2006-1301: NEW ENGINEERING DESIGN CONCEPTS FOR SUSTAINABLE PRODUCTS

Serdar Tumkor, Istanbul Technical University

Dr. Serdar Tumkor is an Assistant Professor of Mechanical Engineering at Istanbul Technical University, Istanbul, Turkey. He has been a full-time faculty member since 1996. Dr. Tumkor received his PhD in Mechanical Engineering from Istanbul Technical University in 1994. His teaching interests are Machine Design, Engineering Design, and Computer-Aided Technical Drawing. His research interests include Ecological Manufacturing, Design Methodology, Design for Disassembly, End of Life Strategies, Automated Disassembly, Electronic Packaging, PCB Soldering, computer integrated design, process planning and manufacturing, gear and continuously variable transmission manufacturing, design for optimum cost, online design catalogs, and web-based collaboration.

Karl Haapala, Michigan Technological University

Karl R. Haapala is an NSF IGERT Doctoral Trainee and Graduate Scholar in the Sustainable Futures Institute at Michigan Technological University. He is currently pursuing a Ph.D. in Mechanical Engineering – Engineering Mechanics focusing on predictive manufacturing process models for improving product environmental performance. He received his B.S. (2001) and M.S. (2003) in Mechanical Engineering from Michigan Technological University.

Vishesh Kumar, Michigan Technological University

Vishesh Kumar is a Henes Graduate Fellow at Michigan Technological University and is pursuing his Ph.D. in the Department of Mechanical Engineering - Engineering Mechanics since Fall 2002. Mr. Kumar received his B.Tech. Degree (Mechanical Engineering) from IIT Kanpur in 2000. Prior to coming to Michigan Tech, he worked as a research engineer in the R&D division of an Indian automotive manufacturer (Maruti Udyog Ltd.). Mr. Kumar's research is focused on economic sustainability of automotive recycling infrastructure and value recovery of various products at the end-of-use stage of the product life-cycle. He has published seven papers in various journal and conference proceedings in the areas of environmental sustainability. He is a member of SME, ASME, SAE and TMS.

John Sutherland, Michigan Technological University

Dr. John W. Sutherland is the Henes Chair Professor in the Department of Mechanical Engineering – Engineering Mechanics and Co-Director of the Sustainable Futures Institute at Michigan Technological University. He received his Ph.D. degree from the University of Illinois at Urbana-Champaign in 1987. Prior to joining the faculty at Michigan Tech in 1991, he served as Vice President of a small manufacturing consulting company. His research and teaching interests are focused on design and manufacturing for sustainability. Dr. Sutherland is the recipient of numerous awards for his education and research activities.

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Abstract

More restrictive environmental legislation as well as increasing environment-related costs have lead to the consideration of new design aspects during product development. Design teams must consider the effects of the entire life-cycle at the product design stage. Engineering design education plays a major role in defining the way to achieve sustainable futures by providing engineering students with the tools necessary to create innovative products with acceptable life cycle costs and environmental impact during and after the product use. To address this need projects are assigned to students in senior-level course MAK422E Engineering Design at Istanbul Technical University Mechanical Engineering Dept. In this course, the projects are prepared as teams of 7 to 8 students with an objective to redesign a product to reduce its environmental impact, while maintaining functionality and costs. To accomplish this goal, several DfE (Design for Environment) approaches (e.g., design for disassembly, design for reuse/remanufacturing, design for recycling, design for energy efficiency, design for minimum material usage, and design for minimum hazardous material) are applied. As a result of this effort several useful and new design concepts have been derived for different household appliances.

In this paper, new aspects in the design process from definition to detail is presented, which is applied by the students for more environmentally-friendly products.

1. Introduction

A variety of design courses exist in engineering education. The primary objective of such courses is to teach engineering design fundamentals utilizing repeatable design techniques. The most popular approach to teach undergraduate engineering design is through a structured, problem solving method that students use to tackle open-ended design problems[1-4]. The focus has been shifting toward providing tools and techniques to new designers that allow them to evaluate the cost, manufacturing, usability, and environmental consequences of their designs. Some senior-level design courses address these issues through the use of Design for X concepts and techniques. Design for Environment (DfE), or Ecodesign, assists product developers in reducing the life cycle environmental impact of a product by enhancing its design. DfE includes reducing resource consumption, in terms of material and energy, and pollution prevention[5-7]. Similarly, Design for Dissassembly (DfD) and Design for Recycling (DfR) allow the product designer to have a substantial, positive impact on the environmental aspects of a product's life cycle.

