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Innovative Design for Active Disassembly and Sustainable Product Recovery

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Innovative Design for Active Disassembly and Sustainable Product Recovery

by

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DECLARATION OF CO-AUTHORSHIP PREVIOUS PUBLICATION

I. Co-Authorship Declaration

I hereby declare that this thesis incorporates material that is result of joint research, In all cases, the key ideas, primary contributions, experimental designs, data analysis and interpretation, were performed by the author, and the contribution of co-authors were as follows:

- In Chapter 2: Ramadan and Elmaraghy contributed to brain storming sessions conducted by the author; also they reviewed and provided feedback about the contents.
- In Chapter 3: Altarazi provided data for the first case study in the chapter. Atwan provided data for the second case study. Elmaragy (previous supervisor) and Azab (supervisor) contributed to the discussion about the validity and correctness of the proposed models; they also reviewed and commented on the writing.
- In Chapter 4: Azab (supervisor) contributed to the discussion about the validity and correctness of the proposed methodology, he also reviewed and commented on the writing.
- In Chapter 5: Ramadan contributed to the data collection and judgment of data related to the auto industry; data were used in second case study in the chapter. Azab (supervisor) contributed to the discussion about the criteria to select the appropriate case study, he also reviewed and commented on the writing.

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II. Declaration of Previous Publication

This thesis includes six original papers that have been previously published/submitted for publication in peer reviewed journals, as follows:

Thesis Chapter	**Publication title/full citation**	**Publication status**
Chapter 2	Ziout A., Ramadan K., and ElMaraghy W. H. (2009). Inventive Conceptual Designs in Active Disassembly Using Theory of Inventive Problem Solving (TRIZ). Proceedings of 16th CIRP international conference on life cycle engineering. Vol.1/517-521.	Published
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Chapter 3	Ziout, A., Azab, A., Atwan, M. (2013[b]). A holistic approach for decision on selection of end-of-life products recovery options. Journal of cleaner production. Submitted (April, 2013)	Submitted
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Chapter 5	Ramadan, K., Ziout, A., and ElMaraghy, W., (2009), "Design-for-Disassembly of Safety Restrain Airbag Modules In the Automotive Industry With Respect to Life Cycle Engineering", Proceedings of the 16th CIRP International Conference on Life Cycle Engineering (LCE), Cairo, Egypt, 4-6 May 2009, pp. 522-526.	Published

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ABSTRACT

Closed loop product lifecycle requires product ease of disassembly. Active disassembly, which uses external triggers that remotely disassemble active joints purposefully impeded in a product, shows great potential.

The objectives of this dissertation are: first, to fulfill the need for comprehensive sustainability assessment that justifies incorporating active disassembly in product design; and second, to provide a methodology that enables systematic design and innovation of active joints that provide active disassembly. These two objectives are accomplished by developing a framework equipped with methods and tools that guide the process of incorporating active disassembly in product design. At the first level of the framework, two assessment models are developed: The first model assesses the opportunity to reuse an end-of-life (EOL) product as a whole, while the second model assesses the opportunity to recover only portions of the EOF product as modules and parts. The proposed models are novel in terms of the logic they apply, comprehensiveness of factor they use, and their balanced consideration of the three bottom lines of sustainability. There is no known literature that encompasses an assessment model combining all of the above features. The second level of the proposed framework addresses the need for Active Disassembly, where active joint design methodology is developed. The methodology, equipped with several tools, helps product designers create and innovate active joints for products. The method is novel in its structure and its targeted design domain (the first dedicated method for active joints).

The applicability of the developed assessment models is validated through two case studies. Results show that EOL decision is significantly improved over what is known in literature (46% - 86%); the first model shows a complete match with industrial practice, while the second model shows a near complete match (i.e.: out of 10 assessed items, 9 are correctly assessed). Two other case studies validate the design methodology. The implementation demonstrates the effectiveness of the method: A new active joint is invented while the other two improved variants of an existing joint are obtained using the method. The results of this research also demonstrated that active disassembly helps close the loop in product life cycle and ultimately contribute to sustainable development.

DEDICATION

I dedicate this work to the two most beloved persons to me, who were with me when I started this work but were not when I finished it.

To the pure souls of my parents

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Friends and colleagues from PLM research lab, IMSC research lab, and department of industrial engineering are acknowledged. My discussion with them widened my scope, motivated me, and invoked new ideas that enriched my research scope. Their researches inspired new directions and extensions to my research. They were helpful. Without forgetting any one, thanks to all of them.

Finally, I'd like to acknowledge my family, especially those who live thousands miles away from me, yet I'm very close to their hearts. They always provide me with love and encouragement. I doubt that my little kids, Sora, basher and Fatimah understood why I had to leave them and to go to school and get to home late. I acknowledge their patience. My deep appreciation goes to my wife, who provided me during this long time and tough situations with unlimited support. She shared with me all my happy and sad moments. To here are my deep thanks.

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ADIS:	Active Disassembly
ASME :	American Society of Mechanical Engineers
ASMS:	Adaptive Structures & Material Systems Committee
CAD :	Computer Aided Design
CPM:	Characteristics-Properties Modeling
DFA:	Design for Assembly
DFD:	Design for Disassembly
DFX:	Design for X
DSM:	Design Structure Matrix
EEE:	Electric and Electronic Equipment
ELDA:	End-Of-Life Design Advisor
EOL:	End-Of-Life
FMEA:	Failure Mode and Effect Analysis
IDEF0 :	Icam Definition for Function Modeling, Level
IP:	Instrument Panel
ISO:	International Organization for Standardization
MEMS :	Microelectromechanical Systems
PESTEL:	Political, Economical, Societal, Technical, Environmental and Legal
PLM:	Product Lifecycle Management
QFD:	Quality Function Deployment
TRIZ:	Theory of Inventive Problem Solving
WEEE:	Waste of Electric and Electronic Equipment

1 INTRODUCTION

1.1 Introduction

Short technology lifecycle and ever-changing customer needs shorten product lifecycle (Ishii, 1995). This contributes to the increasing rate of products being disposed at their end of life. These products are dumped to the environment causing different impacts (Chen, 2001). Many governments respond into the environmental problems caused by industry by introducing and forcing new environmental legislations, which regulate waste management and recycling of products at their EOL. Industries have to adapt to the new environmental regulations, which force manufacturers to be responsible for their products throughout the phases of its lifecycle, including EOL phase.

Lifecycle design approach incorporates sustainability issues in product design at its early developmental stages (Hauschild *et al*., 2005). Economical, environmental, and societal issues have to be considered throughout a product's lifecycle, starting from the definition and design of a product, all the way to proper disposal of the product. .

Design for X methodologies, where X represents design objective, are effective in improving the entire product lifecycle, including the EOL phase (Ishii, 1995). Design objectives such as product recycling, reuse, remanufacturing, etc., require product disassembly. Therefore, incorporating design for ease of disassembly in the design stage is a key element in achieving EOL product objectives.

Product disassembly is needed not only for EOL purposes, but also for product service and maintenance during a product's useful life. Design for disassembly evaluations metrics, guidelines, and tools are researched. More research is needed to address problems related to product disassembly and its related high cost; such as, developing other options for manual disassemblyand improve disassembly automation.

1.2 Problem Background

Sustainable product design using closed loop lifecycle:

Material recycling and energy restoration are no longer enough sustainable treatments for products at their EOL stage. Designers and manufacturers need to consider the new phases in the product lifecycle, namely reuse and high-value recycling. To close the loop in the product lifecycle, product disassembly becomes an important stage in the loop. There are many options to recover EOL products. Some options require product disassembly, while other options such as shredding and incineration do not. These options might satisfy the economical requirements of recycling, but not fully meet the environmental and societal requirements. In most cases of product recovery, complete or partial disassembly is a required step (Willems *et al*., 2007). The role of disassembly can be summarised as the following:

- Product service and maintenance
- Subassemblies or parts reuse, repair, refurbish or remanufacture
- Material recycling
- Hazardous material separation before incineration

Product disassembly

Product disassembly has a key role in closing the loop in product lifecycle. Due to its importance, product disassembly has gained more interest from academic and industrial researchers (Masui *et al*.,1999). Researchers have explored areas such as disassembly process planning and sequencing, disassembly metrics, techniques, and guidelines. Product disassembly requires skilled labour, time, and other costs which make the disassembly economically not feasible (Kriwet *et al*., 1995). To solve this problem, improvements can be sought at three different levels:

- System level – disassembly plant

At the system level, the design of disassembly station, disassembly facility layout, and appropriate logistic systems need more research. Economical feasibility is the determinant factor at this level.

- Process level – disassembly process planning

The profitability of product disassembly can be enhanced by optimising the disassembly process plan. 10%-20% improvement in cost reduction can be achieved by optimizing the disassembly process plan (Desai and Mital, 2003a). Based on the objectives of disassembly process, two distinctive types of disassembly can be followed: selective disassembly or complete disassembly. The purpose of selective disassembly is to find disassembly depth beyond which disassembly process becomes not profitable (Kara *et al*.,2006). The optimal disassembly level can be determined based on user pre-defined criteria, total disassembly time, and economical value recovered.

- Product level – product design

During the design phase, products are usually optimized base on functionality and quality. Few designs are optimised based on product disassembly. To assess a design for ease of disassembly, a set of standard disassembly times was developed by Dowie (1994).

Another approach to assess disassembly tasks is using work measurements analysis (Kroll *et al*,1994). A standard time and a base time is assigned to each disassembly task. To reflect the difficulty of a disassembly task, the base time can be modified based on the following criteria: accessibility, positioning, force, and special condition such as rust and wear.

Design for disassembly (DFD) is a set of design rules and guidelines which help designers to incorporate ease of disassembly in their designs. In fact there are many rules and guidelines for DFD, some of which apply to particular products or sets of products. In general, these guidelines can be categorized in two main categories: Product architecture related guidelines, and joints and fasteners related guidelines (Bogue ,2007)

In spite of the effort made to improve product ease of disassembly, the economical feasibility of a product recovery is not achievable for many products. However, a breakthrough improvement in product ease of disassembly can be achieved through active disassembly.

Active disassembly (A.Dis.)

A.Dis. uses active joints consisting of materials having geometry or characteristics that can be remotely changed to respond to a triggering field. The change causes the parts to de-join which, in return, causes product disassembly. A.Dis. does not require manual labour and it is considered very promising in reducing disassembly effort and cost. By using the active disassembly concept, a 200%-250% improvement in disassembly efficiency can be achieved (Willems *et al*., 2007).

1.3 Problem and Thesis Statements

Based on the literature review conducted in this work, recovery of the EOL product using manual product disassembly is not economically feasible, especially when high value recovery is required (i.e.:recovery of parts, subassemblies, and pure material recycling). The current success stories of EOL product recovery are referred to the manufacturer's commitment to design product for ease of disassembly; this marginal improvement is not yet enough to make it economically feasible for a wide range of products. This can be linked to the use of traditional joining methods which require manual or direct automated disassembly. A novel type of fasteners and joints is introduced to overcome the weaknesses of traditional joints. This type of joining methods is called active joints; these joints use material and/or structural properties to disassemble and release attached components. Active joints are designed to remotely respond to predetermined disassembly triggers without a need for manual interaction. Product disassembly which uses active joints is called active disassembly.

A.Dis. is promising solutions to increase the economical feasibility of EOL product disassembly. Gap assessment on the design for A.Dis. has shown deficiencies in two areas which become the research problem in this dissertation:

Problem Statement:

"First: the literature lacks a comprehensive framework to integrate design for active disassembly with product design process while considering corporate sustainability strategy. Second: product designers' options are limited due to the limited number of existing active joints; and there is no specific design method to assist with design and invention of active joint".

Therefore, it could be concluded that the overall objectives of this dissertation is to bridge these identified gaps, and to this end, the following thesis is stated:

Thesis statement:

"Closed loop product lifecycle can be improved by incorporating design for active disassembly in product design process. A framework equipped with methods and tools is essential to achieve this goal."

1.4 Research Objectives

The objectives of this research are to improve:

1. Sustainable development at large by providing sustainable products which have closed loop lifecycle.
2. Corporate sustainability by improving their product design that help corporate introduce sustainable product to the market.

These objectives are achieved by providing the following research outputs:

1. Framework that incorporate A.Dis. in Sustainable product design process.
2. Decision methods that aid corporate decision makers to assess and decide on the opportunity for closing the loop in their product's lifecycle
3. Active joint design methodology that helps product designers design active joints for their products.
4. New innovative active joint and active fastener that can be used directly by product designers.

1.5 Research Approach

The introduced research approach follows a framework which consists of two levels. At the first level, the purpose of incorporating active disassembly in product design is justified. Manufacturer decision makers are provided with detailed assessments of the opportunity to recover their product. Two decision methods are developed: The first assesses the opportunity of reuse EOL product as a whole, while the second method assesses the opportunity to recover product's assemblies and parts. The first level of the framework justifies manufacturer decision to involve in product recovery and incorporating active disassembly. In constructing the first level of the proposed framework, the research benefited from surveyed comprehensive literature of approaches, methods, and tools in the field of sustainable product recovery.

At the second level of the proposed framework, two well-established methodologies for design and innovation are hybridized, namely, systematic design methodology (Pahl & Beitz, 1996)) and theory of inventive problem solving (TRIZ) developed by Altshuler (1984). At this level, the designer is provided with two means for incorporating active disassembly in product design: first, an active joints catalogue which contains existing active joints. Second, is innovative design methodology for new active joints. The methodology guides product designers throughout the development of their new active joint. It is outlined in four different phases which conceptualize, develop, and detail the invented active joint.

PLM with appropriate design tools (CATIA or NX) can be used to model, analyze, and test the generated joint. Figure 1.1 shows the general architecture of the proposed Framework.

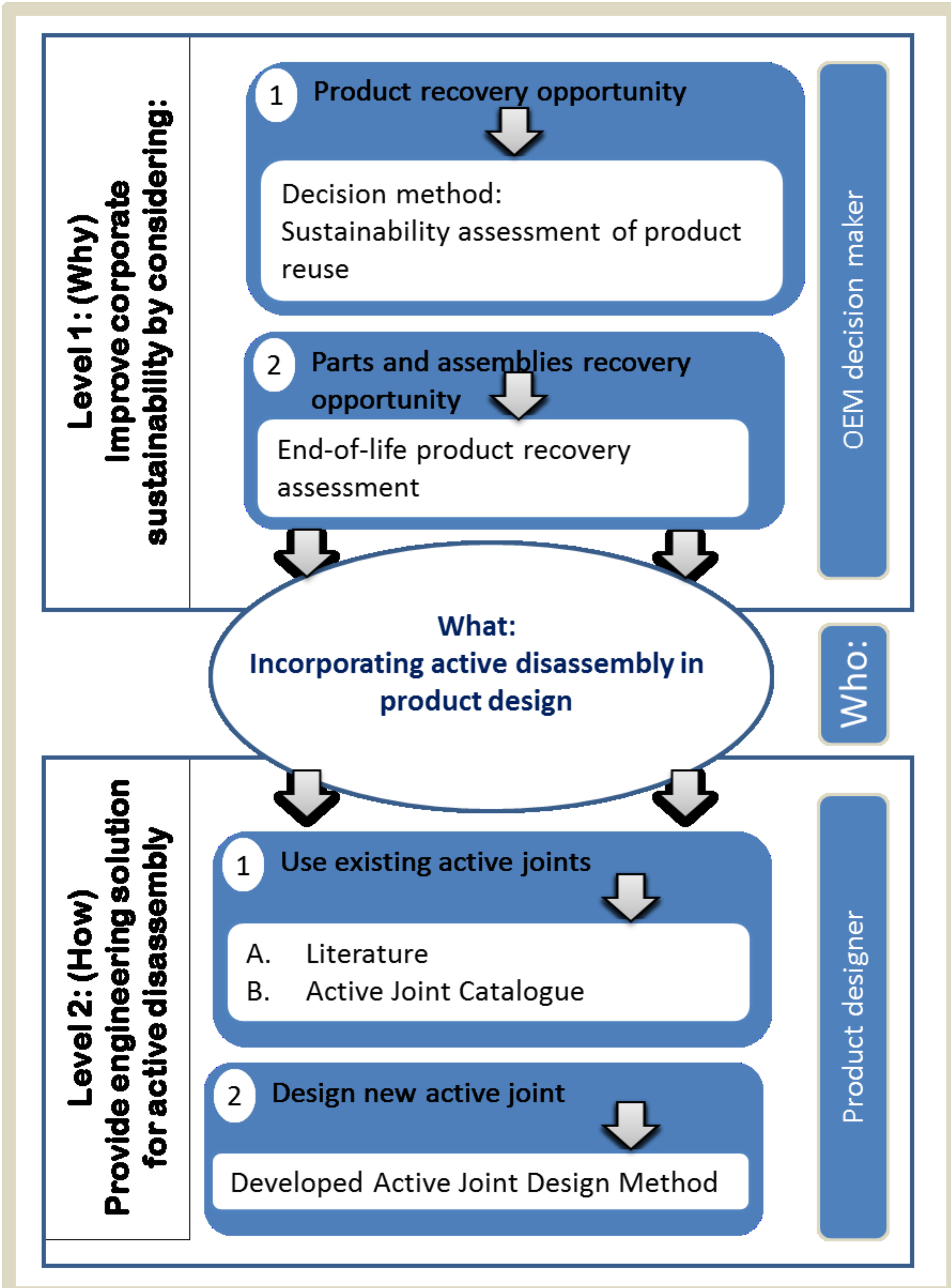


Figure 1.1: Proposed framework for incorporating active disassembly in product design

1.6 Research Contribution

This research fits under product design for disassembly, which is an essential prerequisite for selecting proper recovery strategies for an EOL product; a subfield under the big umbrella of product lifecycle engineering**.** Figure 1.2 positions my research with respect to product lifecycle engineering knowledge.

This research contributes to the current knowledge by adding two blocks to the field of active disassembly. They are integrating ADis within an overall product design framework and design methodology for generating novel active joints.

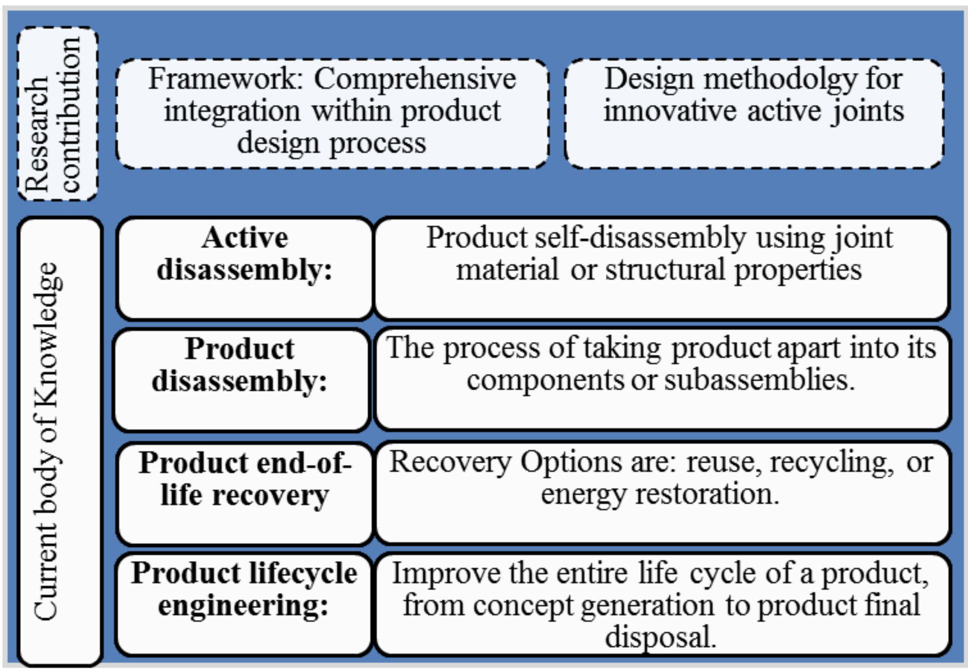


Figure 1.2: Research positioning and contribution to the body of knowledge

1.7 Research Scope and Limitations

Theoretically, the scope of this research may include any product that has two components or more. Design for active disassembly is a valid option in product design as long as it does not generate losses; i.e., design for active disassembly has to have an overall positive value adding during the total product lifecycle.

