concepts have been generated. Often, such reflection produces a feedback loop which really suggests another pass at the design process. We typically don’t have the luxury of time to support such iterative design in the classroom. Interestingly enough, industry also claims to lack such time yet always seems to find time to fix things or do them over when perhaps a little more time and attention during the concept development phase likely would produce a final and successful product both more quickly and with less overall manpower.

**Final Comments**

As was mentioned before, in our product development courses we cover all the key activities of the concept development phase of the PDP. In future papers we will focus on the activities that follow the concept generation task. In one-semester courses, we end the project by having the students build basic prototypes of their product. We ask the teams to prepare virtual prototypes such as CAD models. As can be expected, the degree of sophistication of these virtual prototypes varies according to the level of the course. Also, we require the teams to build and test simple proof-of-concept physical prototypes like the ones presented in Figure 9.
Figure 7. Some of the concepts generated by Team 2
Figure 8. Final concepts selected by the teams working on the “GI Joe® Super Flyer Project”
Figure 9. Physical prototypes prepared by teams working on the “GI Joe® Super Flyer Project”
Assessment of the Proposed Approach

The effectiveness of the approach presented in this paper depends on the level of interest and commitment that the students have to perform the activities involved in each step of the concept generation methodology. There are teams whose goal is to do the minimum necessary to pass the course and, as such, take short cuts and do not devote enough time and effort to the project. This becomes evident while reading their progress reports, during meetings between the instructor and the team, and when their product prototypes are built and tested. Some of those teams even select a product concept shortly after receiving the mission statement and basically spend the rest of the time trying to force the results of each activity of the PDP to try to justify their selection. On the other hand, there are teams that really try to learn the methodology and to apply it in the context of the project in a very professional manner. Although they may make mistakes and end up with a product concept that has weaknesses, they take valuable lessons from the course and are better prepared for the practice of the profession. The old adage that you get out of a course what you put into it could not be better exemplified than it is in a project-based course.

For example, a careful look at Figure 3, Figure 8 and Figure 9, reveals a very marked contrast between the performance of Team 1 and Team 2. It is interesting to note that at least one of the members of Team 2 later joined the SAE Aero Team at the university where he was studying and helped to develop a very good aircraft design for that competition. Another student that was part of that team is currently working at Cessna.

One problem in implementing the methodology is the amount of time that the instructor needs to invest in providing guidance to all the teams, reviewing their progress reports, and giving feedback on a timely fashion. In the student opinion surveys (course evaluations) conducted at the end of the semester the students typically mention that the amount of time required by the project is too much. On the positive side, they comment that they feel well prepared to do and document the activities that need to be performed during the concept generation task.

We have found it critical to have numerous scored deliverables throughout the project to make sure students understand whether or not the process they are following and their documentation thereof is as expected. However, since the instructors tend to serve as process coaches and thus try to avoid offering technical opinions and suggestions related to the project that depart from process advice, teams which are apparently struggling early are typically seen to have increasing difficulties later due to the obvious snowball effect of shoddy early work failing to provide sufficient inputs to the later development activities. We do not see any obvious solutions to this beyond regular and rigorous reporting by the students with prompt instructor feedback (but again not technical suggestions related to the project).

Conclusions

The approach followed by the authors to teach concept generation using a project based learning strategy was presented. Although there are many good product development textbooks that give detailed information about the different activities of the PDP, teaching the subject in an academic setting has its very unique challenges. Although both the instructor and students feel that they need to devote too much time to the course when a project is performed, we feel that it could be
a mistake to remove it because the goal of preparing the students to meet the expectations of their prospective employers may not be fully achieved.

In general the most difficult steps for the students are decomposing the design problem into sub-problems, selecting the critical sub-problems, and performing the internal search. Simple in-class exercises help students to understand the ideas presented during the lectures and also serve as a “stepping stone” to transition from the theory to the practical application in the context of the project.

It is of particular importance to take every opportunity to remind the students that it is crucial to follow a structured approach and to explore all the space of possible solution concepts to make sure that a very competitive product results at the end of the development effort.

Among the possible improvements to the approach that was presented, the use of in-class exercises aimed at improving the creativity of the students could be very beneficial while conducting the internal search.

We have had success at academic levels ranging from sophomores to first-year graduate students. Of course, the complexity of the mission (or more accurately the anticipated complexity of a good concept) is chosen accordingly.

Acknowledgments

The authors would like to acknowledge all the student teams that carried out the projects featured in this paper. The examples presented in this document were compiled or extracted from written reports or PowerPoint presentations prepared by those teams. In particular, the first author wants to acknowledge all the students that participated in the “GI Joe® Super Flyer” design project as part of one of the offerings of the sophomore-level product development course that he taught at SDSM&T.

References