Life Cycle Assesment (LCA) tools also assists the designer in reducing product environmental impacts. The ultimate goal of LCA is to minimize the environmental burden arising from the material acquisition, manufacture, use, and postuse (e.g., reuse, remanufacture, recycle). The following steps are used in LCA: (1) Define scope and boundaries, (2) Conduct a life cycle inventory, (3) Conduct a life cycle impact assessment, and (4) Conduct an improvement analysis.

Many LCA studies have focused on single material products, but such studies for complex products, such as automobiles and home appliances, are not commonly conducted[8,9]. This is primarily due to data aggregation, unavailability, and uncertainties.

Studies have shown the critical importance of integrating end-of-life (EOL) strategies into the early states of product design. Thus, design engineers ought to consciously plan for product retirement. Disassembly is one of the major considerations in designing for EOL processing. Tumkor et al.[10] investigated selective disassembly to extract the maximum value from a product before recycling. The focus was to optimize the conflicting objectives of minimizing product environmental impact and maximizing profit due to recovery. Several EOL options, such as reuse, remanufacturing, primary recycling, secondary recycling, disposal, and special handling were considered to develop an optimization model. This model was used to find the best alternative for different scenarios.

Disassembly modeling and LCA are often too complex and time-consuming to undertake for a course assignment. Therefore, general design guidelines must be developed that can be used by undergraduate students. At Istanbul Technical University, Turkey, the Engineering Design course, MAK 422E, attempts to incorporate such guidelines into its curriculum. The objective is not only to present a comprehensive, consistent, and clear approach to engineering design, but also to have students analyze and redesign an existing product by applying design guidelines. This paper presents the course objectives and content and presents a case study to illustrate the application of design guidelines for an undergraduate design project.

2. Objectives for a Sustainable Design Course

Before introducing the details of the Engineering Design course, MAK 422E, some objectives and guidelines to help companies improve environmental performance are described. Various companies from automotive, energy, and consumer product sectors are adopting environmental or sustainability principles. For example, several have endorsed the Ceres Principles[11] , which is a code of corporate environmental conduct established in 1989. Under this code, companies commit to open dialogue and accountability in terms of the environment. According to these principles, the companies should:

- Protection of the Biosphere - minimize the release of any substance that may cause environmental damage to the earth or its inhabitants,
- Sustainable Use of Natural Resources - make sustainable use of natural resources,
- Reduction and Disposal of Wastes - safely and responsibly reduce/eliminate waste through source reduction and recycling,
- Energy Conservation - use energy in a sustainable manner through conservation and energy efficiency improvements,
- Risk Reduction - minimize risks to workers and people in the surrounding area,
- Safe Products and Services – reduce/eliminate harmful products/services and inform customers about potential harm from their products/services,
- Environmental Restoration - promptly/responsibly correct environmental harm caused by their products/services,

- Informing the Public – communicate with people in the community and workers about incidents/conditions that can impact health, safety, or the environment,
- Management Commitment – consider "demonstrated environmental commitment" as a factor in selecting board members, and
- Audits and Reports – monitor progress through self-evaluation and an annual Ceres Report.

Since universities must adequately prepare designers to fulfill the needs of companies in addressing future sustainability challenges, it is necessary to incorporate new concepts and methods into course curricula[12]. Therefore, universities are tasked with incorporating new sustainability ideology, which often does not have physical meaning, into traditionally concrete design courses. Thus, students of today must learn to apply this ideology through the use of streamlined tools or guidelines, as comprehensive tools are not yet developed. Some guidelines have been recommended by scientists and organizations for sustainable products design[13-16].