Practically, the success of design for disassembly and design for active disassembly in particular is dependent on the involvement and commitment of product manufacturer. A case-based study (Duflou, *et al*, 2008) showed that the involvement of a product's manufacturer is a key factor in determining the feasibility of a product's disassembly. This conclusion can be drawn as a design for active disassembly too. Therefore, design for active disassembly is highly recommended whenever product manufacturers are willing to take responsibility for their product EOL recovery.

The scope of this research focuses on cases where product manufacturer is assumed to participate in a product's recovery process, either directly or indirectly by appointing another party. Geographically, designs for active disassembly may not be found feasible , where labour costs are extremely cheap, and where low manual disassembly costs may not justify investments in active disassembly.

1.8 Dissertation Outline

In addition to the concepts and ideologies introduced in the first chapter, this dissertation will illustrate and elaborate extensively on these concepts in the following chapters:

Chapter two provides literature review about relevant directions of research related to sustainable product design, with emphasis on active disassembly. The literature being studied in this dissertation is critically reviewed and research gaps are identified.

Chapter three addresses the first level in the proposed framework. It composes of three sections: section one defines end-of-life products and possible recovery options; it also identifies stakeholders in recovery process and their interests; section two provides sustainability assessment for product recovery as a whole; section three provides recovery assessment for EOL product as assemblies and parts.

Chapter four addresses the second level of the proposed framework. It represents a hybridized design methodology for active joints equipped with a catalogue of existing active joints.

Chapter five validates the proposed methodology in chapter four by using two major applications. And lastly, chapter six provides general discussions about the research findings and conclude the research by providing future work and extensions.

2 LITERATURE REVIEW

2.1 Sustainable Product

Understanding the meaning of sustainable product comes from understanding the meaning of “Sustainability”. There are many definitions for sustainability that can be found in literature (Ehrenfeld, 2008). The most accepted definition is the 1987 World Commission on Environment and Development definition (WCED), which is: “*Meeting the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, 1987).This definition is very broad and general. In one hand, this generality makes it more comprehensive and gives everyone a duty towards sustainability; on the other hand, the definition lacks criteria to measure sustainability. For more arguments see Adams (2006).

In the same context, a sustainable product can be defined as a product that satisfies the need of current generation without negatively affecting future generations. To bring this broad definition into practice, many researchers set and define concepts, methods, and tools to assess product sustainability. The concept of product lifecycle engineering is defined by Jeswiet (2003); the design and manufacture of products were the core of the definition. The concept of lifecycle engineering has evolved to include more dimensions required by sustainability; such as, recycling, disassembly, and recovery of future products (Jeswiet and Hauschild, 2005,Hauschild, *et al*., 2004).

Although sustainable product is not well defined in literature, its characteristics are clearly identified (Veleva and Ellenbecker, 2001, Nasr, 2009). The most common characteristics are:

1. Minimize material, energy, and resource consumption needed to satisfy functions/requirements.
2. Maximize usage of expended resources.
3. Eliminate / minimize product adverse effects.

2.1.1 Strategies, methods, and tools for achieving sustainable product.

The emergence of sustainable product strategies are driven by pressure from active consumers groups, governments, industry leaders, and benefit/cost opportunities (Polonsky,1994, Rose,2000). These strategies are built around the involvement of both producer and consumer. The major sustainable product strategies found in literature and practices are: Closed-loop product lifecycle strategy, green marketing strategy, and Product-service system.

Closed-loop strategy:

Naser, *et al*. (2006) argue that the rate of energy and resource consumption cannot continue indefinitely. According to Deniz (2002), closing the loop in product lifecycle is a necessity. Rose (2000) developed a web based design tool called End-of-Life Design Advisor ELDA, which is a tool that helps designers decide which EOL strategy is (best) suitable for the product at hand. This tool is based on the analysis of cases gathered from the industry, which are assumed to be the best practices in the field of product recovery; although, the author does not justify this assumption.. Another assessment method similar to ELDA is proposed by Willems *et al.* (2008). The purpose of the assessment is to end up with a single value which assesses the capability of lifetime prolongation of a certain product. This method requires more detailed inputs, some of which are not available in the early design stage. This limits the applicability of the method to existing products only.

Many researchers respond to the End-of-Life Vehicle directive and similar legislations by introducing design methods that enables a closed loop strategy and satisfies new directives. Design for X methodologies are found effective in designing sustainable products. In these methodologies, X represents the design objective, such as design for disassembly, modularity, recycling, reuse, remanufacturing, environment, maintenance, or repair. Design for disassembly and recycling guidelines are suggested by Kriwet *et al*. (1995). New guidelines and design methods for product modularity and disassembly are suggested by Huang *et al.* (2012). Their method is based on satisfying 3R requirements (reduce, reuse, and recycle). An extension for this method is presented by Yan and Feng (2013); in addition to the 3R, recovery, redesign, and remanufacturing are included.

Design for remanufacturing is discussed by Kernbaum *et al*. (2009). The authors present a methodology to evaluate the suitability of electronic equipment for disassembly and remanufacturing. The generalization of this methodology is not discussed. Management and business issues are not fully discussed either. Studying product suitability for any recovery option without considering the management and business issues can lead to false decisions.

Integration, between previously mentioned tools and methods, is essential during various stages of product design. Many of these tools and methods have missed the proper integration. For example, a method that assesses product ease of disassembly without considering possible effects on product assembly could lead to wrong decisions. Jianjun *et al*. (2008) develop a tool which integrates quantitative environmental, technical, and economical information during product design process. The focus of this tool is to assemble, disassemble, recycle, and maintenance; it oversees the consideration of design for remanufacturing and service. The need for integrating recyclability assessment tools in design process is emphasized by Sakundarini *et al.* (2012), where they provide integration framework. Dostatni *et al.* (2013) present a design tool that aid designers in analysing and deciding the recyclability of their product designs. Variety of materials, variety of connections, and recyclability level are the main inputs for this tool.

The environmental assessment of the total product lifecycle is the subject of many standards issued by the International Organization for Standardization (ISO). ISO14001:2004 is environmental management standards that help companies to better manage their environmental performance (ISO, 2010). ISO14044:2006 is a comprehensive standard for lifecycle assessment. The common assessment categories covered by this standard are: global warming, acidification, desertification, habitat destruction, and depletion of resources. The main focus of this standard is the environmental impact of product. The assessment process required by this standard is lengthy and requires information that might not be available at the early stages of product development. This brings a doubt about the benefit of this standard. Table 2.1

summarizes the methods and tools for sustainable product design and lifecycle engineering.

Green marketing strategy uses symbols and eco labels to differentiate green products from conventional ones. The purpose of green marketing is to help consumers make informed decision about what they buy (Lee, 2008). The eco-labeling has different forms, such as:

1- Symbols: Energy Star symbols and recycling are examples of this form.
2- Ranking and rating: products or buildings are rated according to certain standards or criteria.
3- Environmental management system label: such as ISO14001 certificate.
4- Self-declared reports: such as corporate sustainability reports.

(For more discussion about green marketing, see Chamorro *et al*. (2009)).

Product service system (PSS) is a recently emerging sustainability strategy, which aims at replacing physical products with services. This strategy promotes the "sale of use" instead of "sale of product". The application of this strategy is currently limited to a few applications, such as carpooling and chemical management services (Yang *et al*., 2009). Consumer products need more attention in research and practice to qualify for product service system. Cavalieri and Pezzotta (2012) identify service design and development integration in PSS as a major challenge for PSS success. Material efficiency assessment is modeled by Mattes *et al.* (2013); benefits and associated risks with PSS are identified. Technology identification challenge is assessed by Kimita and Shimomura (2013); where customer-driven technology extraction method is developed for PSS.

Industrial product service is a promising branch of PSS. Meier *et al.* (2013) identify Socio-technical aspects of industrial product service systems; aspects such as standardization, knowledge generating, risk management, and business models with focus on workforce planning are explored.

PSS drives manufacturers and product designers toward sustainable product design, product useful life elongation becomes an objective for a PSS provider. Resources utilization and saving is a default outcome of PSS.

Table 2.1: Summary of strategies, methods, and tools for achieving sustainable product

Method/Tool	Type	Methodology	Metrics
Disassembly model analyzer. (Spicer, 19996)	Optimization model	Find the optimal disassembly path based on economical criterion.	Monetary value; benefits or losses.
Product modularity and Disassembly. (Huang *et al.,*2012; Yan and Feng,2013)	Guidelines and method	• Graphical representation of components. • Algorithm for modularization • Modularization with respect to 3R • Identification of disassembly pattern and final design selection	• Components dependency. • Modularity graph • Disassembly patterns • 3R performance expectations
End-of-life design advisor. (Rose, 2000)	Web based tool	The end-of-life strategy is determined based on product's six characteristics.	Absolute number refers to the appropriate end-of-life strategy.
Product lifetime prolongation. (Willems *et al.*, 2008)	Assessment tool	Aggregated metrics are used to find to determine suitability index of a product lifetime prolongation.	Suitability index vale:[0:1] 0: unsuitable. 1: highly suitable for lifetime prolongation.
Design for recycling. (Kriwet *et al.*, 1995).	Guidelines	List of design guidelines were introduced to help in design for recycling.	Set of guidelines.
Design for recycling (Sakundarini et al. 2012; Dostatni et al. 2013)	Framework and Assessment tool	the tool automatically calculate recyclability index for a proposed design based on identified metrics	• Variety in materials • Variety in connections • Type of compatible materials
Design for remanufacturing. (Kernbaum *et al.*, 2009)	Methodology	After conducting market, technology, and environment assessment, the intended product goes into six testing stages and is classified into three quality levels.	Six types of testing, and three levels of quality[A,B,C]
Lifecycle assessment tool (LCAT). (Jianjun *et al.*, 2008)	Decision support tool	Assessment of assembly, disassembly, maintenance, recycling, and overall assessment for the whole lifecycle is carried out.	• Time and cost of assembly, disassembly and maintenance. • Maximum recycling profit. • Typical lifecycle impacts, e.g. Kg, m^3 , KW.

2.1.2 Standards and legislations for sustainable product

Many standards and regulations enforce and encourage adoption of sustainable product. Certain countries have either developed national or adopted international regulations and standards for sustainable product. Table 2.2 shows sample of standards and regulations developed by organizations supported by the European Union.

Table 2.2: Sample of standards and legislations for sustainable product

Standards/legislation	**Scope**	**Objectives**	**Methodology**
RoHS Directive 2002/95/EC (European union, 2003[A])	Electrical and electronic equipment EEE	- Restriction of the use of the hazardous substances in EEE. - contribute to protection of human& environment through sound recovery of waste.	Starting July 1st 2006 member state shall ensure new EEE put on market doesn't have Lead, Mercury, Cadmium, Hexavalen Chromium, PBB, and PBDE
WEEE Directive 2002/96/EC (European union, 2003[B])	Electrical Electronic equipment EEE	- Prevention of WEEE. - Reuse, recycling and other form of recovery. - Improve the environmental performance of the operators involved in the lifecycle of EEE.	- **Design**: member state shall encourage the design and production of EEE which facilitate dismantling and recovery. - **Collection**: Member states shall take measures to minimize the disposal of WEEE. - **Treatment**: member states shall ensure that producers or third parties on their behalf provide treatment of WEEE using best available treatment methods.
End-of-Life vehicles (ELV) Directive2000/53/Ec (European union, 2000) End-of-Life Vehicles (Amendment) Regulations 2010. (Government of UK, 2010)	Vehicles, End-of-Life vehicles, and their parts and materials.	- Prevention of Vehicles, end-of-Life vehicles, and their parts and materials waste. - Reuse, recycling and other form of recovery. - Improve the environmental performance of the operators involved in the lifecycle of Vehicles, end-of-Life vehicles, and their parts and materials. - Amend unclear aspect of the directive	- **Prevention**: limit the use of hazardous substances in the vehicles - **Collection**: Operator has to set up an adequate and available collection system. - **Treatment**: End-of-Life vehicles are stored and treated according to directive 75/442/EC. - **Reuse and recovery**: 85% by weight starting 1 January 2006, and 95% by weight starting 2015.
REACH Regulation	All substances	- To ensure high level of protection of human health	-**Registration**: by the economic operator.

Standards/legislation	Scope	Objectives	Methodology
(EC) No. 1907/2006 (European union, 2006)	imported or manufactured of weight 1 ton and more	and environment - Manufacturers, importers, downstream users shall ensure the substances they use do not adversely affect human health or environment	-**Evaluation**: by European chemical agency. -**Authorization**: by the agency. -**Restriction**: the economic operator has to respect the conditions and restriction on the substances he uses.
Commission Regulation (EC) No 692/2008 (European union, 2012)	Light vehicles emissions	- Amendments to Regulation (EC) No 715/2007	-Set new limits for Nitrogen emissions. -Provides update on emission measurement methods.
Global reporting initiative (GRI) (Globalreporting.org, 2010)	All businesses	- Voluntary reporting on business activities, products, and services.	Reporting on: **-Economical performance** **-Environmental performance** **-Societal performance**
Lifecycle assessment standard. ISO 14001:2004 and Iso140044:2009 standards. (ISO, 2010)	Products and projects	Assessment of common environmental performance metrics: • Mass of consumed resources. • Mass of effluents • Mass of gaseous emissions. • Quantitative metrics.	The environmental impacts during product lifecycle are assessed and evaluated. It consists of three folds, it starts with scope definition, then inventory analysis, and ends with impacts assessment.

2.1.3 Critical review of literature on sustainable product

It is found through the conducted review that the literature, generally speaking, lacks the balanced consideration of the three pillars of sustainability; namely environmental, economical, and societal. It focuses on the environmental aspects of sustainable product, while it is not paying the same attention to the economical and societal aspects. The methods, tools, regulations, and standards reviewed lack this balanced view; this could jeopardize economical sustainability of the product.

Plenty of literature focuses on "what" a sustainable product should be, while few address "how" a sustainable product could be achieved. Literature identifies the requirements and characteristics of sustainable product, while little is mentioned about how to meet these requirements and achieve these characteristics. This could question the applicability of these methods and standards. For example, there are businesses that are aware of their environmental footprint, yet, they are unable to mitigate it without jeopardizing their economical sustainability.

Therefore, it could be concluded that there is a need for tools, methods, legislation, technology, and innovation that consider a balanced view of sustainable products. Product sustainability should not add burden to businesses; on the contrary, it should be a real opportunity for making more profit.

Based on the reviewed literature, most successful sustainable products are the ones that go in a closed lifecycle, while maintaining profitability over the whole lifecycle. In most cases, profitability is achieved by economical product disassembly. The next section reviews the literature on product disassembly, and discusses a new paradigm in product disassembly called active disassembly.

2.2 Product Disassembly

2.2.1 Product disassembly definition

Disassembly is the process of physically separating a product into its parts or subassemblies (Das *et al*., 2000). In the context of engineering, disassembly can be defined as the organized process of systematically taking apart assembled product (Desai and Mital, 2005). The disassembly process can be categorized based on:

- Complete versus partial disassembly.
- Manual versus automated disassembly.
- Non-destructive verses destructive disassembly.

The selection of disassembly process depends on the product's characteristics and the intended purpose of the disassembly. Traditionally, product disassembly is required during the service life of a product. Lifecycle thinking and sustainability requirements added new purposes to a product's disassembly during the different phases of its lifecycle; table 2.3 lists these needs.

Table 2.3: needs for product disassembly during different life phases

	Use phase	End-of-life phase
Needs for disassembly	1. ***Maintenance and service***: it includes activities as measuring, testing, component adjustments, replacing consumable components, and servicing the product with consumables required to maintain product's functionality. Greasing, de-dusting, oil change, or break change are a few examples of product maintenance and services. Disassembly is required for most of these operations. 2. ***Repair:*** the purpose of the repair process is to restore the original functionality and performance of a malfunctioning product. Repair usually requires partial disassembly to replace a broken part or subassembly. Ease of disassembly is crucial for minimising the repair time and cost. 3. ***Reconfiguration:*** partial disassembly is required for reconfiguration of modular products, or specific type of machines and production systems. (Kats, 2007).	1. ***Reuse:*** when the product is no longer satisfying the first user intentions, it might enter another cycle of use, or it might be disassembled fully or partially to take parts or subassemblies to be used in other functioning products. 2. ***Remanufacturing:*** the purpose of remanufacturing is to bring a used part or module to like-new state to be used in a new product. The retired product is disassembled to recover reusable parts or modules, which go into inspection and testing to guarantee their quality. 3. ***Recycling:*** the purpose of the recycling is to retain the materials stored in retired products. Product disassembly is required to have high value recycled material. 4. ***Separation of hazardous materials:*** the disposal of some product is subjected to laws and regulations that require the separation of hazardous material contained in the product before its disposal. In such cases partial disassembly is required to retrieve the part containing the hazardous material. 5. ***Energy restoration:*** Energy is restored from retired products through incineration.

The achievement of economical and environmental objectives of sustainable products highly depends on product ease of disassembly. Economics of reuse, remanufacturing, and recycling are related to product ease of disassembly. Protecting the environment and society from products containing hazardous materials is also facilitated through product ease of disassembly (Harjula *et al*, 1996). Table 2.4 shows the link between different EOL strategies and the required level of disassembly.

2.2.2 Challenges and issues in product disassembly.

Product disassembly is considered a key step in most product maintenance and recovery strategies. Figure 2.1 shows the key role of product disassembly in relation to different product recovery strategies.

The economics of product disassembly is not only related to the technical properties of the product, but also to other forces, such as market forces and reverse logistics (Wadhwa et al., 2009).

Table 2.4: Product recovery options after disassembly. (Thierry *et al*., 1995)

Option	Objective	Level of disassembly	Result
Reuse	Restore functionality	Product or subassembly	Product or part reuse
Remanufacturing	Restore quality level as new	Part level	Used and new parts in new product
Recycling	Restore energy or materials	Material level	Material or energy used in new product
Hazardous material separation	Protect the environment	Part level	Disposed products free of hazards

According to the literature, the issues related to product disassembly can be classified into two categories: management and engineering.

A. Management issues.

From a management perspective, Kapetanopoulou *et al.* (2011) and Thierry *et al*. (1995) identify the following management issues regarding feasibility and applicability of product disassembly as an operation within the EOL product recovery:

- Reverse logistic issues, which are the uncertainty in composition, quality, and quantity of return flow.

- Specialized expertise and know-how is needed which is governed by labour market.
- Management of product recovery and waste management operations are considered as inconsistent with and complicate company's operation.
- Market information about disassembled products, parts, or materials.
- Management considers EOL product disassembly as economically unjustifiable and risky in investment.

In attempt to solve the management issues related to product disassembly at the system level, Basdere and Seliger (2003) suggest and test the use of lifecycle unit (LCU). LCU is an electronic circuit that can be attached to the product to acquire, process, and transfer data during the entire lifecycle of the product. The purpose of the LCU is to use collected data to assist in solving management issues related to product disassembly. Kiritsis (2011) suggest that intelligent products should have data sensing, processing, and communication to improve product lifecycle management and help manual and automated product disassembly.

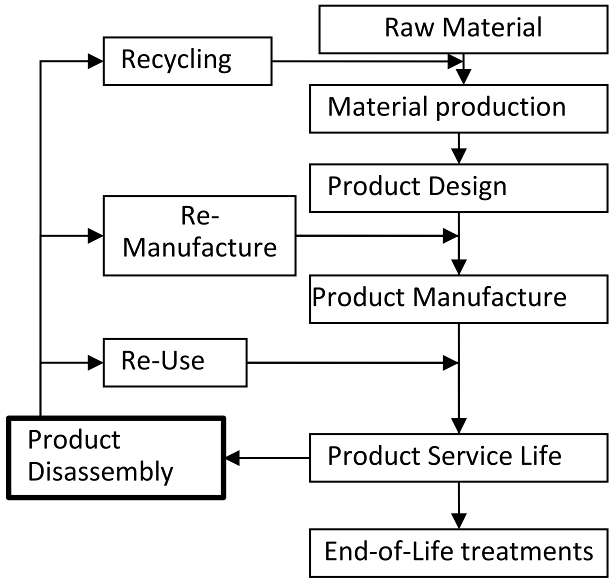


Figure 2.1 Product disassembly in relation with product recovery strategies. (Ziout *et al*, 2009).[1]

B. Engineering issues

Disassembly issues related to engineering perspectives are summarized by Mukherjee and Mondal (2009) as follows:

- Product design issues: products originally designed for ease of disassembly are more susceptible for end of life recovery processes.
- Level of technology and tools for disassembly.
- Manual versus automated disassembly.