3. Engineering Design Course, MAK 422E

As a component of engineering design education in MAK 422E, students must undertake a project that includes the redesign of a product. The main redesign objective is to reduce the environmental impact, while maintaining functionality and minimizing costs. For this purpose the students are divided into design teams of five to seven members, which aids in innovative thinking and concept generation[17-19]. The emphasis is to redesign home appliances with the objective to make them more environmentally friendly. Home appliances were chosen for analysis as the Waste Electrical and Electronic Equipment (WEEE) directive from EU has been the focus of attention with the governments and public [20, 21].

The students, in MAK 422E Engineering Design course, are expected to progress through three phases of product development study, which can be listed as clarification of the task/specification, conceptual design and embodiment. These steps can be redefined in the aspect redesign since redesign is the detailed study and analysis of an existing product to collect information, remake the design decisions and improve the product designed initially by the original design team. (Figure 1)

Searching for customer needs and market analyses initiate the effort of redesigning the product. By using these data and information from literature survey, the teams have to prepare a short requirement list to depend on while redesigning the product. However, not to limit the creativity of the teams the requirement list remains as a live document which can be modified. This also maintains the open-ended nature of the design process

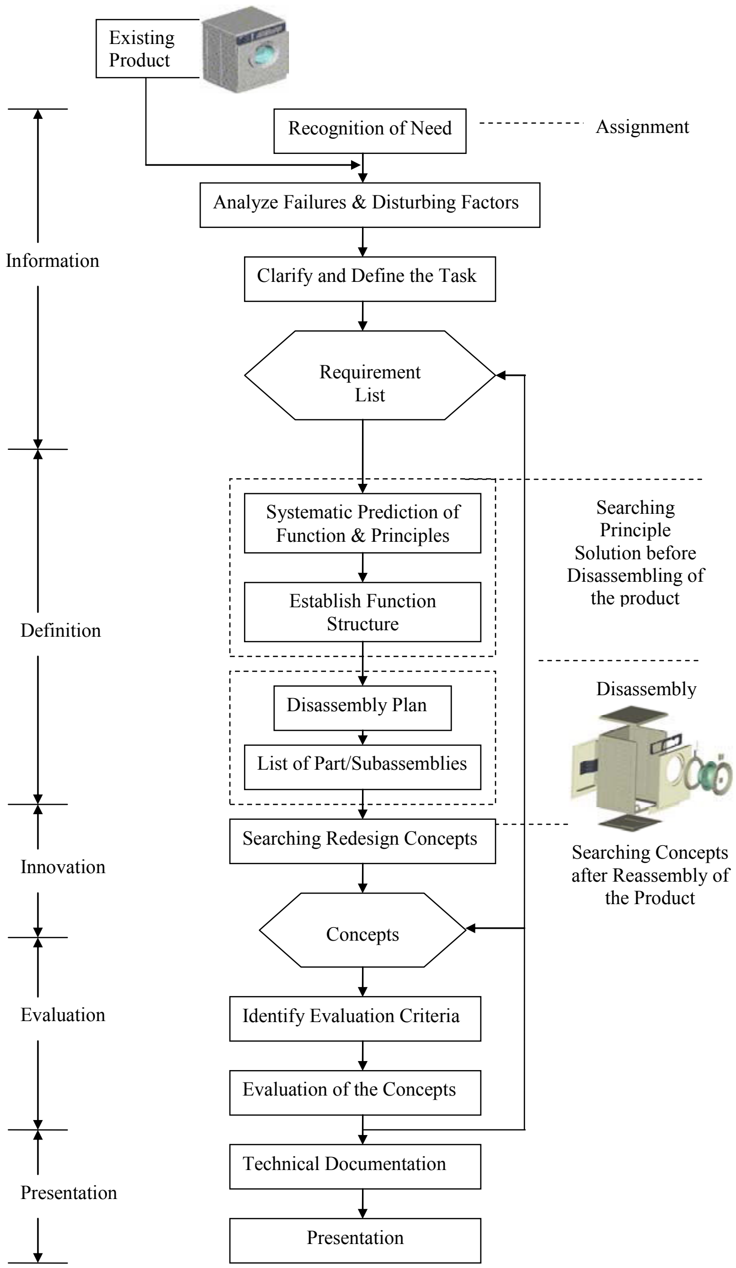


Figure 1 Redesign Steps in the Course

After systematic prediction of the functions and principles that solve the needs in the requirement list, a reverse engineering study of the existing product is undertaken by carrying out the disassembly of the product. This step helps the student in understanding the actual function and form of the product and each component as well. The students document the steps of disassembly by making a disassembly plan (in order to calculate disassembly time and also to aid in reassembling the product) and also develop a bill of materials that lists all of the parts /subassemblies contained within the product. Design modeling and analysis follows the reverse engineering phase of the project. The intent in this phase is to fully understand the physical principles and design parameters for the product.

After the student have an understanding of the existing product, the idea generation step for redesign is done, where every team members is encouraged to independently generate their concepts. The students are free to make hand sketches or parametric solid models that can be modified to express their ideas. The emphasize while developing these concepts is on the idea of design for environment, e.g., design for disassembly, design for reuse/remanufacturing/recycling, energy efficiency, minimum material, pollution prevention, and minimum hazardous material. The project ends with a final report and presentation of the concepts developed by each team.

Evaluation criteria for sustainable design

In the course, each design team evaluates the redesign of their product based in the following sustainability. Though some principles seem conflicting, the students are required to optimize the requirements based on these principles.

Material Selection and Conservation:

- Minimize the use of materials in regulated and restricted supply
- Use recycled materials wherever possible
- Minimize the use of materials whose extraction is energy intensive
- Minimize the number of different types of material
- Minimize the number of different materials that are used in its manufacture
- For combined parts, standardize on the same or a compatible material
- Ensure material homogenity within a part
- Minimize material variety and/or use compatible materials for different parts
- Avoid non-rigid and elastic materials or cover them with a rigid shell material
- Mark the material on all the recyclable parts
- Use high strength-to weight materials
- Use low alloy metals that are more recyclable than high alloy ones where possible.
- Use refillable or reusable containers for liquid materials
- Minimize single use and dispose consumable components
- Minimize restricted supply materials in consumable components
- Minimize toxic or otherwise undesirable materials in consumable components
- Hazardous parts should be clearly marked and easily removed.
- Avoid use of periodic disposal of solid materials such as cartridges, containers, or batteries

Energy Conservation:

- Minimize energy use while in service
- Insulate heated systems
- Permit user to turnoff system in part or whole
- Choose the least harmful source of energy, (renewable energy: solar/human/wind-powered)
- Minimize the use of materials whose extraction is energy intensive

- Avoid materials whose transport will require significant energy use
- Avoid producing residues whose recycling will be energy intensive
- Enable energy intensive easy disassembly processes
- Minimize energy use while in service
- Renewable energy should be encouraged
- Minimize energy-intense production steps such as high heat differentials, heavy motor, cooling, etc.
- Minimize energy-intense evaluation steps
- Minimize the use of packaging materials whose extract or processing energy intensive
- Avoid energy intensive packaging procedures
- Minimize energy use in the product distribution plan
- Have enhanced insulation or other energy conserving features
- Monitor and display its energy use while in service
- Minimize the use of energy-intensive process steps in disassembly

Environmental Burdens:

- Avoid/minimize materials containing restricted, toxic or hazardous substances which could have an impact at any stage of the life cycle
- Minimize materials whose extraction or purification involves production of much solid/ liquid/ gaseous residues
- Avoid materials whose transport will result in signification solid/ liquid/ gaseous residues
- Avoid or minimize toxic materials
- Avoid or minimize radioactive materials
- Use production that uses cogeneration, heat exchange, and other techniques to utilize wasted water
- Minimize and reuse as much as possible manufacturing solid residues (mold scrap, cutting scrap, etc.)
- Minimize toxicity and optimally of liquid product residues
- Utilize the maximize amount of recycled liquid species from outside suppliers
- Apply alternatives to CFCs or HCFCs
- Minimize greenhouse gases used or generated in any manufacturing process
- Minimize any odorants used or generated in any manufacturing process
- Minimize the product packaging mass and the number of different materials
- Avoid toxic materials in the product packaging
- Use recyclable packing materials
- Avoid packaging with toxic or hazardous substances that might leach if improperly disposed of

Service Extension and Disassembly for EOL:

- Design modules/ subassemblies for ready maintainability rather than solely for disposal after malfunction.
- Design for serviceability (commonality, upgradeability, and modularity)
- Ensure that different materials are easy to identify and separate
- Locate unrecyclable parts in one subsystem that can be quickly removed

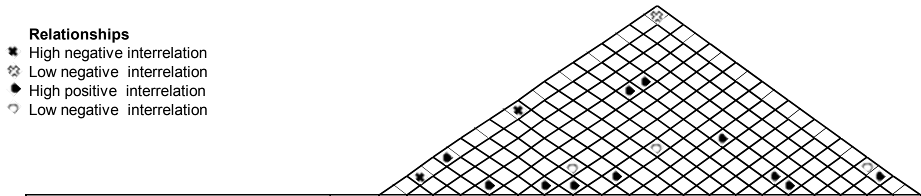
- Locate parts with highest value in easily accessible place
- Access points should be made noticeable and easy to access
- Reduce the disassembly time
- Avoid long disassembly paths
- Design the product whose parts are appropriate for straight disassembly motion in gravity direction
- Use standardized types of joining elements
- Minimize the number of joining elements
- Minimize the number and variety of disassembly tools needed
- Use joints which can be designed to break as an alternative to remove
- Design removable snap fits without breaking, particularly for reusable parts
- Reuse the materials while retaining their embedded energy
- Minimize transport of recycled materials to the recycling facilities
- Assemble with fasteners such as clips rather than chemical bonds or welds
- Avoid joining dissimilar materials
- Apply ISO markings as to their content
- Use unplated metals that are more recyclable than plated.

Teams are recommended to practice House of Quality (HoQ) to see and analyze importance of the principles for the specific product. Figure 2 shows one such analysis done by the team who was looking at improving the design of a washing machine. The students also apply Quality Function Deployment (QFD) method to analyze the customer needs, since functionality, cost should be maintained and requirements should be fulfilled.

4. Case Study – Washing Machine

As an example, a washing machine redesign case study is presented using the evaluation criteria for Service Extension and Disassembly for EOL, as mentioned above. One of the problems with recycling is difficulty in disassembly of the original components and having more than one material which causes separation problems in the recycling. The aspects and criteria, which are explained before, have been used in the idea generation and evaluation phase.

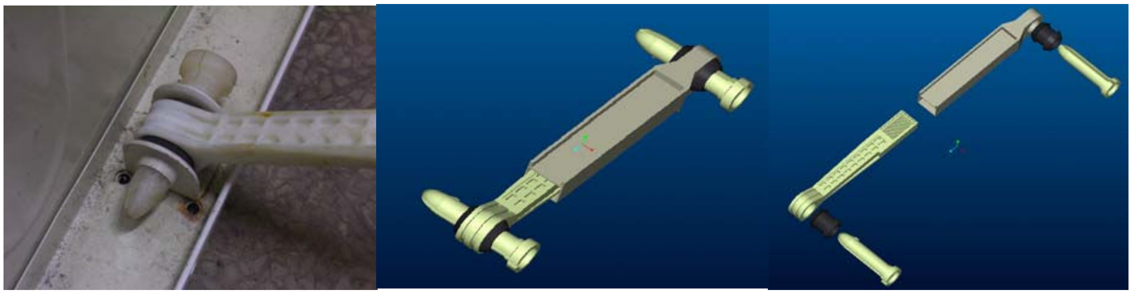
One of the selected components to redesign is the damper in the washing machine. The washing machine has two symmetrical dampers to absorb the vibrations. They connect oscillating system to the main frame. The part consists of an outer body, an inner body, two pins and two dashpots on the ends.