The major challenges for product disassembly are:

1. Economical feasibility which is mainly governed by market dynamics: material prices, oil prices, etc.

[1] This is outcome of joint research

2. Available technologies, tools, and techniques for disassembly.
3. Variation in EOL products returned flow. Which is referred to many reasons, such as changes and variations made on the product during use phase.

The study of market dynamics is beyond the scope of this research and will not be discussed here. Manual and automated disassembly has been proven not to be economically feasible for low value products, and partially feasible for high value products (Williems 2007, Dufluo *et al.* 2008).

The technologies and tools for disassembly are addressed by Feldman *et al*. (1999), who propose three innovative tools to assist in manual and automated disassembly process: drill-driver, drill-gripper, and splitting tool. Seligr *et al*. (2002) develop a similar flexible tool for disassembly to deal with the different acting surfaces of screws that have different conditions. A recognizable effort to automate the disassembly process is done through a collaborative research project led by the Technical University of Berlin, Germany. A pilot plant is built inside the university. The plant has three 6-axis robots linked together with a flexible transportation system (Ewers *et al*., 2001). The plant is mainly for research purposes, and it uses home appliances such as washing machines to run experiments. Schmitt *et al.* (2011) introduce the flexible gripper for a Lithium ion battery automated disassembly.

To tackle the variation in EOL product returned flow, Kim *et al*. (2006) further develop the use of LCU to generate automatic disassembly sequence based on the data and knowledge stored in the LCU. The purposes of this research are to lower the cost of idle automated disassembly plant, and to generate a flexible disassembly sequence based on the conditions of the product to be disassembled. Kim *et al*. (2007) expand the previous concept to include hybrid assembly systems, where manual and automated disassembly is integrated for better flexibility. Kim *et al.* (2009) conclude that unavailability of customized control systems which can handle variations in EOL returned flow limits the viability of automated disassembly. Radio frequency identification (RFID) is found to be a promising technique to facilitate EOL recovery processes, including disassembly; Yet O'conell *et al.* (2013) who have investigated this technique believe that it is still in the concept level. Vongbunyong and Kara (2013) investigate the use of vision-based cognitive robotic disassembly process. Their results show that cognitive robotics is effective in performing automated disassembly as long as all the disassembly real world knowledge and behaviours are captured; a challenge that has not been resolved yet. They conclude that the automated disassembly process is significantly limited by many factors such as sensing, for example.

Duflou *et al*. (2008) provide a case based review of automated disassembly systems in the industry. According to the review, the most economical case is the disassembly plant for inverse manufacturing of Kodak's single use camera in Japan. Four cases out of 17 in the study are found highly profitable; six cases are intermediately profitable; four cases breakeven; and the remaining are loss making.

2.2.3 Methods, guidelines, and standards for product disassembly

Methods:

Methods to optimize disassembly process planning are used to generate different process plans and selecting the optimal one. Many studies are done in this area. Gungor and Gupta (1997) introduce a method for disassembly process optimisation based on total disassembly time. Due to the combinatorial nature of the problem, a heuristic approach is used to determine a near optimum disassembly sequence. Spicer (1996) developed a tool to generate product disassembly plan based on economical benefits of recycling and reuse. The author assumes the economical factor to be the only decision factor in the product recovery process, while other factors like environmental and societal benefits need to be considered. The model is also built and tested based on information from the auto industry; this questions the applicability of the model to other types of products. Spicer (1996) concludes that disassembly process in the automotive industry is economically not feasible under the studied conditions. This conclusion agrees with results showed by Feldman *et al*. (1999), which shows the optimization of the disassembly process contributes only 10-20% improvement of disassembly process. Hence, it is not promising enough for disassembly process improvement, since the product should be originally designed in a way that facilitates the disassembly process in the first place.

Since complete disassembly is not economically viable, Kara *et al*. (2006) develop a methodology for selective disassembly sequencing based on precedence diagrams. They used liner programming techniques to find the optimal sequence of removing a part based on the user's selection. Smith and Chen (2011) develop a rule-based method to optimise the disassembly process. The method adopted selective disassembly as an alternative for complete disassembly which is not considered as being cost effective.

Guidelines

Dewhurst (1993) mentions different principles and guidelines applicable to product disassembly, such as: 1) the use of simple product structure, and 2) Minimum number of different parts and materials. These guidelines are similar to the ones proposed by both, himself and Boothroyed, for design for assembly; yet, they are valid and important guidelines for disassembly.

Desai and Mital, (2003) summarize seven factors that affect the disassemblability. These factors guide product designer to design an easy to disassemble product. These factors are:

- Use of force: minimal use of force is recommended.
- Mechanism of disassembly: simple mechanism is preferable.
- Use of tools: standard tools are preferable to specialized ones.
- Repetition of parts should be minimised for easy identification.
- Recognisability of disassembly points.
- Product structure: simple structures are preferable.
- Use of toxic material is not recommended.

Vikrant (2012) identified DFD guidelines that maximize both manufacturing and EOL phases in product lifecycle. The mentioned factors and similar design guidelines can be categorised according to Bogue, (2007) in three categories:

1. Selection and use of material.
2. Design of components and the product architecture.
3. Selection and use of joints, connectors and fasteners.

It is recommended for the designer to look beyond these guidelines to include post disassembly operations and recycling process requirements. These guidelines are helpful for the designers for designing products with ease of disassembly and suitability for recycling.

Standards

In an effort to standardise disassembly operation times, Dowie T. (1994), in her PhD. dissertation, conducts a series of disassembly experiments. Operations involved in disassembly are identified and classified; set of times corresponding to these operation is established, and design rules for ease of disassembly are developed. The study does not account for access issues or execution problems, which are typically found in retired products disassembly process stages.

Kroll *et al*. (1996) develop a tool for estimating the ease of disassembly using work measurement analysis. The relative difficulty of each disassembly task is evaluated in four categories: accessibility, positioning, force, base time, and special conditions. The outputs of their study are the following: 1) standard times for disassembly tasks, and 2) evaluation charts that can be used to evaluate the difficulty of disassembly process. In this study, the base time is established based on standard tools. The use of specialised tools will significantly change the base time, which might totally affect the difficulty index; yet, the evaluation charts remain valid, since they are used for comparing different design options under the same conditions. Yi *et al.* (2003) provide new revised standard disassembly times based on type, size, and weight of connectors. Results were matched with actual manual disassembly times.

German standard, VDI 2243, provides comprehensive standard on product design for disassembly. It covers the different aspects of disassembly process; it considers the environment, technology, and economy of product disassembly (Association of German engineers,2002). The standard provides examples on how it can be applied during the early phase of product development.

Table 2.5: Methods, tools, and guidelines in manual, automated, and hybrid disassembly

	Method/Tool					
	Process optimization	**Standard disassembly times**	**Design for disassembly**	**Destructive disassembly**	**Adaptive disassembly sequencing**	**Support tools**
Manual disassembly	Kara *et al*., 2006. Gungor *et al*., 1997. Spicer 1996. Smith and Chen 2011	Dowie 1994. Kroll *et al*. 1996 Yi *et al.* 2003	Dewhurst 1993. Desai and Mital 2003. Bogue 2007. Harjula *et al*., 1996 Smith and Chen 2011			
Automated disassembly			Dewhurst 1993. Bogue 2007 Kiritsis 2011	Feldman *et al*., 1999. Seligr *et al*., 2002. Vongbunyong and Kara (2013)	Basdere and Seliger 2003. Vongbunyong and Kara (2013)	Kim *et al*., 2006. Kim *et al*., 2007. Schmitt *et al.* (2011) O'conell 2013
Hybrid disassembly		Dowie 1994.	Dewhurst 1993. Bogue 2007.	Feldman *et al*., 1999. Seligr *et al*., 2002.	Basdere and Seliger 2003.	Kim *et al*., 2007. O'conell 2013

2.2.4 Critical review of literature on product disassembly

The reviewed literature shows the following results:

1. Product original manufacturer involvement is essential for improving product disassembly operations profitability.

2. It is noticed that the depth of disassembly increases when the disassembly is performed by parties closely affiliated by the original manufacturer of the product.

3. Higher degree of automation of disassembly process requires higher cooperation between EOL treatment facility and original product manufacturer.

A very clear conclusion, which can be drawn from the previous results, is that the involvement of the original manufacturer in disassembly process makes it more feasible. That is because the ease of disassembly is noticed to be originally impeded in product design in the first place. This clearly shows that the manufacturer involvement is a key factor for success by incorporating and accounting for disassembly at the design level. Having many guidelines might limit the flexibility and freedom the designers should have. Complying with all these guidelines could result on a weak product design or product partial malfunctioning. These guidelines tell the designers what to do, but it does not tell the designers how to do it; in other words, it does not provide ready solutions to be used by the designers. An overview of researched methods and tools in manual, automated, and hybrid disassembly is provided in table 2.5; the following observation can de deduced:

- Current guidelines and methods are not addressing all aspects of sustainability; it focuses mainly on economical aspects, partially on environmental aspects, and rarely on societal aspects. This is because the disassembly process is usually driven by economical values, not environmental or societal values. Sustainable design guidelines and frameworks are highly needed to bridge this gap.
- It is obvious that many design guidelines could limit the creativity of designers. Fewer guidelines are needed instead; yet, they must be more comprehensive and efficient. Guidelines that lead to solutions would be more helpful than ones imposing roles and limits on designers.
- Current methods and procedures fail to highlight the importance of selecting proper joints and fasteners for ease of disassembly. For example: joints and fasteners are selected for ease of assembly; yet, no design guidelines suggest joint selection based on ease of disassembly.
- The optimisation of the disassembly process plan does not provide required improvement in disassembly time that makes disassembly process economically feasible; reduction between 60-75% is needed according to Willems (2007)

Based on the previous review, there is a *need for new methods for product disassembly which satisfy all sustainability requirements; environmental, societal, and economical requirements.*

Active disassembly A.Dis., a new field of research in product disassembly, is emerging. It uses active joints and fasteners, which can be disassembled in response to external triggers without direct contact between the product and the labour. This field is very promising in reducing the disassembly times, up to 200-250% improvement in disassembly effort. Compared to manual effort, improvement in disassembly effort can be claimed upon the use of active disassembly concept (Willems *et al*. 2007).

2.3 Active Disassembly (A.Dis.)

2.3.1 Concept of active disassembly

The concept of A.Dis. was first introduced by Boks and Templelman, (1998). They define A.Dis. as "the products that take themselves apart or split open at the end of their lifecycle. This can be accomplished for instance by using a drastic change in temperature or an electrical charge. In order for this to happen, the product would require an actuator inside it or less desirably, applied to it after its useful lifecycle." A panel of about 70 specialists are asked to evaluate the concept through a Delphi study carried by Boks and Templelman, (1998). The opinions of the panel members are divided into three categories:

1. This concept will never become feasible.
2. It will not be in use until after 2020.
3. By 2005-2010 this concept may indeed be in use.

The current status of this A.Dis. fits the third opinion, which is the most optimistic one. According to activedisassembly.com (2009) there are products that currently use this concept to disassemble them at their EOL stage.

The concept of active disassembly has developed since 1998. Many research centers are engaged in the development of the active disassembly concept. Currently, active disassembly concept is defined as "a built–in disassembly feature using innovative material or joint structure. This feature can be activated by external trigger(s) to initiate unfastening process of connection or set of connections".

The research in this field is fairly new and little; it was initiated as a prepare-ahead for the coming waste laws in European communities, especially the waste of electrical and electronics equipment directive (WEEE). The purpose of the research in active disassembly is to find technical and economical alternatives for manual disassembly. The targeted products for A.Dis. are considerably covered by WEEE (Carrell *et al.*, 2009). While the current researches and applications are targeting wide ranges of product, in concept, A.Dis. is applicable to any product (Duflou *et al.*, 2006).

2.3.2 Current types of active disassembly

The review of the research in (A.DIS.) showed that two types of active joints are used to initiate the disassembly process:

A. Joints based on material properties:

These are active joints that use material property of one or more of its element to activate the disassembly process; an example would be snap-fits made of smart materials that respond to heat triggers. Another example would be joints that use soluble nuts. The following details this type of active joints:

1-Shap memory polymers and alloys:

An advanced research in this field has been done by a research group at Brunel University, UK. The research group investigated the use of smart materials such as Shape Memory Alloys (SMA) for actuator devices and Shape Memory Polymers (SMP) for releasable fastener devices (Chiodo *et al*. 1998). The material used in this research has the property of changing its shape into another predefined shape if it is subjected to a specific temperature. Actuation of the SMAs and SMPs would happen just outside the product working-ambient temperatures for safety and practical reasons. Shape change occurs only under the predetermined temperature; this 'predetermined' temperature is based on material composition, and is therefore consistent and stable (Chiodo, *et al*. 1999[a]).

Smart materials are tested in disassembly of electronics product. Promising results achieve one to two seconds disassembly time. This improvement is made with a screws consisting of novel SMP 'thread loosing'. These screws achieved non-destructive A.Dis. of a Nokia 6110 cellular phone within a time of 1.5 seconds (figure 2.2). A.Dis. that use these types of SMPs provid the self-dismantling of a product housing without any destruction to the product (Chiodo, *et al*., 1999[b]).

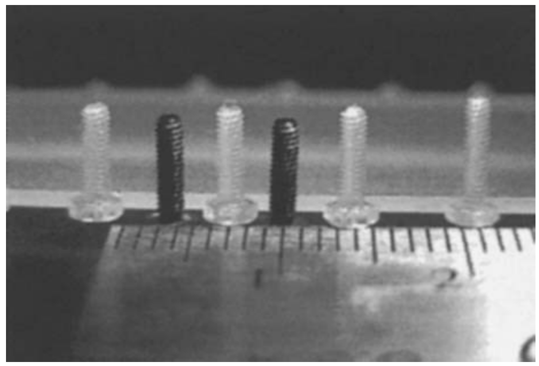


Figure 2.2: SMP screws used for (AD) of cell phone (Chiodo *et al*., 2002)

The use of smart material is also tested in A.Dis. of auto parts such as windshield removal, and disassembly of steering wheel airbag (Jones, N., 2003)

Chiodo and Ijomah (2012). Introduced new type of smart materials in A.Dis. Interstitial layer (IL) is a thin coating sprayed on components to join them; at EOL, components joined by IL can be disassembled by heating the joining IL.

He *et al.* (2013) investigate a new design of SMP snap-fit. A hollow snap-fit is designed based on maximum deflection and mating force. The design gives improved carrying load for the active snap-fit.

Liu *et al.* (2012) and Liu et al. (2013) introduced the concept of multi triggers, they propose a new design for A.Dis. SMP snap-fit. A decapitated head snap-fit is proposed where the joint is made of SMP snap-fit and SMA components, both responsible for providing the required separation force. The effect of heating media on SMP snap-fits is examined by Correll *et al.* (2011). Oil bath was found to be the optimal heating media.

2- Hydrogen storage alloy

The use of hydrogen storage alloy in A.Dis. is researched by Suga and Hosoda, (2000). Al- LaNiAl alloy joint, which is bonded by the surface activating bonding method, can be de-bonded using the hydrogen absorption phenomenon. The study demonstrates that a construction using an LaNiAl intermediate bonding layer can collapse in a media containing hydrogen under the pressure of 3 MPa at room temperature. Figure 2.3 shows the concept.

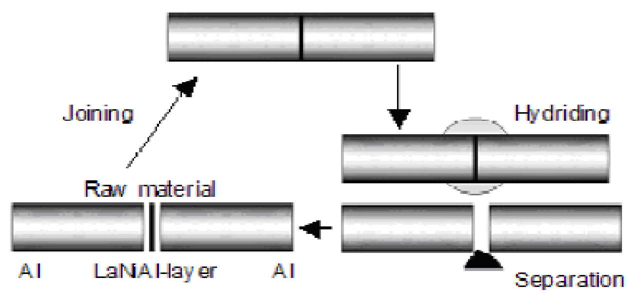


Figure 2.3: (A.Dis.) using hydrogen storage alloy (Suga and Hosoda, 2000)

Nakamura and Yamasue. (2010) provide, for the first time, LCA of hydrogen storage alloys fastener for home appliances. Fastener is made from mischmetal which can be triggered by Hydrogen absorption. Their results encourage serious consideration of A.Dis. in electric and electronic equipment (EEE).

3-Intermetalic compound

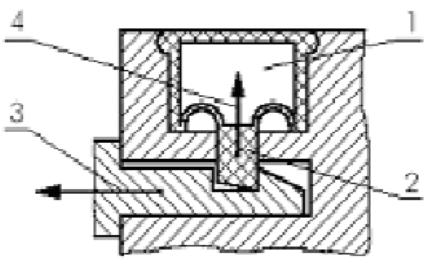
Embrittlement of the bonded interface by formation of brittle intermetallic compounds is also investigated by Suga and Hosoda (2000). A typical example is the Cr-Ni stainless steel. This joint can be actively disassembled if it is heated up to 800°C. High temperature reactions take place between the Al and Cr-Ni steel, and the joint collapses without applying any external force due to formation of the intermediate layer, with an amount of intermetallic compounds.

4- Trapped water in Si wafers

A.Dis. of bonded Si wafers is investigated by Kasa and Suga, (1999). A very simple concept is used to separate two wafers which were bonded while water is purposely trapped between them. When the wafers are heated enough, the trapped water evaporates, creating voids between the bonded wafers. The amount of water required to cause this type of de-bonding is calculated.

5- Pneumo - element

At technical university of Dresden Germany, a research is conducted on the physical properties of water and air to form conceptual designs for A.Dis. (Neubert, 2000). The research suggested three concepts; the first is based on pneumatic expansion. This physical phenomenon is applied in so-called "pneumo-elements", which are air-filled, closed, hollow bodies with partially flexible or mobile walls. By increasing the ambient pressure, the air included in the element is compressed. Differences of pressure between the enclosed gas volume and the environment are used to generate a displacement. Figure 2.4 demonstrates the concept.

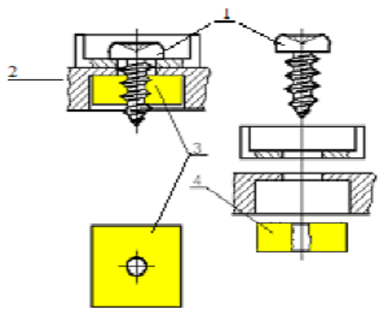


1) Closed air chamber,
2) Moving shape element,
3) Degree of freedom of the snap fit,
4) Degree of freedom of the shape element

Figure 2.4: Example of a pneumo-element (Neubert, 2000)

6- Water soluble element

The second concept is the use of water-soluble connections, see figure 2.5. Two kinds of materials are used: Methyl Cellulose (MC) and Carboxy Methyl Starch (CMS).These connections are soluble in water to the extent that they can lose their function as a fastener.



1) Regular screw,
2) housing,
3) water-soluble element in use,
4) water-soluble element after partially dissolving in water

Figure 2.5: Example of a water-soluble fastener (Neubert, 2000)

7- Freezing element

The third concept uses the volume expansion of water when it freezes. The volume increase in frozen water is used to generate enough displacement to unfasten the joint. This concept is considered impractical due to the large size of the freezing element needed to provide the required displacement for the disassembly process.

B. Joints based on structural properties

These are active joints that use geometry, shape, and sometimes material properties to provide disjoining action that disassemble the joint. An example of this type is the pneumatic snap-fit that respond to external pneumatic pressure as a trigger to activate joint disassembly. The following details this type of active joints

1- Heat activated snap-fit

Heat activated snap-fit was designed by Li *et al*. (2001). The design used both material and structural properties of the proposed joint. It comprises of two major parts: plastic part and metallic part, the plastic part provide the engagement mechanism, the metal part provides the thermo-mechanical force needed to disengage the snap-fit. Figure 2.6 shows the concept. The deflection of the metal causes disengagement of the plastic part.

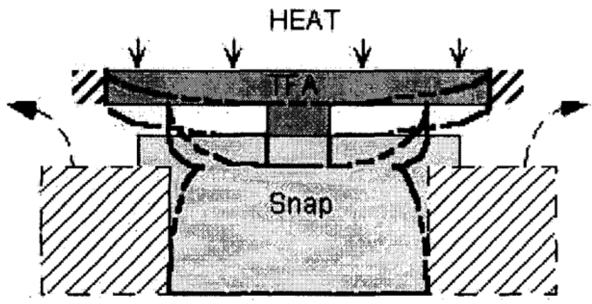


Figure 2.6: Design concept of a heat activated snap-fit. (Li *et al*. 2001)

The structure of this joint is optimised using the topology optimization method. The purpose of the optimization is to find the optimal structure that uses minimum heat and gives maximum displacement.

2-Pressure activated snap-fit

A research project at Katholieke University Leuven, Belgium develops and designs an innovative pressure activated snap-fit. (Willems, 2007). The research team develops a snap-fit that can be actively disassembled using high ambient pressure (Willems, 2007). The research team introduces the one-to-many disassembly concept; i.e., one triggering action (pressure) initiates many disassembly actions (all pressure-triggered snap-fits in the product) (Willems and Duflou, 2006). This concept drastically reduces the disassembly time for a product using this type of pressure activated snap-fits.

The concept of A.Dis. using pressure as a trigger is modelled in two-dimensional space (Willems and Duflou, 2006), see figure 2.7

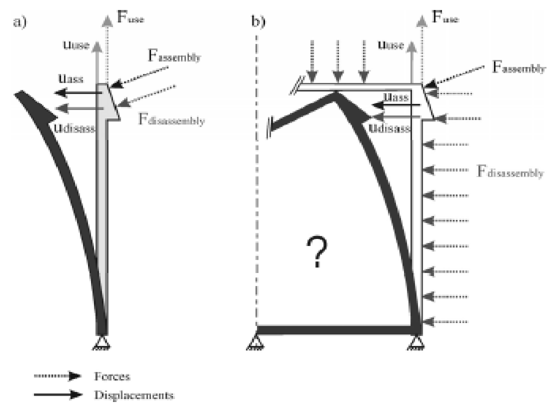


Figure 2.7: two dimensional snap-fit. a) Traditional snap-fit b) active snap-fit. (Willems and Duflou, 2006).

The three-dimensional version is developed in (Willems *et al*., 2007). The proposed design uses a pressure load of 50 Bar to produce 1.57mm displacement, which is needed to disengage the snap-fit. Further improvement is done by the team to reduce the pressure needed to activate the disassembly process; using the lever action, it is possible to reduce the pressure from 50 bars to 7 bars (Dewulf *et al*., 2009).

2.3.3 Potential triggers for active disassembly

There are a few possible physical phenomena that can be used as physical triggers for active disassembly process. Table 2.6 summarizes potential triggering principles for active disassembly suggested by Duflou *et al* (2006).

Table 2.6 :Possible physical principle for active disassembly. (Duflou, 2006)

External trigger mechanism	Possible trigger principle	Possible effect
Mechanical force	• Centrifugal force • Acceleration • Water jet	**Deformation** • Elastic, plastic **Material failure** • Erosion, splintering, breakage **Function Failure** • Removal of blockage element
Vibration	• Mechanical Vibration • Sound wave • Water wave	**Material failure** • Destruction after reaching eigen frequency **Function Failure** • Removal of blockage element

External trigger mechanism	Possible trigger principle	Possible effect
Pressure	• Pressure variation (Air/water)	**Deformation** • Elastic, plastic **Phase transformation** • Melting, evaporation, sublimation
Electrical	• Electric current	**Deformation** • Elastic, shrinking, expansion **Phase transformation** • Melting
Chemical reaction	• Reagent in surrounding atmosphere • Submerging in reagent	**Deformation** • Shrinking, expansion **Material failure** Changing material properties • Corrosion, dissolving, pyrolysis, pulvarization
Thermal reaction	• Joule effect • Radiation • Microwave • Submerging in hot water tubs	**Deformation** • Elastic, plastic, shrinking, expansion **Phase transformation** • Melting ,evaporation **Material failure** Changing material properties • Creep, brittleness, viscosity change, thermal shock, inverse material expansion
Magnetic field	• Presence of electromagnet • Magnetic ray interference	**Deformation** • Elastic, plastic **Phase transformation** • solid to liquid **Function failure** • attraction vs. repulsion
Light radiation	• UV-radiation	**Material failure** • Surface corrosion, brittleness
Biological action	• presence of bacteria • Enzyme producing chemical reaction • Biologically designed systems	**Deformation** • Shrinking, expansion, **Material failure** Changing material properties • Corrosion, dissolving, pulverization, melting, evaporation, sublimation

2.3.4 Design for active disassembly methodologies

Design guidelines for active disassembly are suggested by Chiodo *et al* (2005). These guidelines are developed solely based on the author's experience and their previous research; no diverse experiences are taken into consideration while creating these guidelines. The first set of guidelines are related to the economical feasibility of a design for active disassembly; it includes necessity, viability, effect on EOL, and disassembly level. The second set of guidelines includes: disassembly methods, actuator material choice, actuator design, orchestration, use phase, and output logistics. This set of guidelines is specific to one type of active disassembly method, namely smart materials.

A general framework for new fastener development is suggested by Willem *et al.* (2005) and Willems (2007). This framework consists of four functional requirements:

1. Degree of authorization: Easily, restrained, and non-detachable fasteners are suggested to match the proper level of authorization.
2. Degree of flexibility: new fastener development should maintain the designer flexibility.
3. Degree of functionality: triggered threshold level should not be reached during the operational period.
4. Degree of freedom: should be maximized in order to not affect the designer creativity.

Beside the four functional requirements, the frame work assumes that the economical feasibility of active disassembly is fulfilled.

Ideation tools are found useful for creating conceptual designs suitable for active disassembly. Due to the inventive nature of active disassembly, innovation tools were also used to create new conceptual designs for active disassembly. The following tools were cited in the literature of active disassembly.

- Brainstorming: Duflou *et al*. (2006) successfully used the brainstorming techniques to come up with many ideas and physical principles that might be used for active disassembly
- TRIZ contradiction matrix was used to create the possible conceptual design for active disassembly (Ziout *et al*., 2009). Chen *et al* (2007) used the same tool to invent the smart nut and central empty machine screw
- TRIZ Su-field was used to come up with a new active fastener using the magnetic field (Chen *et al*, 2007).

TRIZ, with its many innovation tools, looks like a promising methodology for creating new concepts for active disassembly.

2.3.5 Critical review of literature on active disassembly

All methods and concepts found in A.Dis. literature were individually evaluated in table 2.7. Thorough evaluation of A.Dis. literature shows the following common **deficiencies** and **gaps** among the proposed concepts:

1. Many existing A.Dis. concepts are proposed to target certain group of products, mostly WEEE products. Most of these concepts lack the applicability to a wide range of products.
2. Invention and development of A.Dis. joint requires deep knowledge and understanding of science.
3. These concepts came out of the expertise and knowledge of the researchers. This creates a meaningful doubt about the ability of designers to come up with similar inventive concepts suitable for their designs.
4. There is no framework found in literature, which systematically includes A.Dis. in product design and development process.
5. Most of current active disassembly concepts are triggered by temperature or pressure. New triggering concepts need to be investigated.

Current approaches in active disassembly have major deficiency, it does not consider all sustainability requirements in product design before incorporating A.Dis.. For example, the societal dimension of sustainability is missing in many of these approaches. In addition, some approaches focus on economical requirements while giving little importance to the environmental impacts of the proposed design.

The definition of active disassembly is not unified among researchers. Some researchers consider active disassembly as just the use of smart materials. However, a clear definition and characteristics of active disassembly are needed.

Based on this gap analysis, the following conclusions can be made:

- A generic A.Dis. definition would be helpful; it can be used to identify new potential concepts that can fit the definition and serve the purpose.
- There is a need for design methodology that can be used by product designers to innovate and design active joints that fit their product. This methodology is

expected to reduce the need for user's deep knowledge in science and principles of physics needed for active joint innovation.

- A research that produces new active joints would be a significant contribution to the A.Dis. field.
- Sustainability assessment that justifies A.Dis. consideration in product design would have positive impact on sustainable product design and sustainable development in large.

Table 2.7: Critical evaluation of current A.Dis. methods and concepts

Proposed method/concept	Critical evaluation of method/concept
The use of SMA to develop snap-fits and other fasteners that can be actively disassembled using heat (Chiodo *et al*., 1998).	• Cost of manufacturing of the SMA is considerable in comparison to standard engineering material. • Overall cost based on product lifecycle approach for this method needs to be compared to other alternatives. • Triggering temperature for disassembly is within possible working range, this could lead to unsafe conditions due to unwanted disassembly. • Not suitable for wide range of product. • Joint behaviour is not fully expected over long lives.
Interstitial layer (IL): a thin coating sprayed on components to be joined; IL. (Chiodo and Ijomah , 2012).	• IL can be disassembled by heating at elevated temperature which could cause damage to other parts.
Hollow snap-fit is designed based on max deflection and mating force. (He et al., 2013).	• The design gives improved carrying load for the active snap-fit. • Subjected to SMP drawbacks mentioned above.
Decapitated head snap-fit is proposed, the joint is made of SMP snap-fit and SMA components 9Lui et al., 2012)	• New design for A.Dis. SMP snap-fit makes separation easier than not decapitated snap-fit. • Subjected to SMP and SMA drawbacks mentioned above.
Use of hydrogen absorption to de-bond Al-LaNiAl alloy (Suga and Hosoda, 2000).	• The triggering pressure can be destructive for some products or parts (30 bars). • The joint is irreversible. • Suitable for metallic joints only. • The strength of the joint was not stated in the research.
De-bonding by evaporating trapped water between the Si wafers. (Kasa and Suga, 1999).	• High temperature is needed (200°C). • Very limited application.
Pnemo-element (Willems *et al*., 2005).	• Structure of the element was not optimized to get the maximum displacement with the minimum pressure. • Joint should be exposed to the applied pressure, joints inside product's case cannot be disassembled using this concept.
Water soluble connections (Willems *et al*., 2005).	• Cannot be used in humid environment. • Inadvertent use of water could ruin the product.
Freezing element (Willems *et al*., 2005).	• Low energy efficiency for this concept. • Large volume is needed to produce required disconnecting displacement (water expansion factor is 2%-4%).
Heat activated snap-fit (Li *et al*., 2001)	• Local application of heat is required. • Time consuming, since each snap-fit needs local

Proposed method/concept	**Critical evaluation of method/concept**
	application of heat.
Pressure activated snap-fit. (Willems and Duflou, 2006), (Willems *et al*., 2007), (Dewulf, *et al*., 2009).	• High pressure is needed to produce required displacement for disassembly (50 – 70 bars). • Using lower triggering pressure require bigger volume of the snap-fit. • Trade-off between triggering pressure and snap-fit size affect the suitability of this kind of snap-fits to many products.

3 END-OF-LIFE PRODUCT RECOVERY OPPORTUNITY ASSESSMENT[2]

This chapter provide assessment on the opportunity of incorporating active disassembly in product design. The purpose of this assessment is to identify EOL product recovery options and prove their feasibility. This chapter is organized in four sections: the first section defines EOL products, their recovery process, recovery options, and major stakeholders in the recovery process with their interests. The second section provides sustainability assessment for the opportunity to recover an EOL product through reusing the product - as a whole- in another use cycle. The third section provides a comprehensive assessment to recover EOL products - as parts and assemblies – through a set of potential recovery options. Lastly, the fourth section links the assessment results to the decision of incorporating A.Dis. in product design. This chapter is based on theories from Ziout *et al.* (2013[a]) and (2013[b]).

3.1 End-of-Life Product Recovery

3.1.1 End-of-Life Product Defined

A succinct and comprehensive definition of EOL product is laid by the European Economic Community directive on waste, which define EOL product as "*any substance or object which the holder discards or intends or is required to discard*" (waste directive 75/442/EEC., 2003). This definition is also adopted by directive 2000/53/EC to define EOL vehicles. Kiritsis *et al*. (2003) define EOL product as a product retired from functional environment due to technical, economical, social, and legal reasons. Waste directive identifies sixteen types of substances and objects to be considered as EOL products. These types of EOL product can be assigned to product life phases shown in figure 3.1; for example, mining residues or oil field slops are EOL products for the material extraction phase. Machining/finishing residues or off-specification products are

[2] This is outcome of joint research

EOL product examples of the manufacturing phase. Based on the previous definitions, and with the aid of closed loop lifecycle phases shown in figure 3.1, EOL product can be defined as material or product that does not fulfill the intended purpose of use during any phase of product lifecycle. EOL product will have this meaning throughout this Dissertation.

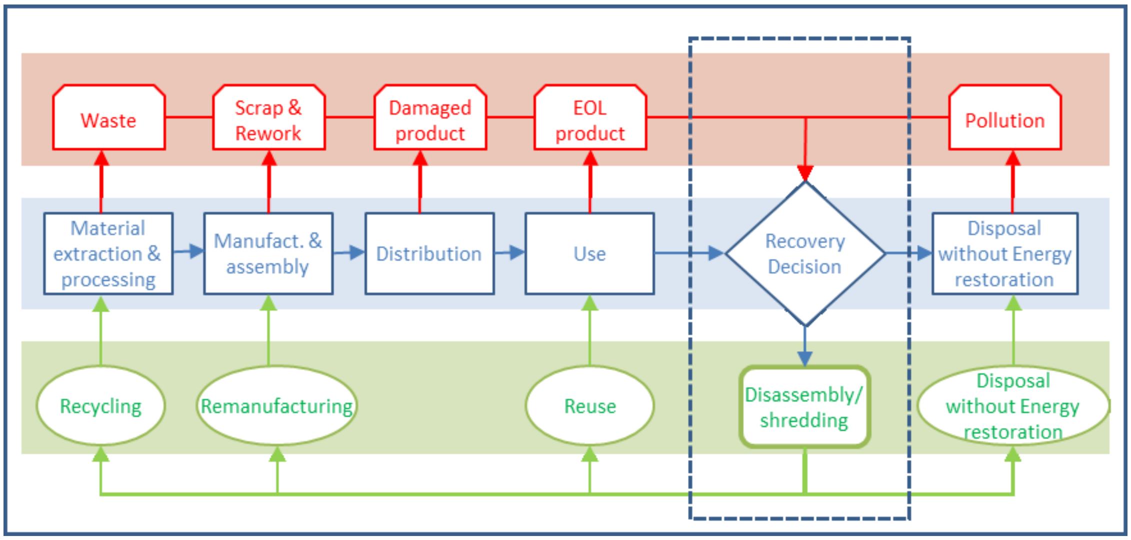


Figure 3.1: Types of EOL products related to product lifecycle phases

EOL products contain value which is usually not completely restored . Hence, the objective of EOL product recovery is to restore this contained value. Saman M. *et al.* (2010) identifies three types of values: first, value contained as energy, second, value contained in materials, and third, value contained in parts, assemblies, or product. Traditionally, the amount of value restored as energy is less than the material, and material value is less than the contained value in parts or products. This general ranking is followed in the recovery process.

3.1.2 Recovery Process

EOL product recovery process is studied from different perspectives. Legislation is considered to be the main starter to initiate the process (Rahimifard *et al*., 2009). The impact of legislation is clear through EU directives and national legislations. Comprehensive view of recovery process is shown in figure 3.2 through the IDEF0 diagram, which analyses a process from four perspectives: process inputs, outputs, controls, and mechanisms.

1. Recovery process input: the only input of recovery process is the returned flow of EOL products. Quality, quantity, technical characteristics, and timing of returned flow are the major factors to be included.

2. Recovery process output: the direct outputs from the recoverer point of view are recovered object (energy, material, or product) and profit. Indirect outputs are sometimes overlooked by the recoverer. Hula, *et al*. (2003), Lee *et al*. (2001), and Staikos, (2007) count environmental benefits as an output of the recovery process. Societal benefits are considered by Chan, (2008), Toffel, (2002), and Kiritsis, (2003). Compliance with corporate citizenship and improving its reputation are also indirect benefits that should be linked to recovery practices (Matsumoto and Umeda, 2011).

3. Recovery process controls: they are factors that govern recovery process and have influence on its strategic decisions. Leberton (2006) concludes that direct legislative pressure drives OEM to recover their products when recovery process is not profitable. Matsumoto and Umeda (2011) consider OEM involvement as a major factor to control and direct the recovery process. Goggin (2000) demonstrates the influence of the supply-demand relationship on recovery process. Also, governmental taxation and incentives control the recovery process of certain products within a region.

4. Recovery process mechanisms: actions that make the recovery process happen include: EOL product collection systems and transportation, recovery options and processing technologies, and distribution channels. Innovations in recovery technologies have enlarged the feasible space of recovery options; Shu and flowers (1999) relate possible recovery options to cost of recovery technologies.

Process mechanisms are the operational aspect of the recovery process; it requires major attention from the decision maker. Once the input product is determined, the decision maker needs to decide the mechanisms of the recovery process to optimize the value of its output (output product and profit). Direct and indirect (environmental, societal, and corporate intangible benefits) outputs are considered in this work. To optimize the output value, the decision maker needs to investigate all possible recovery options. Possible recovery options are explained in section 3.1.4

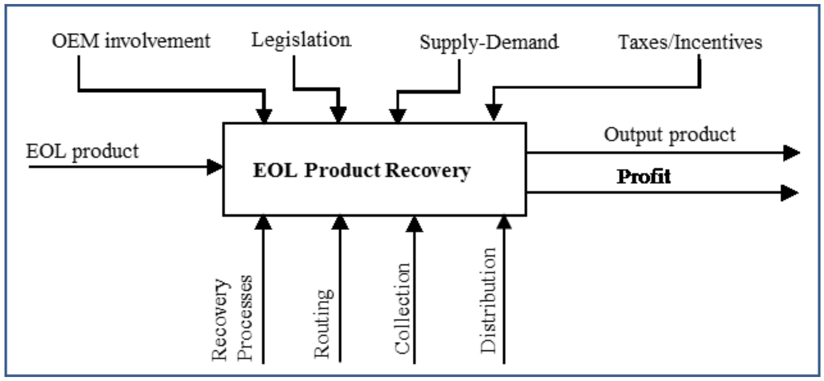


Figure 3.2: IDEF0 of EOL product recovery process

3.1.3 Interested parties and their drivers in end-of-life product recovery

Four major interested parties in EOL product recovery can be identified; original equipment manufacturer (OEM), independent recoverer, end user, and governments and municipalities, who are the major players in the recovery process. OEM involvement could be driven by technical issues such as providing spare parts in the case of engine remanufacturing (Seitz and Wells, 2006). Also, OEM is driven by financial and/or environmental objectives. The number of remanufacturing business in USA is estimated about 73 thousand firms with annual sales of $53 billion (Hauser and Lund, 2003). Independent recoverers are driven merely by economical benefits (Matsumoto and Umeda, 2011).

End users drivers for product recover vary due to variation in the type of end users and their purpose of ownership. Stevels and Boks (2000) identify three types of users; Private (personal), professional, and institutional end users. The end users' involvement in product recovery can be rooted to economical gain of reselling/ buying used products, improving product functionality through repair and refurbishment, or driven by their awareness towards their society and environment. Governments and municipalities build and run recovery facilities for the benefit of the society and environment. Indirect economical benefits also could drive governments' involvement in product recovery (energy restoration projects).

Knowing interested parties in the product recovery process and their drivers helps in designing a decision method which can effectively and efficiently address the decision maker's needs and preferences. Although the drivers for involvement in the recovery process are similar, their weights are different from one party to another. The reviewed literature in section 3.3 2.3 shows that most decision methods lack this inclusiveness feature. The majority of the decision methods found in literature approach the problem from limited perspectives.

3.1.4 Recovery Options

Identification and definitions:

Different terminologies of recovery options exist. A few to mention are: resale, reuse, remanufacture, repair, refurbish, reclamation, high grade recycling, low grade recycling, incineration, scrap, and disposal to landfill. Clear cuts between options are sometimes hard to define. The problem becomes more ambiguous when it comes to terminologies used by industries in their daily activities; for example, auto recyclers use the terminology "recycling" to refer to parts reused. In literature, authors have attempted to define and classify recovery options based on assumed criteria. Wadhwa *et al*. (2009) identify five recovery options based on operational perspective criteria; based on degree of required disassembly: repair and reuse, refurbishing, remanufacturing, cannibalization, and recycling. Jun *et al*. (2007) classify recovery options based on recovered input (product, part, material). At the part level, four options are identified: disposal and replacement, reuse, reconditioning, and remanufacturing. Thierry *et al*. (1995) classify recovery options according to two major criteria identity and functionality of EOL product; repair, refurbish and remanufacturing. These options are identified when the product keeps its original identity. Repair is selected when the purpose is to bring the product into functioning state,refurbish is to bring functionality higher than in repair, and remanufacturing is to bring the product to as-new functionality. If the product loses its identity then recycling and canalization are identified, in cannibalization selective components retain their functionality.