Costumer Requirements	Priority	Maximum rotation rate	Dry laundry load	Wet laundry load	Lifting the pump motor	Motor power	Dimensions	Volume	Weight	Material and shape of the body	Material of lower chassis	Appearance group elements	Balance weight	Type of joints	Structure of joint holes	Minimizing the parts	Aimed disassembly duration	Material resists corrosion and vertical position	Reducing discarded material in manufacturing	Resistance to dynamic stress and light	Life	Comparing with other washing machines according to customers' demand 1: lowest 5: highest (1 3 5)
Usage of recyclable raw material	5									5	5	4	5									
Decomposing of End-of-Life materials	4										4		4			4	3					
Easy separation of different material types during the recycling	5										5	4	4			5						
Easy disassembly	5				5		3		3	4	5	3			5	5	5			3		
Recycling returned parts during or after the production	4									4	5	3				4			5			
Endurance of reusable parts	5								3			4					4	4		3	5	
Usage of standard parts	4									3	3				3	3	5				3	
Serviceability	4				4		3		3	4	4					5					4	
Easy disassembly of joining elements	5	3								4	5	3			4		5					
Minimizing the energy consumption	4	3			5	5																
Low noise level	3	5			4					3		3			4	4				3	3	
Using simple and less parts	5				5				4	4	5	4			4	5	5			3	3	
Lightweight	4				3		5		5	4	5				3	5	3			4		
Collecting, transfering and storing the End-of-Life products easily	4						4	4								4				3	4	
Loading from the front	3		4	4				4	3			4										
Comparing with other washing machines according to technical properties 1: lowest 5: highest	1																					
	2																					
	3																					
	4																					
	5																					
Aimed Value		1200 rpm	5.5 kg	10.5 kg		250 Watt	60×55×85	280.5 L	75 kg	Stainless Steel	Species of plastics	Plastic	Concrete with plastic additive	not using bonding and welding joints	Conical Structure	Bended U-shaped body design	X Minutes		Not using low tolerances	usage of ABS/PE	10 years	
Technical Difficulty Values (1 difficult - 5 easy)		5	5	5	3	5	5	5	4	5	3	5	3	4	5	4	3	4	4	4	5	

Figure 2 House of Quality Performed by Students

Outer body is made of aluminum, inner body and pins are made of plastic, and dashpots are made of rubber. Figure 3 show the actual assembly of the damper (a), a CAD model (b), and the exploded view of the CAD model (c). During the analysis of the design of the damper, the students found that it is extremely difficult to disassemble the damper since the pins have an interference fit. In addition to great amount of disassembly time, excessive work and strength was also required to disassemble the parts.



(a) (b) (c)

Figure 3 Original Damper

Some of the concepts generated by team members are shown in Figure 4 (a)-(d).
(a) Dampers are assembled to the washing machine base and tub with bolts instead of interference fit. By this way, suspension can be assembled by turning and fastening. Although this process would also take time to disassembly, less strength is needed to take suspensions out, then the strength required in interference fit method. Moreover, the disassembly process would be suitable for automation. In addition to these, the suspension could be made of two sub-assemblies. There would be no extra need for separate pins. They are designed as a part of the damper.
(b) The body of the damper can be made cylindrical or rectangular as it is now. Two standard screws can be used such as M8 to assembly the suspension. In this way, disassembly process would be easier and take much shorter time. Again it is also more suitable for automation. Moreover, after unscrewing the connection, the outer body and inner body of the suspension can be separated easily and recovered. Therefore there is no need to select from the same or compatible materials.
(c) This solution integrates the main parts of suspension with the pins. Thus, while disassembly processes are reduced to one dimensional linear motion, it also reduces the number of parts in the suspension. But in this solution the plastic dashpots are have to be assembled to frame and drum.
(d) Three components are used and the number of components is halved in this design. It can be dis/assemblied without any special tool. The thickness of the notch and the width of the cylindrical contact surface are specified according to the strength of the material and vibration forces during the washing process.
Table 1 show the evaluation of each design concept based on the Service Extension and Disassembly for EOL criterion. It can be seen from the table that design (c) was judged as the best design for this criterion. At this point, it should be noted that the designers should look as other evaluation criterion as well before making a final decision on which design to use.