Researchers attempt to define recovery options by giving criteria specific for each option instead of giving general criteria that work for all options. Ming *et al.* (1997) define the following recovery options: resale when EOL product is recovered and sold with minimal intervention, remanufacturing when EOL product restore its functional and cosmetic value to its original condition, upgrade is done on existing product at owner premises to add new functionality, recycling is to recover materials and perhaps components, and the last option is scrap, that is when product is sent to landfill or incineration. A concise definition of remanufacturing is set by Hauser and Lund (2008) after accumulating twenty years of practical experience in the USA remanufacturing business; remanufacturing is defined as the process of restoring a non-functional, discarded, traded-in product to like-new condition.

The reviewed literature shows that clear cut on recovery options definition does not exist in literature or practice. Also it is clear that the suggested criteria used to identify recovery options are not capable to do so without interfering and tangling between options. For example, a downgraded component could lose its identity while it is recovered for reuse purposes. Also in real life practice, some refurbished products are at like-new condition with a warrantee matches the OEM warrantee without being considered as a remanufactured product. This research provides a new identification method which consists of two hierarchies; at the first level, recovery options are classified, for the first time, based on recovery process output. At the second level recovery options are projected along a continuous scale showing the degree of reprocessing. At the first level, three recovery options can be identified. When the recovery process output is a product (whole, subassembly, or component) then reuse is identified. If the output is materials, then recycling is identified, and energy restoration is finally identified when the output is energy. At the second level, each option is further classified based on the degree of reprocessing involved. Figure 3.3 explains the suggested classification.

Recovery options hierarchy:

Recovery options are prioritized similar to Lansink's ladder for waste management which is followed in the EU countries. For example, the environmental management act of Netherlands (2004) prioritizes recovery options as the following: "Recovery through reuse, recovery through recycling, recovery as fuel". Similar and more detailed hierarchy is suggested by Stevels and Boks (2000); from an environmental perspective, they prefer reuse of product as a whole, then subassembly or component, then material recycling in its original application, or if it is not possible, in a lower application, and finally energy recovery as direct fuel or as heat to generate electricity. Mazhar *et al*. (2005) argue that a considerable amount of resources can be saved by avoiding the premature disposal of components. In addition, large manufacturing costs saving can be achieved by shifting material recovery towards component reuse. Nasr and Thurston (2006), and Mangun and Thurston (2002) argue the same.

Prioritizing recovery option from an environmental perspective is important; yet, it is not sufficient. Sustainability point of view would be more accurate and comprehensive; economical, environmental, and societal perspectives need to be considered in prioritizing recovery options. Moreover, it has been argued that reuse of consumed product is not necessarily better for the environment and resource conservation. Compared to used products, new products could be superior in saving energy and efficient resources utilization. This could outweigh the savings result from reuse technologically obsolete product, which is proved by Ziout et al. (2011). Their sustainability assessment approach, using an example of an EOL manufacturing system, shows that the decision is case-dependent and reuse is not always preferred over using new product. The next section provides a model to evaluate the reuse of a retired product against a new one.

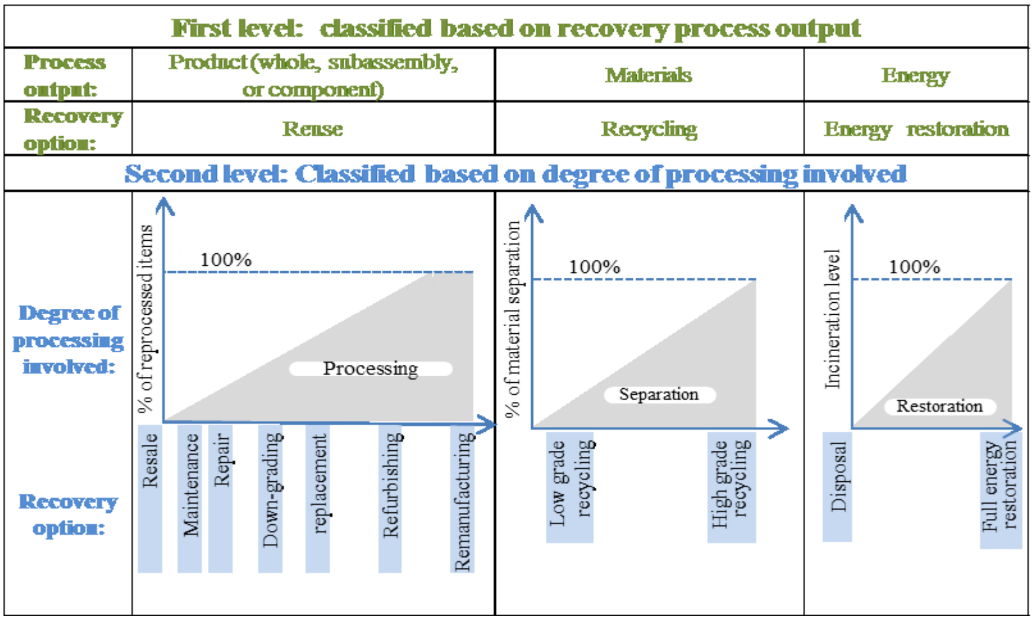


Figure 3.3: Classification of EOL recovery options

3.2 Assessment of sustainable recovery for EOL product as a whole

3.2.1 Purpose of the assessment

Reusing retired products is driven by pressure exerted by active consumers groups, legislation, industry leaders, and benefit/cost opportunities (Polonsky 1994, Rose 2000).

The decision to put a retired product into another use cycle after its first use is not only a financial decision, but also an environmental and societal one as well. A cost model is developed by Kaebernick *et al*. (2003) to assess a product's EOL options. The purpose of EOL products reuse is to save resources that would be needed to build new products and reduce their environmental burden. These resources include materials, energy, capital, and skills. Saving these resources is one of the goals of sustainable development.

This section provides decision makers with a method to assess the sustainability of reusing an EOL product; the assessment is conducted with respect to use a new product. Although it looks more preferable to use, an EOL product compared to its identical new one, research and practice prove that it is not always true. For example, savings made by using EOL white goods (washing machine, fridge, and stove) do not usually outweigh savings made by using new goods due to their energy efficiency. The proposed model is different from previous literature in its scope and focus; it addresses a specific case of EOL product reuse. The model focuses on the use phase of an EOL product.

The purpose of this assessment is to comply with the requirements of the proposed framework in this research, which requires this assessment to prove the feasibility of reusing an EOL product as a whole from sustainability point of view. Once the EOL product is proved for reuse, then this option will be the most preferred comparing to options such as parts and assemblies reuse, recycling, or dumping.

3.2.2 Assessment model development

3.2.2.1 Scope of the assessment

The scope of this assessment is EOL products. The assessment includes the three pillars of sustainability; , economical, environmental, and societal sustainability. Although the assessment model can be used by any potential EOL product user; institutional users might find it more useful than consumer users. Consumers make primitive cost/ benefit analysis to decide whether to buy a used or new product, while institutions need to do more comprehensive assessment to take this decision. Institutional EOL products such as machines, equipment, tools, and transportation means that they have – comparing to consumer products- longer life, higher economical value, and higher environmental and societal impacts. Therefore, reuse of these EOL products requires sustainability assessment developed in this section

3.2.2.2 Data collection

The proposed model has to consider the three pillars of sustainability- economical, environmental, and societal. Effective sustainability assessment models should have the following characteristics:

1. Usage of available data
2. Ability to address case-specific issues, e.g. EOL product reuse under varied conditions and geographical regions
3. Provide reliable and consistent information.

Effectiveness of the model depends on quality of indicators used in the model. Feng and Joung (2010) mentioned seven characteristics for effective sustainability indicators (being measurable, relevant, understandable, manageable, reliable, cost effective, and measurable in timely manner). While considering these requirements, the final list of sustainability indicators for the developed model is collected through two stages:

1. Initial list of indicators which are gathered from reviewed literature.
2. Final list of indicators which are selected based on experts judgement obtained by a field survey.

The final list of indicators and their weights is extracted by extended survey results which target the reuse of retired manufacturing systems as EOL products. Manufacturing system reuse includes a single machine, work cell, or production line. The targeted geographical area is developing in non-industrialized countries

Survey structure:

To address the sustainability aspects of EOL manufacturing system reuse, the survey is structured in three sections, plus one more general section; each section deals with one aspect.

Section one: deals with economical aspects,

Section two: deals with environmental aspects.

Section three: deals with societal aspects.

Section four deals with general issues related to the sustainability of manufacturing system reuse in non-industrialized countries.

On a scale between one and four, participants were asked to carefully rate selected key indicators related to each aspect.

The survey is designed to answer the following research questions:

1. What are the most relevant indicators to assess sustainability of manufacturing system reuse?
2. What is the best metric to measure, calculate, or estimate each indicator?
3. What are the appropriate weights for each of the aspects?

Sections1-3 answer the first two questions, while part four answers the last question. These results and data obtained from this survey are used to develop the proposed assessment model.

Survey results

Analyses of the survey revealed the following results:

Demographics of the surveyed companies

The survey covered a wide spectrum of industries in the Middle East, specifically in Jordan. The survey targets the population of manufacturing companies in Jordan who showed interest in manufacturing system reuse. Eleven completed surveys were received from companies who work in fabrication, automotive, polymers' producers, hygiene paper, and chemicals' producers. Most of the surveyed companies are of medium size, where the number of employees ranges from 50 to 250. With exception of one company, all companies have facilities in only one country; the exception happens to be part of a group that has facilities in multiple countries. Generally, the surveyed companies were established 20 to 50 years ago, mostly with customers of local nature.

Economical indicators

Participants rated seven indicators related to economical aspect of reusing EOL products in general and EOL manufacturing system in particular. Out of the seven indicators, six were rated as important or very important. These indicators are:

E1: Expected revenues to be generated by EOL product, where:

$$E1 = B - C \quad (1)$$

(B is total benefits; C is total cost.)

E2: Capital investment in EOL product, where:

$$E2 = Capital\ investment \quad (2)$$

E3: Expected value added by EOL product, where:

$$E3 = S - C_m \quad (3)$$

S is Expected sales or service generated by the product; C_m is Expected costs of materials and consumables consumed by the product.

E4: Infrastructure investment needed by EOL product, where:

$$E4 = \sum_{i=0}^{n} (Infrastructure\ cost)_i \quad (4)$$

E5: Financial risks related to environmental and governing laws violation, and other risk factors caused by using EOL product. It is assessed through two factors: The magnitude and the probability of the loss, where:

$$E5 = L * P(L) \quad (5)$$

L: Financial loss ($), P(L): Probability of occurrence, P(L) can be calculated based on the company's historical data, or it can be estimated where data is not available.

E6: Expected increase or decrease in invested capital in EOL product. Inflation rate and depreciation rate governs the net value of E6, where:

$$E6 = E2 * (f - Dp) \quad (6)$$

f: Inflation rate, Dp: Depreciation rate

Environmental indicators

In evaluating environmental sustainability indicators, participants selected six indicators out of eight as the most related. These indicators are classified into two groups:

First group: Natural resources utilization indicators. Three indicators related to natural resources utilization are identified (V1, V2, V3).

V1 is materials yield, which relates to the efficiency of EOL product in turning input materials into useful output - a key indicator for EOL product environmental sustainability. Figure 3.4 shows material flow for EOL product. Input materials include direct materials that appear in the final output and indirect materials used by EOL product to indirectly produce the required output. V1 considers both the quantity in (kg) and material's sustainability in terms of its recyclability and renewability. Total input materials are calculated using equation (7).

$M_{input} = \sum(W_i * PF_i)$ (7)

Where W_i: weight of material i needed to produce one unit weight of final output, and PF_i: Potency factor of that material. PF = [1/3; renewable and recyclable materials, ½; renewable or recyclable, 1; not renewable and unrecyclable].

Materials yield of an EOL product is calculated using equation (8).

$$V1 = \frac{M_{out}}{M_{Input}} \quad (8)$$

M_{out} : is the unit weight of final output produced by the product.

V2 is the quantity of water used by the EOL product to produce the unit weight of output. It worth mentioning that the region where the survey was conducted is among the water poorest regions in the world. V2 was calculated using equation (9).

V2= annual water consumption / annual weight of output (9)

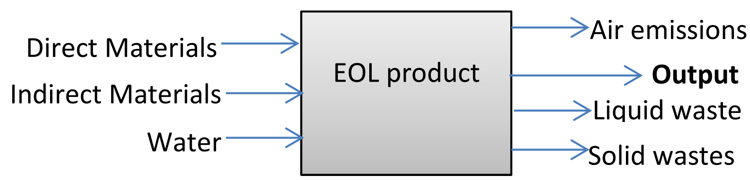


Figure 3.4 : Material flow for EoL product

V3 is quantity and type of energy needed to produce a unit weight of final output. It also considers percentage of total primary energy resourced from renewable resources. V3 was calculated using equation (10).

$V3 = [Energy_{per\ unit\ of\ weight}]. [(Total\ energy - Renewable\ energy) / Total\ energy]$ (10)

Second group: Indicators related to pollution (V4, V5, and V6). To reflect individual importance of each substance; quantity is rated by Toxicity and an Environmental Score TES. TES is a measure developed by an agency for toxic substances and disease registry ATSDR (2011). TES determines the minimum quantity of a substance that can cause harm to the humans or the environment.

V4 is a type and quantity of air emissions caused by EOL product. V4 Is calculated using equation (11).

$$V4 = \sum_{i=0}^{n} \frac{W_i}{TES_i} \quad (11)$$

$W_{i:}$ is hourly weight of substance *i* emitted to air. TES_i : Toxicity and environmental score of substance *i. n:* total number of all air emissions caused by EOL product operations.

V5 is type and quantity of liquid and solid waste caused by EOL product. V5 is calculated using equation (12).

$$V5 = \sum_{i=0}^{n} \frac{W_i}{TES_i} \tag{12}$$

$W_{i:}$ is hourly weight of solid or liquid waste *i* produced by EOL product operations. TES_i: Toxicity and environmental score of substance *i. n:* total number of all solid and liquid wastes caused by EOL product operations.

V6: Type and quantity of hazardous waste caused by EOL product. V6 is calculated as in V4 and V5 with exception that only hazardous substances are taken into consideration. The Code for Federal Regulations- title 40 (CFR, 2012) is adopted to identify hazardous waste. According to the code, waste is considered to be hazardous if it is ignitable, reactive, corrosive, or toxic. V6 is calculated using equation (13).

$$V6 = \sum_{i=0}^{n} \frac{W_i}{TES_i} \tag{13}$$

$W_{i:}$ is hourly weight of Hazardous waste *i* produced by EOL product operations. TES_i: Toxicity and environmental score of substance *i. n:* total number of all hazardous wastes caused by EOL product operations.

Societal indicators

Few indicators from societal aspect of EOL product reuse are identified to be important; only three indicators out of ten are selected by the survey participants to be the most related. They are:

S1 is an impact of EOL product operations on local communities, in terms of health, education, housing, infrastructure, etc. S1 is calculated as the total expected money to be spent on community development activities. It is calculated using equation (14).

$$S1 = \sum_{i=0}^{n} (Expense\ of\ comunitiy\ development\ activity)_i \tag{14}$$

n: total number of community development activities sponsored by the institution who use EOL product

S2 is the ability to operate the EOL product using existing local skills. It is calculated using equation (15).

$$S2 = \text{No. of local skills} / \text{total no. of required skills} \quad (15)$$

S3 is impact of EOL product on operator safety, productivity, and cost. Total number of hours needed to train operators to safely and productively operate EOL product is strongly measure the ease of operating an EOL product, and consequently its impact on operators safety and productivity. S3 is calculated using equation (16).

$$S3 = \text{Total hours of training} \quad (16)$$

Issues related to EOL products reuse in non-industrialized countries

The survey results showed that sustainability aspects are not of equal importance; at least from the participants' point of view. This is due to the fact that each country has its own regional sustainability priorities. The results found in the survey are supported by the following facts about non-industrialized countries:

1. The existence of fierce competition coming from foreign industrial giants. This makes economical sustainability first priority for EOL product reuse in non-industrialized countries.
2. Cheap labour costs makes EOL products that require intensive manual work a feasible option compared to new high tech automated products.
3. Non-industrialized countries are not environmentally polluting countries. This gives their institutions a relief from considering environmental sustainability as first priority.
4. Ineffective governmental regulations, weak consumer pressure, and poor management awareness put environmental sustainability at the end with low importance (8%). Institutions and corporations are not fully taking their responsibility towards environmental sustainability of community where they perform their operations.

Considering all these facts and results with the aid of the theoretical base explained next, a model to evaluate sustainability of reusing EOL product is proposed. The model gives decision makers a single value that can be used to compare sustainability of EOL products with the identical new product.

3.2.2.3 Theoretical base of the prosed model -Analytic Hierarchy Process-

The proposed model is developed based on the Analytic Hierarchy Process (AHP) theory, which relies on judgment of experts to derive a priority scale (Saaty, 2008). AHP is developed by Saaty in 1980 as multi-criteria decision tool that can be used to select the best alternative that fits a certain goal according to specific criteria. Since then, AHP has been applied in a wide range of applications; military, transportation, resources allocation, product design, and sustainable manufacturing.

The use of AHP is preferred in the case where absolute data is either not available or their interpretation is subjective. To tackle these challenges in decision making, AHP provides a consistent method of deciding upon different alternatives. As per Saaty (2008,1990), the method consists of the following steps:

1. Define problem in hand, and determine kind of knowledge sought.
2. Rephrase the problem in the hierarchical structure: top level has the goal of the decision, intermediate levels have the criteria and sub criteria, and the lowest level has the alternatives or options to satisfy the goal in the top level.
3. Construct the pairwise comparison matrices. Comparison matrices are constructed by conducting pairwise comparison between the elements of each level with respect to each element in the immediate upper level.
4. Use eigenvector of each matrix to find element's relative weight. For each eigenvector check for consistency index CI and consistency ratio CR. For further details see next section.
5. Select the alternative that scores the highest in satisfying the goal

AHP is used in the field of sustainable manufacturing; Shaik and Kader (2011) use AHP to assess sustainability aspects of revers logistic system. Jawahir *et al*. (2009) use AHP to assess product sustainability using lifecycle approach. Gupta *et al*. (2011) use AHP to study product design for sustainability and provide sustainability index for alternative designs.

3.2.2.4 Development of analytic hierarchy process model

Based on literature reviewed on sustainability assessment, the assessment is usually conducted by evaluating many indicators separately without trying to lump these indicators together as one figure. The AHP model is developed to tackle this and other challenges in sustainability assessments of EOL product reuse. The model is developed according to the steps suggested by (Saaty, 2008,1990).

Problem definition:

Sustainability assessment for EOL product is needed to help decision makers choose between buying an EOL product or its identical new one.

Problem hierarchical structure:

The problem is structured in three major hierarchies: top, intermediate with two internal levels, and bottom level. At the top, level 1 has the goal of the problem which is selection of the most sustainable option from the available options, namely new products and used products. At the intermediate hierarchy two levels are defined; level 2 and level 3.Level 2 contains the three aspects of sustainability assessment, which is considered as the major criteria for satisfying the goal "selection of most sustainable option". Level 3 contains the sub-criteria of each aspect in level 2. These sub-criteria are the indicators determined using survey results. At the bottom hierarchy, level 4 has on hand alternatives. In this study two alternatives are available: EOL product and its identical new one. This does not mean the proposed model is limited to two alternatives; in fact, it can take two or more alternatives without a need for any modification of the model.

Importance matrices:

Importance matrices are the core of the AHP model. It is a systematic way of translating a subjective qualitative assessment into a quantitative assessment. Importance matrix is formed by conducting pairwise comparison between a set of criteria. Comparison is made with respect to an element immediately in the upper level. The purpose of importance matrices is to find weight of each criterion. A set of criteria weights is called eigenvector. The importance rating suggested by Saaty (2008) shown in table 3.1 has been adopted throughout this work. Importance matrices are constructed from top to bottom of the structure as shown below.

Level 1 importance matrix: since there is only one element in level 1, the importance matrix is 1X1 matrix with one scalar entry which is 1. This indicates that the element has the same importance compared to itself.

Level 2 importance matrix: level 2 has three criteria that need to be compared with respect to the element in level 1. The matrix in the case of level 2 is 3X3 and is shown in table 3.2.

The importance matrix in table 3.2 is to be read as follows: criterion of row 1 (economical) has equal importance as that of criterion of column1 (same); it is seven times more important than the criterion in column 2 (environmental), and five times more important than the criteria in column 3 (societal). The same interpretation applies to the criterion in row 2 and 3. The importance in ratings (matrix entries) is based on the survey results using rating scale shown in table 3.1. The eigenvector is calculated according to Saaty's (1990) method (see last column of Table 3.2). This necessarily means: "with respect to selection of most sustainable option, economical aspect weighs 73.1%, environmental aspect weighs 8.1%, and societal aspect weighs 18.8%".

To assess to which extent the calculated weights represent expert's actual judgements, consistency index CI and consistency ratio CR are calculated. According to Saaty (1990), the value of CI is $((\lambda max - n)/ (n-1))$, where λmax is the principal eigenvalue of importance matrix, and n is number of elements in the matrix. CR is the ratio between calculated CI and average CI of completely random matrices of the same size n. CR has to be ≤ 0.1; otherwise, the importance matrix is not consistent and hence, the calculated weights do not reflect the expert's actual judgements.

Level 3 importance matrices: pairwise comparison of economical indicators in level 3 with respect to economical aspect in level 2 gives 6X6 importance matrix. Environmental indicators pairwise comparison with respect to environmental aspect gives also another matrix of same size (6X6). Pairwise comparison of societal indicators gives a 3X3 matrix. The entries for the three matrices are obtained from the conducted survey and reflects the judgement of experts being surveyed. Users of the proposed model have the option to use these entries or modify them according to their experience and judgement.

Table 3.1: Importance rating (Saaty 2008).

Importance	*Definition*	*Explanation*
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favors one activity over another
5	Strong importance	Experience and judgment strongly favors one activity over another
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2-8	Intermediate values	If the activities are very close
Reciprocal	reciprocal of above values	If activity i has one of the above non-zero numbers assigned to it when compared to activity j, then j has the reciprocal

Weights shown in table 3.3 are local weights; i.e., they are weights with respect to the corresponding criterion in the upper level, while global weights with respect to the goal should be sought. Global weights of sub-criteria can be calculated by multiplying their local weights by the weight of corresponding criteria in the upper level. For example, economical indicators in global weights will be their local weights multiplied by the weight of the economical aspect in level 2. It would be [0.731].[0.509 0.290 0.101 0.085 0.034 0.034]^T. Hence global weights are [0.372 0.212 0.074 0.062 0.025 0.025]^T . Similarly, global weights of environmental indicators are [0.029 0.002 0.013 0.004 0.004 0.029]^T ,and societal indicators of global weights are [0.063 .063 0.063]^T. Sub criteria global weights are used to evaluate alternatives with respect to the problem's goal.

Table 3.2 : Importance matrix of criteria at level 2

	Economical	Environmental	Societal	***Weight***
Economical	1	7	5	***0.731***
Environmental	1/7	1	1/3	***0.081***
Societal	1/5	3	1	***0.188***
CI = 0.032	***CR = 0.056***			

Level 4 importance matrices: level 4 has the available options, which are new and used product. It worth mentioning, as highlighted before, that although this model uses two alternatives, it is still capable of evaluating more than two. Importance matrices at this level are constructed through pairwise comparison of the two options with respect to each indicator in level 3. So, fifteen matrices are obtained at this level. Pairwise comparison between alternatives is obtained through specifications and performance of each alternative with respect to the indicator in question. Experts' judgment can be used whenever data is not available. Once importance matrices entries are determined, weights, CI, and CR are calculated for each matrix.

Best Alternative selection:

To select the alternative that mostly satisfy problem goal (most sustainable option), sustainability index for each option need to be calculated. A sustainability index vector that represents all alternatives can be calculated through the following equation:

[Sustainability index] = [Alternatives' weight matrix] . [Indicators' global weight vector] (17)

The best alternative will be the alternative corresponds to the highest value in the sustainability index vector calculated above. The case study in the following section demonstrates the use of proposed model:

Table 3.3: Importance matrix of Criteria at level 3

With respect to economical aspect								*With respect to environmental aspect*								*W.R.T. societal aspect*				
	E1	E2	E3	E4	E5	E6	**Weight**		V1	V2	V3	V4	V5	V6	**Weight**		S1	S2	S3	**Weight**
E1	**1**	3	7	7	9	9	**0.509**	V1	**1**	9	3	7	7	1	**0.353**	S1	**1**	1	1	**0.333**
E2	1/3	**1**	5	5	7	7	**0.290**	V2	1/9	**1**	1/5	1/3	1/3	1/9	**0.027**	S2	1	**1**	1	**0.333**
E3	1/7	1/5	**1**	1	5	5	**0.101**	V3	1/3	5	**1**	5	5	1/3	**0.165**	S3	1	1	**1**	**0.333**
E4	1/7	1/5	1	**1**	3	3	**0.085**	V4	1/7	3	1/5	**1**	1	1/7	**0.051**					
E5	1/9	1/7	1/5	1/3	**1**	1	**0.034**	V5	1/7	3	1/5	1	**1**	1/7	**0.051**					
E6	1/9	1/7	1/5	1/3	1	**1**	**0.034**	V6	1	9	3	7	7	**1**	**0.353**					
CI= 0.072				**CR=0.058**				**CI=0.046**				**CR=0.037**				**CI=0**		**CR=0**		

3.2.3 Model application in machinery reuse

3.2.3.1 Case study of single screw extruder pelletizer - capacity 250 Kg/hr:

A facility, which works in preparing composite polymers pellets located in the same geographical region where the survey was conducted, is planning to buy a machine for manufacturing composite polymer pellets. The product in this case study is a machine which mixes polymeric virgin pellets with its additives (such as CaCo3, heat stabilizers, plasticizers, etc.) to from composite pellets. Although it is a common practice in that region to buy used plastic machinery and not new ones, the company is interested in making their decision based on comprehensive sustainability assessment for both options.

3.2.3.2 Analysis

Data are collected from the company and presented in table 3.4. The proposed model has been implemented. Indicators are determined by the survey, and results are used as criteria to evaluate the available options. Comparison matrices constructed based on the survey results are also used. Analysis is detailed in the following steps:

<u>Step1- Define problem goal:</u>

The goal of this problem is to choose the most sustainable single screw extruder pelletizer between the two available options: EOL machine and new machine.

<u>Step2- Construct problem hierarchy:</u>

The hierarchy of this problem comes in four levels: goal at the very top level, followed by criteria, sub-criteria, and finally alternatives.

<u>Step3- Find global weight vector for all sub criteria</u>**:**

Since the problem on hand belong to the same geographical region where the survey was conducted, weight vectors for this problem are decided to be the same ones calculated based on experts' judgement in the survey as outlined in Table 3.4

Table 3.4: Indicators' Global weights vector

Indicators	E1	E2	E3	E4	E5	E6	V1	V2	V3	V4	V5	V6	S1	S2	S3
Global Weight	0.372	0.212	0.074	0.062	0.025	0.025	0.029	0.002	0.013	0.004	0.004	0.029	0.063	0.063	0.063

<u>Step4- Find weight vectors for alternatives in level 4:</u>

As mentioned in section 3.2.2.4, importance matrices are constructed through pairwise comparison of available alternatives with respect to every indicator in the immediate upper level. Weight vectors are calculated based on importance matrix entries. In this case, fifteen importance matrices are constructed, and consequently, fifteen weight vectors are calculated. Table 3.5 shows three examples of such matrices with their corresponding weight vectors.

Table 3.5: Example importance matrices for pairwise comparison of alternatives

With respect to E2: Capital investment				**With respect to V2:Water consumption**				**With respect to S2:Hire local Skills**			
	Used	New	**Weight**		Used	New	**Weight**		Used	New	**Weight**
Used	1	1/9	**0.100**	Used	1	1	**0.500**	Used	1	5	**0.833**
New	9	1	**0.900**	New	1	1	**0.500**	New	1/5	1	**0.167**

Importance matrix entries are based on the performance of each machine in the alternative set with respect to a specific indicator. Input data obtained from the company regarding the performance of each alternative is shown in table 3.6

Table 3.6: Indicators' values for both used and new extruder

Indicators	**Unit**	**Used extruder**	**New extruder**	**Ratio of Used /New**	**AHP values**
E1: Revenues	%	0.130	0.130	1.000	1
E2: Capital investment	JD	50000.0	150000.0	0.333	1/9
E3: Value added	JD	50000.0	50000.0	1.000	1
E4: Infrastructure cost	JD	15000.0	15000.0	1.000	1
E5: Financial risk	JD	4500.0	2000.0	2.250	9
E6: Inflation/deprecia.	ratio	2500.0	7500.0	0.333	1/9
V1: Materials consumpt.	ratio	0.960	0.960	1.000	1
V2: Water consumpt.	m3	0.500	0.500	1.000	1
V3: Energy consumpt.	JD/month	600.000	700.0	0.857	1/3
V4: Air emissions	ratio	4.00E-07	4.0E-07	1.000	1
V5: Solid& liquid waste	ratio	4.00E-05	4.0E-05	1.000	1
V6: Hazardous waste	ratio	1.00E-03	1.0E-03	1.000	1
S1: Local community	JD	500.000	2000.0	0.250	1/9
S2: Hire local Skills	ratio	0.500	0.300	1.667	5
S3: Impact on labour	hours	24.000	40.0	0.600	1/5

Ratios between used and new extruders' indicators are calculated and shown in table 3.6 The purpose of calculating these ratios is to provide a systematic method for assigning AHP importance values for alternatives importance matrices. The range of calculated ratios is matched with the range of AHP importance values, as shown in figure 3.5, which works as scale for selecting accurate AHP importance value and eliminate subjectivity in AHP values assignment.

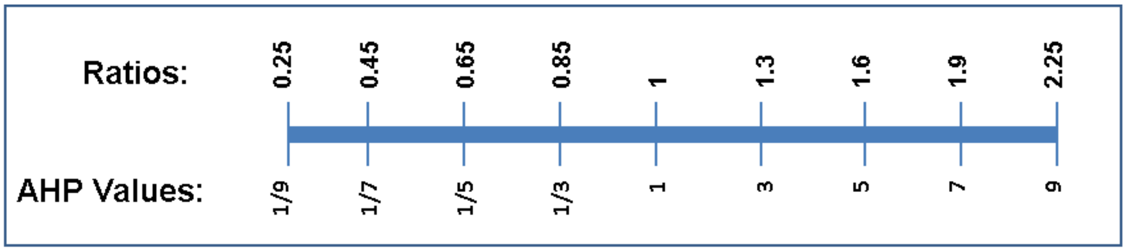


Figure 3.5: AHP importance value scale based on manufacturing system ratios

Weight vectors calculated from the alternative comparison matrices are given in table 3.7; weight vector indicate the performance of the used extruder compared to a new one.

Table 3.7: Alternatives' weight vectors with respect to sub-criteria (W1….W15)

Sub-criteria weight	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15
New Extruder	0.500	0.100	0.500	0.500	0.900	0.100	0.500	0.500	0.250	0.500	0.500	0.500	0.100	0.833	0.167
Used extruder	0.500	0.900	0.500	0.500	0.100	0.900	0.500	0.500	0.750	0.500	0.500	0.500	0.900	0.167	0.833

Step5- Find sustainability index for each Alternative:

The vector of sustainability index is calculated according to equation 17. The multiplication of alternatives' weight matrix in table 3.7, with indicators' global weights vector in table 3.4, gives the following sustainability index vector:

$$\textbf{Vector of sustainability indices} = \begin{pmatrix} \textbf{Used system index} \\ \textbf{New system index} \end{pmatrix} = \begin{pmatrix} \textbf{0.633} \\ \textbf{0.367} \end{pmatrix}$$

Step6- Select best alternative:

The goal is defined in step one as the most sustainable extruder. Based on sustainability indices vector calculated in step 5, the most sustainable alternative is the one with the highest index; thus, the used extruder is selected and purchased.

3.2.3.3 Results

The identified indicators are selected based on the use of field survey. This method is accurate in selecting the most related and influential indicators. The selection is based on preferences and experience of experts in the field. This resolve a valid concern about the cut offs and criteria used to consider or disregard a specific indicator. In this model, indicators which are rated as important by surveyed experts are considered in the development of the model. Six indicators are selected for both economical and environmental. Only three indicators are identified as important for societal aspect of EOL product reuse. This indicates that there is a room for investigating more indicators that could be important to the society, but not yet to the decision maker. Trends in large enterprise decision making processes show the consideration of societal impacts in their decisions. Although the survey targeted a specific sector of potential decision makers on EOL product reuse, the results are valid for others. The targeted sector shared the same conditions as other potential users of the proposed model. Low value EOL product users are not expected to use a structured, highly comprehensive model to decide on the usage of new or used EOL product. Organizations similar to the surveyed ones are the expected users of this model.

Calculations of sustainability index (SI) show that economical sustainability was the main factor behind the selection of used machine over new one. This is due to the high capital investment associated with purchasing new machines. This is expected due to the fact that the in profit seeking companies cost/benefit analysis usually drives their decision. A low weight of environmental sustainability aspect makes improvements regarding the environmental performance made by new machine negligible. Improvements in material utilization, emissions, and waste should strongly contribute to the selection of a new machine over an EOL one,. As of societal sustainability impact, the used machine was able to hire local skills, since the used machine is less technologically developed and challenging; hence, it does not require higher competency and knowledge of more advanced technology that might not be locally available. Based on the results obtained from applying the proposed model, buying a used machine was a more sustainable option than buying a new one. This case study emphasizes the importance of considering all sustainability aspects when making decisions regarding investments in EOL products, in this case an EOL machine. Generally speaking, the proposed model serves as a tool that enables decision makers to make precise informed decision about reusing EOL products.

Model's sensitivity and limitation studies are performed for the case study at hand. The model is tested by assigning extreme values of importance (highest or lowest) for each sustainability aspect. Table 3.8 shows tested scenarios. Sensitivity analysis shows that the new machine in this case study is not competitive with the used machine under all scenarios. The best case happens (score=0.44) when environmental aspect is given the highest importance (see second scenario in table 3.8). Based on results of first and third scenarios, both economic and societal indicators contribute to the selection of the used machine. This also can be concluded from the fifth and seventh scenarios, where both sets of indicators are given the lowest rate; hence, the used machine gets lower scores. The scenario of equal importance is also assessed. Equal importance rate is given in all aspects; this scenario is important for decision makers since it works as a base for comparison with scenarios of different importance rates. Under this scenario, the used machine remains better than the new one. The analysis shows that the improvement in environmental performance of the new machine cannot outweigh the advantages of the used one, especially when it comes to savings of local jobs and capital investment.

Table 3.8: Sensitivity analysis of the proposed model

Scenarios		**Used system Score**	**New system Score**
Highest importance rate (AHP value = 9) is assigned to:	Economical aspect	0.61	0.39
	Environmental aspect	0.56	0.44
	Societal aspect	0.62	0.38
Equal importance (AHP Value = 1)	All aspects	0.60	0.40
Lowest importance rate (AHP value = 1/9) is assigned to:	Economical aspect	0.59	0.41
	Environmental aspect	0.62	0.38
	Societal aspect	0.58	0.42

3.3 Assessment of sustainable recovery for EOL product as parts and assemblies

3.3.1 Purpose of the assessment

EOL products which are not qualified for reuse, according to the assessment made in section3.2, are directed to a lower level of recovery. The proposed framework requires the investigation of the most sustainable recovery option for product components (parts and assemblies). According to Lansink's ladder for ranking recovery options (see section 3.3.2.4), recovery of functional items are ranked first, then material recovery, and lastly energy recovery. Then, the purpose of assessment in this section is to allocate the most sustainable recovery option for each item in an EOL product. To address the problem, literature is surveyed. The problem scope could be extended to include products or by-products that might result from product lifecycle phases (see figure 3.1). The scope of solution space that can be implemented for solving the problem is shown in figure 3.3; it ranges from component (part or assembly) resale without a need for any recovery processing to complete disassembly and materials/component separation for recycling or incineration and landfilling.

The literature survey shows that the problem has multi aspects with some interaction between these aspects; example of this is the type and preference of the decision maker. Section 3.1.3 explains the influence of types and preferences of decision makers on the solution space and criteria for selecting the best recovery option.

3.3.2 Assessment method development

3.3.2.1 Holistic approach

The decision on EOL recovery option is influenced by plenty of factors; a holistic approach is needed to address these factors. PESTEL analysis is a comprehensive approach developed by Carpenter and Sanders (2009) for screening macro factors that affect the working environment of an organization. PESTEL stands for **P**olitical, **E**conomical, **S**ocietal, **T**echnical, **E**nvironmental and **l**egal aspects of an organization's work environment. PESTEL has evolved from the PEST model by including environmental and legal dimensions to PEST, and it has been successfully used as a comprehensive framework for studying firm's macro environment in different business sectors (Carpenter and Sanders, 2009). Typically, PESTEL analysis is done in two stages: First stage: with the help of the typical lists of PESTEL factors, implementation process starts with determining the relevance of the typical factors to a particular context (e.g. Product recovery); brainstorming sessions, literature, and practical experience can be used to collect and identify the influencing factors.

Second stage: relevant factors are grouped and categorized in an informative hierarchy which is meaningful and logical to a particular context. The grouping is aimed to facilitate proper addressing of identified factors; factors belong to a group could be addressed similarly and managed by one authority. Section 3.3.2.2 details the implementation of PESTEL approach.

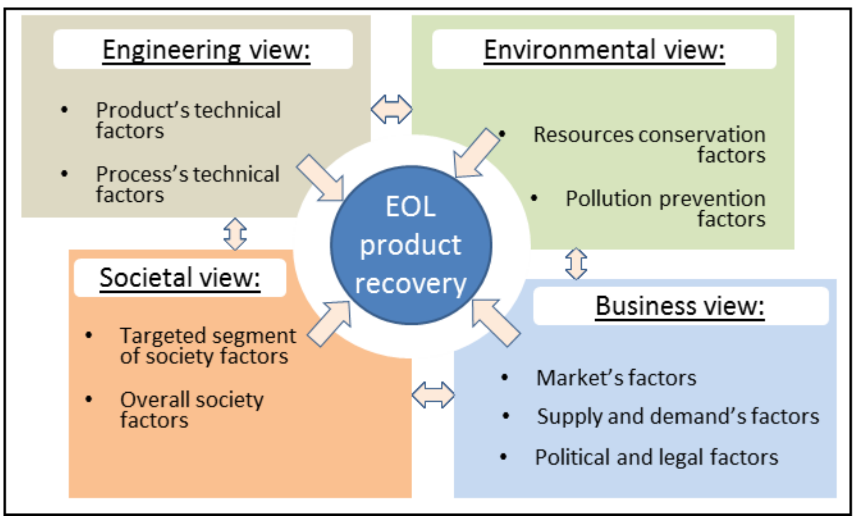


Figure 3.6: Holistic view at EOL product recovery problem

3.3.2.2 PESTEL analysis: Influencing factors

This research uses PESTEL analysis as a holistic approach for considering all influencing factors in the decision process of ranking appropriate recovery options and selecting the optimal option for an EOL product. The search process for influencing factors is guided by PESTEL and depends on three sources; published literature including a review paper by Ilgin and Gupta(2010), published technical reports, and experiments performed by the author. Table 3.9 demonstrates the implementation of stage one of PESTEL analysis. At this stage general factors that affect the recovery options are brainstormed and identified; their relevance to the problem is categorized. High and medium relevant PESTEL factors are used to identify context related factors which affect the decision on ranking and selection of recovery options.