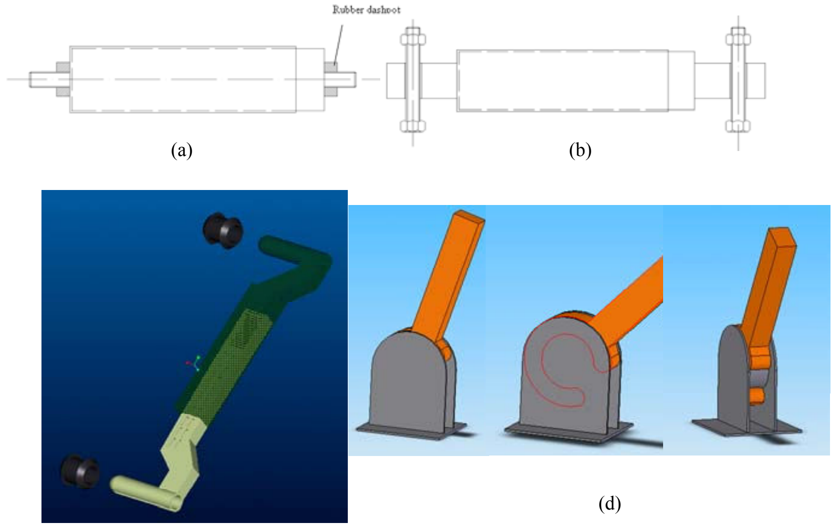


Figure 4 Different concepts generated by team members

Evaluation Criteria		**Damper Concepts** 1:lowest 5: highest				
		Original Design	(a)	(b)	(c)	(d)
Direction of disassembly		2	3	2	4	5
Number of disassembly steps		1	4	3	5	5
High strength		3	4	5	3	2
Easy manufacturability		2	2	4	4	5
Manufacturing cost		3	3	4	4	4
Convenience to automation		1	3	2	5	5
Duration of disassembly		1	3	4	5	5
Disassembly with tool/without tool		1	1	1	5	5
Number of sub assembly		1	2	3	4	4
Material convenience		1	5	5	5	5
Accessibility		1	3	4	5	4
Easiness of assembly		1	3	4	5	5
Disassembly frequency (low/medium/high)		5	5	2	5	5
Material/component Recovery	Recycle	2	3	3	3	5
	Remanufacture	1	3	3	2	5
	Reuse	2	5	5	5	5
Weight		3	3	2	3	4
Recyclable/reusable parts combination		3	2	2	4	4
Less material variation		4	3	3	4	3
Standardized joining elements usage		4	4	4	4	4
Less variation of joining elements		2	3	3	4	5
Snap fits usage		1	1	1	1	5
Material convenience between part and joining elements		1	3	2	2	2
Easy access of joining elements		1	3	4	2	4
Symmetry among joining elements		2	3	4	3	3
Number of tools used for disassembly process		3	2	2	4	5
Total Value		***52***	***79***	***81***	***100***	**113**

Table 1 Evaluation matrix of the damper concepts

5. Student Feedback

To evaluate the effectiveness of the course and projects, the students were asked to provide feedback what they found most beneficial outcome in this course and what they would recommend changing.
The following is a summary of the responses:

- Most valuable benefit was learning how to work as a team and feel the responsibility.
- I learned about sustainability.
- I learned how an engineering design project is prepared.
- I did not realize that the recognition of the need and problem definition so important in the product design.
- I learned how important is the disassemble ability for recovery in product design.
- We learned the importance of communication and reporting among the team members for the success.
- Construction of a prototypical product would be interesting.
- More time is needed for better presentations.

6. Conclusions

Environmental issues are gaining justifiable popularity among society, governments and industry due to negative environmental developments. The environmental friendly products are crucial in order to minimize the use of virgin resources. This can be achieved by educated design engineers.
Students are encouraged to take part in a project team in this course. They learned how to prepare a project as a group. All the students expressed their design solutions individually. They used intuitive methods and conventional methods. With the help of intuitive methods like brainstorming, 6-3-5 method, etc., they improved their creativity for the design steps. During the development of the redesign project, students are informed about the flow of work during the process of planning and designing. They studied on planning and clarifying task, conceptual design, embodiment design and detailed design, step by step. They realized how to consider the design criteria such as design for minimum cost, design for environment, design for disassembly etc. They also experienced practical applications besides theoretical applications during this course. The students prepared for their professional life in means of how to work a design project and how to present their reports. They learned that there will never be just one right answer for engineering design problems, but also find out that the right answers are not found accidentally.

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