Table 3.10 shows the results of identification and grouping of influencing factors which are directly related to the context of the EOL recovery. The identification process starts by brainstorming and gathering factors that could be related to the problem; factors were collected from experiments conducted by author, technical reports, and literature. The initial list of these factors is distilled to a shorter list, which has factors that are matched with factors identified in stage one of the PESTEL analysis. The final factors are shown in table 3.10 and grouped into four major categories; engineering factors include technical factors related to the EOL product and recovery processes, business factors include economical factors, in addition to political and legal factors that affect the business aspect of the problem, environmental factors include factors related to natural resources utilization and factors related to pollution that could be caused by recovered product or recovery process, societal factors include factors that affect people who are targeted by the recovered product and factors that affect the entire society. It was concluded that political and legal factors can be allocated to the category addressed by these factors. For example, political and legal factors that address the environmental aspects of the problems are grouped with factors under the same category. Detailed descriptions and calculations of influencing factors are found in section 3.3.3.2

3.3.2.3 Method selection

EOL recovery options selection is a multi-criteria decision making process. To select the appropriate method, literature is consulted. Bufardi *et al*. 2004 suggest a comprehensive approach for selecting appropriate multi-criteria decision methods. The approach consists of four levels:

1. First level: type of the problem; Roy (1996) identified three fundamental types of multi criteria decision problems: selection of best option from a group of options, sorting options into groups according to norms, and ranking options in ascending or descending order.

2. Second level: type and nature of data; this could include; size of database, qualitative verses quantitative data, methods of data evaluation and estimation, and exhaustive enumeration verses probabilistic values.
3. Third level: type of decision maker; this relates to whether it is a person or group of personas. Decision maker qualifications and preferences affect selection of the appropriate method.
4. Fourth level: technical aspects of possible methods such as aggregation modes and methods of decision maker's preferences modeling.

EOL product recovery problem can be considered as a selection and ranking problem. This depends on the decision maker objectives; it would be a selection problem if decision maker seeks the best option among all available recovery options, while it could be ranking problem if the objective is to find all appropriate recovery options ranked according to certain criteria. In terms of data nature and types; it

Table 3.9: Typical PESTEL factors affecting EOL product recovery

Identification and grouping of Influencing factors of EOL recovery option selection **First stage: Typical PESTEL factors**											
1.Political factors	**Relevance**	**2.Economic factors**	**Relevance**	**3.Social factors**	**Relevance**	**4.Technological factors**	**Relevance**	**5.Environmental factors**	**Relevance**	**6.Legal factors**	**Relevance**
1.1 Regional and global law	Med.	2.1 General growth trends	Low	3.1 Age range	Low	4.1 Hardware	High	5.1 Susceptible to natural disasters	Low	6.1 Age discrimination	Low
1.2 National law	High	2.2 Interest rates	Med.	3.2 Attitude towards consumerism	High	4.2 Software	Low	5.2 Pollution and deforestation;	High	6.2 Local by-laws	High
1.3 Trade unions	Low	2.3 Taxation	High	3.3 Income brackets	High	4.3 IT for management	Med.	5.3 Sustainability	High	6.3 Minimum wage	High
1.4 Taxation policies	High	2.4Insurances	Med.	3.4 Ethnicity	Low	4.5 IT for communication	Low	5.4 Recycling	High	6.4 Consumer laws	Low
1.5 Equality	Med.	2.5 Funding sources	Med.	3.5 Life-style	High	4.6 Equipment	High	5.6 Waste disposal/ management	High	6.5 Competition laws	Low
1.6 Vulnerable people	Med.	2.6 Inflation and exchange rates	Low	3.6 Shopping trends	High	4.7 Materials	High	5.7 Energy-efficiency	High	6.6 Employment laws	High
1.7 Party politics	Med.	2.7 Economic competiveness	Low	3.7 Social trends	High	4.8 New developments	High	5.8 Fuel	Med.	6.7 Health and safety legislation	High
1.8 Green activist pressure	High	2.8 Globalisation Vs. Localisation	Med.	3.8 Attitude towards environmentalism	High	4.9 New technologies	High	5.9 Move towards more environmentally friendly products	High	6.8 Cost of regulatory complia	High

Identification and grouping of Influencing factors of EOL recovery option selection First stage: Typical PESTEL factors											
1.Political factors	**Relevance**	**2.Economic factors**	**Relevance**	**3.Social factors**	**Relevance**	**4.Technological factors**	**Relevance**	**5.Environmental factors**	**Relevance**	**6.Legal factors**	**Relevance**
										nce	
1.9 Subsidising firms	Med.	2.9 Unemployment rate	High	3.9 Willingness of individuals to work	High	4.10 New product	High	5.10 Resource mix	Low	6.9 Environmental protection laws	High
1.10 Governmental business support	Med.	2.10 Labor cost	High	3.10 Size and mix of population	High	4.11 New processes	High			6.10 Regulations on waste and energy	High
1.11 Economy infrastructure quality	High			3.11 Equalities	Med.	4.12 Skills availability	High			6.12 Intellectual property law	Med.
1.12 Stability of political system	Med.			3.12 Wealth	High					6.13 Monopolies regulations	Med
1.13 Social welfare policies	High			3.13 Health	High						

Table 3.10 : EOL recovery influencing factors

Identification and grouping of influencing factors of EOL recovery option selection Second stage: context related factors (EOL product recovery)					
Hierarchy 1	**Hierarchy 2**	**Influencing factors**	**Unit**	**PESTEL Ref.**	**Factor is used or suggested by:**
Engineering factors	Product's factors	Item useful life time	Year	4.10	(Rahimifard, *et al*. 2009), (Mangun, 2002)
		Technology/design cycle,	Year	4.8, 4.9,	(leberton and Tuma, 2006), (Zwolinski *et al*., 2005), (Rose, 2000), (authors' experiments)
		Wear-out life	Year	4.1, 4.7	(leberton and Tuma, 2006), (Rose, 2000), (authors'' experiments)
		Standard or interchangeable item	Yes/No	4.11, 4.8, 5.4, 4.12	(Toffel, 2002), (Seitz and Wells, 2006), (authors' experiments)
		Number of components	Integer No.	4.6	(Fan et al., 2013),
		Product architecture, Level of integration	Modular/integrated	4.1, 4.2	(Zwolinski *et al*., 2005), (Fan et al., 2013), (authors' experiments)
	Process factors	Disassembly effort	Time(s)	2.10	(Fan *et al.,* 2013), (Xanthopoulos, and Iakovuo, 2009), (authors' experiments)
		Materials separateability	% by weight	4.7, 4.11, 6.9, 6.10	(Zwolinski *et al*., 2005)
Business factors	Market factors	Investment costs	H,M,L / option	2.2, 2.3, 2.5, 2.6	(Boks and Stevele, 2001)
		Recovery process cost	H,M,L option	2.9, 2.10, 4.11	(Chung and Wee, 2012), (authors'' experiments)
		New item value	Monetary unit	2.7, 3.5,3.6, 1.4	(Rahimifard, *et al.* 2009), (Zwolinski *et al*., 2005), (kumar *et al.,* 2007)
		Used item value	Monetary unit	1.4, 1.9, 3.7, 3.12	(Rahimifard, *et al*. 2009), (Zwolinski *et al*., 2005), (authors' experiments)
		Lost sale in primary market	No. of units/time unit	3.6	(Rahimifard, *et al.* 2009), (Zwolinski *et al*., 2005),
	Supply-	EOL product location	Km	2.8, 3.10,	(Rahimifard, *et al.* 2009), (Hula *et al*.,

Identification and grouping of influencing factors of EOL recovery option selection Second stage: context related factors (EOL product recovery)					
Hierarchy 1	**Hierarchy 2**	**Influencing factors**	**Unit**	**PESTEL Ref.**	**Factor is used or suggested by:**
	demand factors				2003)
		Collection cost	Monetary unit	1.11, 2.10, 5.8, 6.10	(Zwolinski *et al*., 2005), (Jun et al., 2012)
		Demand volume	No. of units/time unit	3.3, 3.6, 3.10, 5.9	(Jun *et al.,* 2012)
	Legal and political factors	Cost of legal compliance	Monetary unit	6.2, 6.3, 6.7, 6.8, 6.9	(Baker and Rahimifard, 2007)
		Regulations on recycled quota	Yes/No	6.10	(Iakovou, *et al*., 2009)
Environmental factors	Resources conservation	Energy yield	KJ/recovered item	5.7, 5.8	
		Material yield	% by weight	5.3, 5.4, 6.10	(Ziout *et al*, 2013[a]), (authors' experiments)
	Pollution factors	Liquid and solid waste	H,M,L / option	5.2, 5.3, 5.6, 6.9, 6.10	(Ziout *et al*, 2013[a])
		Air emissions	H,M,L / option	5.2, 5.3, 5.6, 6.9, 6.10	(Ziout *et al*., 2013[a])
		Hazardous material contents	% by weight	1.8, 3.8, 5.6, 6.9, 6.10	(Wang *et al*., 2013), (Rahimifard *et al.,* 2009)
Societal factors	Targeted segment	Reason of discard	Fail, obsolete, outdated	3.2, 4.9, 4.10	(Rahimifard, *et al.* 2009), (authors' experiments)
		Purpose of ownership	Functional, aesthetic, both	3.2, 3.5	(Leberton and Tuma, 2006), (authors' experiments)
		Consumer opinion toward used product,	Favour, neutral, against	3.9	(Krikke *et al.,* 1998)
	Overall society	Damages/benefit to human health	Damage, neutral, benefit	3.13, 6.7, 6.2	(Chan, 2008), (Staikos and rahimifard, 2007)
		Society involvement in recovery programs	Success rate	6.4, 3.8	(Fernandez *et al*., 2008)
		Green party pressure	Yes/No	1.8, 3.8	(Gehin, *et al*, 2008)

is certain that data could be linguistic (fuzzy), exhaustive enumeration, probabilistic, qualitative, quantitative, measured, or estimated data with a size varies according to the product under evaluation. The user of such method could be one person (business owner), group of persons (product design team), or governmental bodies (municipalities, or legislators). This variation in type of users suggests using a method that does not require the user to have a pre assumed knowledge about how the method works. Meanwhile, the method should be able to handle wide range of user preferences and priorities.

By analysing the technical aspects of possible methods, it is found that mathematical optimization methods are not the best methods to use. This is due to the type and nature of the data involved in the product recovery problem; they appear superior in solving specific aspects of the problem, but not the problem as a whole. For example, mathematical optimization is used to find optimal disassembly effort and optimal network design for reverse supply. Computer based clustering and classification methods (Cladistics, decision tree analysis, neural networks, etc.) are good candidate methods. Yet, they are suitable for selection and sorting but not for ranking. Most of these tools are knowledge based; they require large sets of training data which also makes the method limited for products similar to those which were used in training. Modeling large and complex problems such as closed loop product lifecycle requires a decision method that can decompose the problem in manageable sub problems, and can be solved at different hierarchical levels. The Analytic Hierarchy Process (AHP) satisfies this requirement in addition to the requirements resulted previously in analysing the first three levels of method selection. AHP, as an alternative decision making method, uses criteria weights to reflect a decision maker's preferences. The use and selection of criteria weights is crucial for proper use of the method (Kiritsis, 2003). the AHP method insures the proper use of criteria weights through its consistency index. The assessment method in this section is built around AHP method; following sections show the development and logic flow of the proposed method.

3.3.2.4 Method structure and logic flow

The proposed method provides hierarchical decisions on each constituent of an EOL product, and it is structured in two phases;

A. Phase 1 is used to decide the first level of appropriate recovery options (See table 3.3); AHP ranks these options according to multi-criteria which are developed in table 3.10.
B. Phase 2 of the method uses a cost/benefit analysis to decide on the second level of the recovery options (see table 3.3).

To reduce the complications of the decision process and eliminate unpromising solutions, the following modelling assumptions are made:

1. From an environmental point of view, Lansink's ladder is followed to rank the recovery options; Reuse is better than recycling, and recycling is better than incineration. As an extension to this, the recovery option that requires less re-processing is ranked higher than the option that requires more re-processing.
2. Users can obtain disassembly time of their product using any algorithm which gives them optimal or near optimal product disassembly plans, algorithm which applies to manual, nondestructive, and complete disassembly. The method that Azab *et al*. (2010) introduces can be used for this purpose.
3. Reuse of EOL product is preferred over using new products. This can be verified (accepted or rejected) using the authors' previous published work, (Ziout *et al*., 2013[a])
4. EOL products are structured in three levels; whole product, subassemblies (two or more components do specific functions), and components (an entity in the product consists of one material).
5. If an ancestor in the product disassembly tree is qualified for a recovery option, there will be no need to check its predecessors against recovery options, which are lower in their Lansink hierarchy.

3.3.2.5 Method development

A. <u>Phase 1: Decision on first level of available recovery options</u>

This phase starts with identifying the items in the recovery options of which need to be ranked; these items will be referred to as decision items which include assembly, sub assembly, and component. The author has developed an algorithm to find optimal or near optimal, manual, complete, and non-destructive disassembly sequence for an EOL product (Azab *et al*. 2010). EOL product disassembly planning is modelled as sequencing a global set of disassembly operations of a given product that is also subject to a number of precedence constraints. This problem has already been proven to be NP-hard. Hence, the algorithm uses a new heuristic search based on Simulated Annealing (SA). SA is a hill-climbing search method suitable for solving combinatorial problems as well as continuous problems with multi-modal objective functions. A heuristic search based on SA is tailored towards the problem at hand. The problem of ordering n disassembly operations is formulated as a Travelling Salesperson Problem (TSP), where each disassembly task is modelled as a city that has to be visited once and only once by a salesperson. The main constraint is precedence relations between disassembly operations. Sequence independent operation times are assumed.

The algorithm requires parts list, disassembly operations precedence diagram with their respective required tooling, part orientations/setups and coordinates. The total travel distance to be minimized is that of the disassembly tool, such that all the tasks would perform with minimum total transient time between each two consecutive tasks. The time objective function is composed mainly of three different components: part orientation changes, tool changes, and tool traverse. Tool traverse in this case is quite indicative of accessibility. Rectilinear distances were taken. The setup change (part orientation) cost has been taken of the highest cost. A ratio of 3:1 was used between the part orientation and the tool changeover cost components. The output of this algorithm is optimal or near optimal sequence of disassembly operations. Also for each component, its disassembly time is obtained.

The input for phase1 of the assessment method are influencing factors identified in section 3.3.2.2 and disassembly planning output mentioned above. These data and the values of influencing factors are used by the method to rank the available recovery options.

Decision method: this phase uses the Analytic Hierarchy Process (AHP) decision theory which was developed by Saaty in 1980 as a multi criteria decision tool that can be used to select the best alternative that fits a certain goal according to specific criteria. AHP relies on expert's judgement to conduct pairwise comparison between weighted criteria (Saaty, 2008).

AHP provides consistent decision method when absolute data is either not available or subjective in their interpretation, a case which is typical in the EOL product recovery problem. According to Saaty (2008,1990) the method consists of the following steps:

1. Define problem in hand, and determine the kind of knowledge sought.
2. Rephrase the problem in hierarchical structure: top level has the goal of the decision, intermediate levels have the criteria and sub criteria, and the lowest level has the alternatives or options to satisfy the goal in the top level.
3. Construct the pairwise comparison matrices. Comparison matrices are constructed by conducting pairwise comparison between subcriteria with respect to their ancestor
4. Use eigenvector of each matrix to find element's relative weight, and check for Consistency Index (CI) and Consistency Ratio (CR) for each eigenvector. For further details, see Saaty (1990)
5. Select the alternative with the highest rank

These steps are applied in this section to develop phase 1 of the method.

Problem definition:

For EOL products, a decision is needed to be taken by a recovery process owner in order to select the most suitable recovery option which satisfies a predetermined set of criteria. At this phase of the problem, a decision is made regarding the first level of recovery options shown in table 1, namely: reuse, recycle, and incineration; the optimal option is selected and the remaining two options are ranked. This is needed for EOL product assemblies, subassemblies and components.

Problem hierarchical structure:

The problem is structured in three major hierarchies: top, intermediate, and bottom level. At the top; level 1 has the goal of the problem which is selection of the most appropriate recovery option while the remaining possible options are ranked. At the intermediate level, three sub-levels are defined: sublevel 2.1 contains the four major criteria that should be considered in the decision process for EOL recovery, sub-level 2.2 contains subcriteria of each major criterion in level 2.1, and sub-level 2.3 contains the influencing factor under each subcriterion. Influencing factors are determined based on the PESTEL analysis methodology. At the bottom hierarchy, level 3 has all potential recovery options. At this phase of the decision process, three options are considered: reuse, recycle, and incineration.

Importance matrices:

Importance matrices are considered to be the core of AHP model due to the following two reasons:

1. The capability of considering different decision makers preference using the same method. The EOL product recovery problem has many stakeholders; each has his own preferences and perspectives with different objectives which can sometimes conflict with other stakeholders objectives. The importance matrices in the AHP method give this capability.
2. Systematic way of translating subjective and qualitative assessment into quantitative assessment. Importance matrix is formed by conducting pairwise comparisons between a set of criteria. Comparisons are made between elements in a level with respect to their ancestor in a higher level. The purpose of importance matrices is to find the weight of each element in the overall hierarchy. A set of criteria weights is called eigenvector. The importance rating suggested by Saaty (2008) shown in table 3.11 has been adopted throughout this work. The structure of Importance matrices are constructed from top to bottom.

At level 1; importance matrix of the goal:

Since there is only one element in level 1, the importance matrix is 1X1, matrix with one scalar entry which is 1. This indicates that the element has the same importance compared to itself and consequently its weight is 1.

At level 2.1; importance matrix of major criteria:

Level 2.1 has four criteria that need to be compared in respect to the element in level 1. The resulting comparison matrix for level 2.1 is a matrix of 4X4 order. Importance matrix is to be interpreted as follows: the criterion of row_i is w_{ij} , and is important when comparing it to the criterion in $column_j$ with respect to their ancestor criterion in the previous higher level; if the order is reversed the importance becomes ($1/w_{ij}$) (see table 3.12) . Importance ratings (matrix entries) are based on the expert's judgements which reflect the decision maker preferences. The importance matrix is used to calculate the weights of the four criteria; weights are the eigenvector of the importance matrix which can be calculated as per Saaty (1990).

To assess the calculated weight consistency in presenting actual expert's judgment, Consistency Index(CI) is calculated. Consistency Ratio (CR) is the ratio between calculated CI and the average CI of completely random matrices of the same size, n. CR has to be ≤ 0.1; otherwise, the importance matrix is not consistent;hence, the calculated weights do not reflect the expert's actual judgements. According to Saaty (1990), the value of CI is $((\lambda max - n)/ (n-1))$, where λmax is the principal eigenvalue of importance matrix, and n is the number of elements in the matrix.

At level 2.2; importance matrices of subcriteria:

The decision maker has the chance to give different weights for subcriteria within their ancestor major criteria. Importance matrices are used to systematically calculate these weights. Four importance matrices are constructed, one matrix per each major criteria. For example: Business criteria are found in three subcriteria; market, supply and demand, economical related political and legal criterion. If these three subcriteria are not of the same importance, compression matrix can be constructed to find their relative weights.

At level 2.3; importance matrices of influencing factors:

Weight of each influencing factor with respect to its ancestor subcriteria is calculated using its importance matrix. For each group of influencing factors there is an importance matrix. The Eigenvector of each matrix indicates the weights of its factors. Since these weights are calculated with respect to the previous ancestor, they are called local weights.

Global weights of influencing factors:

Local weights calculated in the previous steps are not the target; global weights which refer to influencing factors to the goal in level 1 are needed. They are used to calculate the rank of available options. They are calculated as follows:

$$\text{Global weight}_{\text{influencing factor}} = (\text{Local weight}_{\text{influencing factor}}).(\text{Local weight}_{\text{subcriteria}}).(\text{Local weight}_{\text{major criteria}}) \quad (18)$$

At level 3: importance matrices of recovery options:

Level 3 has the potential recovery options, which are reuse, recycling, and incineration. Importance matrices at this level are constructed through pairwise comparisons of the three recovery options with respect to each influencing factor in level 2.3. So, twenty eight matrices are obtained at this level. Pairwise comparisons between options are obtained based on specifications and performance of each option with respect to the influencing factor in question while considering a specific decision item. Experts' judgment can be used whenever data is not available. Once importance matrices entries are determined, weights, CI, and CR are calculated for each matrix.

Output: *Ranking the available options*

To select the alternative that mostly satisfies the problem goal (Best recovery option), rank for each option is calculated. Ranks vector that represent all alternatives can be calculated through the following equation:

[Options ranks] = [alternatives' weight matrix] [Influencing factors global weight vector] (19)

The best alternative will be the alternative correspondent to the highest rank. It is worth mentioning that the previous calculation is needed each time a decision is needed to rank recovery options for a specific decision item. It is the choice of the decision maker to keep or regenerate new weights at level 1, level 2.1, level 2.2,and level 2.3 when decision objects change, since these weights reflects the importance of the influencing factors with respect to the problem goal. While weights at level 3 represent the performance of recovery options of a specific decision item, this performance differs from one decision item to another.

Table 3.11: Importance rating modified from (Saaty 2008).

Importance	*Definition*	*Explanation*
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favors one activity over another
5	Strong importance	Experience and judgment strongly favors one activity over another
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2-8	Intermediate values	If the activities are very close
Reciprocal	reciprocal of above values	If activity i has one of the above non-zero numbers assigned to it when compared to activity j, then j has the reciprocal

Table 3.12: General importance matrix of three criteria

	Criteria1	Criteria2	Criteria 3	***Weight (Eigenvector)***
Criteria1	1	W_{12}	W_{13}	***E1***
Criteria2	1/ W_{12}	1	W_{23}	***E2***
Criteria3	1/ W_{13}	1/W_{23}	1	***E3***
CI = ((λmax –n)/ (n-1))			***CR = < 0.1***	

B. Development of phase 2: (Decision on second level of available recovery options)

The input for this phase is the output of phase 1, which is a set of ranked options for each decision item. The purpose of this phase is to decide on the level of reprocessing items qualified for reuse, level of separation for items qualified for recycling, and level of incineration for items qualified for incineration. The decision at this level is mainly driven by economical factors, so cost and benefit analysis is developed as follows:

1. For Items qualified for reuse:

As shown in figure 3.3 there are many sub options under the reuse option. The only difference between these options is the level of reprocessing, which include disassembly, inspection, replacement of failed items, applying further refurbishing processes (which could be any typical manufacturing processes), assembly, testing, and packaging the recovered item. The objective at this stage is to select the recovery option associated with the maximum profit. For each decision item the following cost and benefit calculations need to be done:

1.1. Resale option: (no reprocessing)

The returned product is introduced to the reuse cycle without any further, or very minimal, reprocessing. In this case, the cost of recovery processes is zero. An example of this is the resale of used books. The profit generated can be calculated as the following:

$$\text{Benefit} = \text{Revenue}_{resale} - C_{resale} \quad (20)$$

1.2. Maintenance, repair, replacement, and downgrading options: (partial reprocessing)

Selective disassembly is carried out to reach a specific item in the product or its subassemblies. An action is then taken – based on the status of the targeted item- to maintain, repair, replace, or downgrade the item. Finally, the item is reassembled and sold with functioning quality level. The benefit generated from any of these fixing options can be calculated as the following:

$$\text{Benefit} = \text{Revenue}_{Fixing} - C_{disassembly} - C_{fixing} - C_{reassembly} - C_{testing} \quad (21)$$

1.3. Refurbishing option: (partial reprocessing)

Refurbishing usually involves more reprocessing than in the previous options, cleaning could be added as well. The main objective of refurbishing an item is to improve its functionality and appearance by adding a new item or replacing obsolete items by a better performance item. Refurbishing benefit can be calculated as the following:

$$\text{Benefit} = \text{Revenue}_{refurbishing} - C_{disassembly} - C_{refurbishing} - C_{reassembly} - C_{testing} \quad (22)$$

1.4. Remanufacturing and biological reprocessing options (complete reprocessing)

This option requires complete reprocessing for all constituents of an item to bring it to a like-new state. Theoretically, any manufactured product can be remanufactured;, practically high remanufacturing costs render this option. For example, high cost prevents recovered water from the sewage to be qualified as drinking water. The remanufacturing benefit can be calculated as the following:

$$\text{Benefit} = \text{Revenue}_{reman} - C_{reman.} - C_{disassembly} - C_{reassembly} - C_{testing} - C_{packaging} - C_{warrantee} \quad (23)$$

It's worth mentioning that since the objective of the previous calculation is to compare between the fourth options, there is no need to consider the common cost that applies equally to all options, such as core collection cost and cost of selling recovered items.

2. For items qualified for recycling

The objective at this stage is to decide about the level of separation that gives the maximum profit. Two Scenarios exist:

2.1. Scenario 1: Separation using disassembly

This option gives higher material purity while costing more, (Staikos and Rahimifard, 2007) calculate the benefit of this scenario as the following:

Benefit of scenario1= benefit(material weight*value/kg)- $C_{disassembly}$ (24)

2.2. Scenario 2: Separation using shredding

Shredding is a cheaper option than disassembly; meanwhile, it depends on the separation technology to determine the purity of recycled material and amount of residues.

Benefit of scenario 2 = benefit (material weight*value/kg)- $C_{shredding\ \&\ separation}$ (25)

3. For items qualified for incineration

The incineration option ranges from no energy recovery, by dumping EOL product to landfill and pay landfilling fees, to full energy recovery and generate either profit or loss based on the operational and investment cost of the incineration process. Assuming both options are available, then the decision will be incineration as long as equation (26) produces net profit.

Benefit = Net energy recovered *(price) - Weight landfilled * (disposal rate) (26)

The developed assessment method is validated and demonstrated in the following section using a real life product which is in its research and development phase; which is the proper phase to consider and design for an EOL option by design for ease of disassembly, and potentially include A.Dis.

3.3.3 Method application in renewable energy products

3.3.3.1 Fuel Cell Case Study Description

Problem background:

Gradual depletion of world oil reserve and increased concerns about its environmental impact triggers the need for alternative sources of energy. Renewable energies are an optimal sources for energy due to their lasting sustainability; energy harvested from sun, wind, biofuel, and water are examples of renewable energy.

Automotive industry – one of the largest consumers of energy - explores opportunities for migrating from fossil-based fuel to renewable energies. Even though research for such opportunities started very early, marketable cars which uses completely renewable energy and completely able to phase out an oil driven car is not accomplished yet.

General Motor (GM) is a leading automaker in exploring and implementing renewable energy initiatives in their products. Hybrid, electrical, and hydrogen cars are examples of such initiatives. GM is currently consolidating the largest hub in the world for research and development of fuel cell. This step is motivated by their initial promising results and their commitment to the objective. Commercially, a fuel cell powered car is projected to be available by 2022.

The method developed in this work uses GM fuel cell to demonstrate the method's applicability and usefulness. Proton Exchange Membrane (PEM) fuel cell stack of 80KW is the subject of this case study. Fuel cell is the main part of hydrogen power system in a car, the system, consists of many modules: hydrogen supply, oxygen supply (ambient air compressor), cooling, and a stack of fuel cells which together give the required output power.

Fuel cells stack working principle:

Fuel cell stack is a replication of identical fuel cells, which together contribute to the total produced electrical current by the stack and is fed to the car's electrical motor. The working concept of the fuel cell is demonstrated in figure 3.7. At the anode, a chemical reaction between hydrogen and the catalyst material (Platinum) decomposes hydrogen atoms into protons and electrons; protons move through the membrane to the cathode. While electrons cannot penetrate the membrane, electric conductive wire is used to transmit them to the cathode. At the cathode, with the aid of the catalyst, oxygen atoms combine with protons at the presence of electrons and produce water, which can be collected or dispensed harmlessly to the environment. Electrons produced from the anode reaction can be collected and added to ones resulting from multiple cells to form an electrical current capable of driving an electrical motor that would replace the traditional car engine.

Fuel cells stack end-of-life

Theoretically, the useful life time of the fuel cell is unlimited; while in practice, an existing fuel cell's useful life ranges between four to six years. Deterioration in catalyst performance limits the fuel cell's useful lifespan. Fuel cell performance deterioration can be noticed after two years of operation. Improper working conditions such as poor cooling contribute to the deterioration. Regardless how much improvement and extension on stack useful life, its maximum lifespan is limited by the car's useful lifespan, which ranges between 10-15 years. Not only stack short lifecycle make its EOL recovery preferable, but excessive consumption of platinum, which is a scarce material, makes stack EOL recovery a must. Hence, the purpose of this case study, besides demonstrating the proposed method implementation and validity, is to provide an informed assessment of EOL recovery options for each component in fuel cells stack. This assessment would benefit future stack designs in accommodating stack recovery.

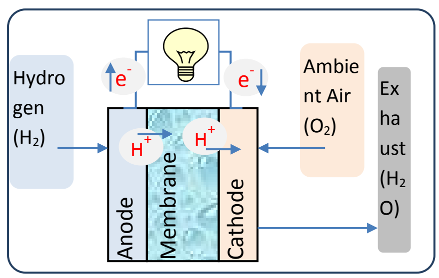


Figure 3.7: Fuel cell concept

Stack components:

The number of stacked cells in a fuel cell stack depends on the required output power; more power requires an increased number of individual cells. In this case study the stack has 200 cells. Figure 3.8 shows a stack of fuel cells (for clarity, only two cells are shown). Table 3.13 shows stack items:

Table 3.13: PEM fuel cells stack components; source of data is (James, et.al, 2010)

Item	Quantity	Description
End Plates	2 per stack	Made of special coated stainless steel; provide structure for the stack and uniform compression pressure to prevent leakage between cells
Membrane electrolyte assembly (MEA):	1 per cell	The membrane material system consists two elements: the Nafion® ionomer and the ePTFE substrate.
1. Gas diffusion Layer (GDL)	2 per MEA	GDL consists of a dual-layer sheet, with macroporous & microporous layers. The 0.28 mm thick macroporous layer made of carbon attached to 0.04 mm thick microporous layer of PTFE and Vulcan XC.
2. Anode and cathode catalyst	1 anode per MEA 1 cathode per MEA	Nanostructured Thin Film Catalyst (NSTF); Active catalyst (platinum) is deposited on high surface are substrate with very precise and even manner.
3. Membrane	1 per MEA	it consists of two materials the Nafion® ionomer and the ePTFE substrate. It is highly ion-conductive. It functions as a cation exchange polymer. The polymer has sulfur.
Bipolar plates	2 per cell	Progressive die stamped stainless steel coated with corrosion resistant material. It provides manifold function for coolant, and collect cell local current
Gaskets	2 per cell	Made of synthesized rubber and silicone to provide leakage prevention between cells layers.
Current collectors	2 per stack	Two cupper plates used to collect the electrical current results from each cell.
Electrical jumpers	2 per cell	copper wires to transmit current from the cells to the current collector
Bolts	4 per stack	Stainless steel gold coated bolts with nuts are used to connect components together and apply uniform pressure at stack components enough to prevent fuel and coolant leakage.

3.3.3.2 Analysis

Product:

Direct hydrogen Proton Exchange Membrane (PEM) fuel cell stack of 80KW suitable for powering light duty vehicle is the subject of this case study. It consists of 200 stacked fuel cells.

Data gathering and sources:

1. Direct contribution from GM fuel cell R&D expert,

2. USA Department of Energy (DoE) PEM fuel cell system cost study, (James, *et al*.,2009).

3. USA Department of Energy (DoE) PEM fuel cell system cost study, (James, *et al*.,2010).

Note: Data provided by GM experts are either published data or scaled; absolute numbers of this study is not recommended to be used as is.

Assumption and limitation made:

In addition to the assumptions stated in the DOE studies regarding component costs, this study is limited to USA as the geographical region and the people of USA as a society.

Input data:

Necessary input data is shown in appendix 3-A.

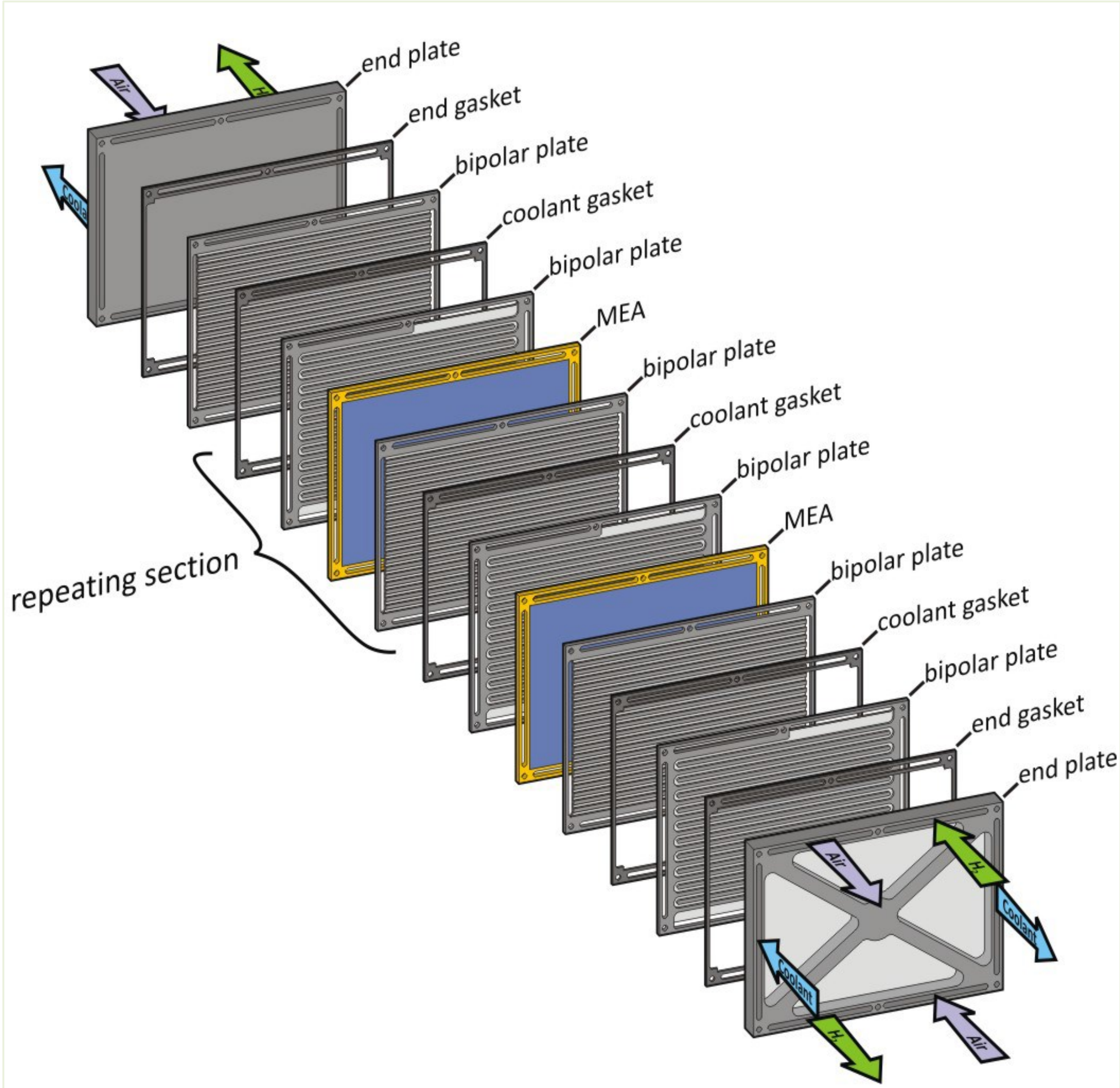


Figure 3.8: Exploded view of fuel cells stack (source: James and Kalinoski, 2009)

EOL analysis and results:

Phase 1:

Analysis starts in phase 1 by identifying the enduser of the developed method who is also the decision maker. In this case study, the decision maker is the OEM, namely general motors is represented by their fuel cell R&D expert. His expertise is used to judge subjective data and estimate non existing ones. To decide on the higher level of recovery options the following analysis is done:

1. Construct importance matrices for all problem hierarchies: level 1, level 2.1, level 2.2, level 2.3, and level 3.

a) Level 1: Level 1 is the top of the hierarchy: namely, the decision on the best recovery option of each item in the fuel cell stack. No importance matrix is needed at this level.

b) Level 2.1: The four major criteria identified are used to construct the importance matrix. The input of this matrix represents the preference of the decision maker. Table 3.14 shows the matrix with calculated weight of each criterion.

Table 3.14: Importance matrix of major criteria and their calculated weights

	Engineering	**Business**	**Environmental**	**Societal**
Engineering	1	2	3	5
Business	1/2	1	3	4
Environmental	1/3	1/3	1	5
Societal	1/5	1/4	1/5	1

Level 2.2 (sub criteria level): As shown in figure 3.9, engineering criterion has two sub criteria: product and process. Both criteria are equally important to the decision maker. The business criterion has three sub criteria: market, demand-supply, and legal and political sub criteria. Sample calculations for importance matrix and weights are shown in table 3.15. Both environmental and societal criteria have two sub criteria. Their weights are shown in the figure 3.9 below.

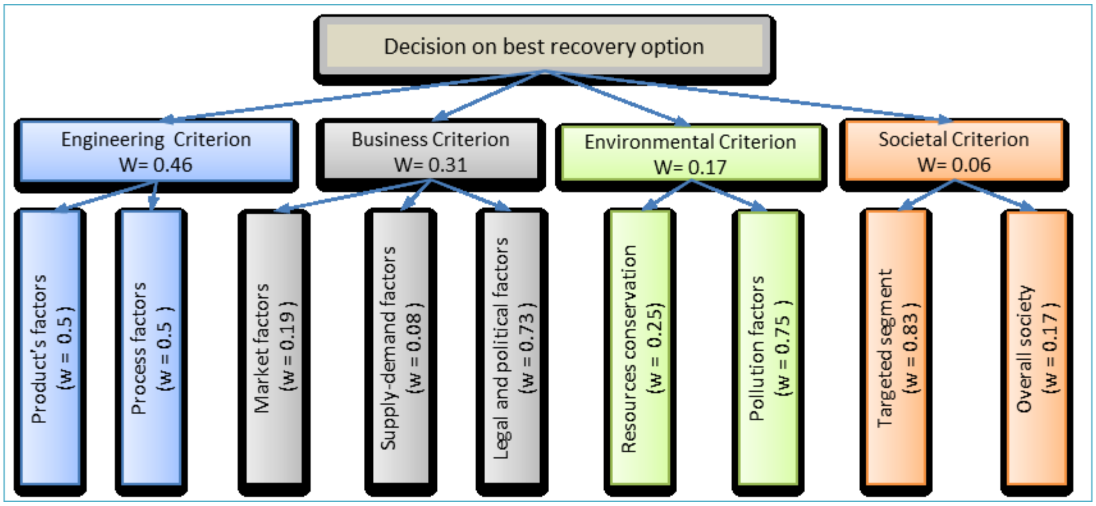


Figure 3.9: Sub criteria with their calculated weights

Table 3.15: Importance matrix of sub criteria belong to business major criterion

	Market factors	**Supply-demand factors**	**Legal and political factors**	**Weight**
Market factors	1	3	1/5	**0.188**
Supply-demand factors	1/3	1	1/7	**0.081**
Legal and political factors	5	7	1	**0.731**
	CI=0.032		*CR=0.056*	

c) Level 2.3 (Influencing factor): influencing factors belonging to each sub criteria are compared together in order to construct their importance matrix and ultimately calculate their weights. Since there are nine sub criteria, the same number of importance matrices is expected. Table 10 shows the importance matrix of influencing factors under "product's factors" sub criteria; this matrix is shown as a sample that demonstrates construction and calculation of the other nine matrices. The weights calculated in the above table are local weights; it indicates the importance with respect to the sub criteria, while the sought weights are the ones with respect to decision in the highest level of hierarchy. Equation (18) is used to calculate influencing factor global weights which are shown in appendix 3-B.

Table 3.16: Importance matrix of influencing factors under "product's factors" sub criteria

	Item useful life time	Technology/ design cycle,	Wear-out life	Standard or interchange able item	Number of components	Product architecture, Level of integration	Weight
Item useful life time	1	1/3	1/3	5	7	7	**0.04**
Technology/design cycle,	3	1	1	7	7	9	**0.08**
Wear-out life	3	1	1	5	7	7	**0.07**
Standard or interchangeable item	1/5	1/7	1/5	1	5	3	**0.02**
Number of components	1/7	1/7	1/7	1/5	1	1/5	**0.005**
Product architecture, Level of integration	1/7	1/9	1/7	1/3	5	1	**0.04**
		CI = 0.123			*CR= 0.099*		

d) Level 3 (Recovery options weights): recovery options are compared according to their performance with respect to each influencing factor. for example, for an item whose useful life time is short - influencing factor #1 in sub criteria "product's factors"- the importance of a reuse option would be less than the recycling option. Whereas for an item with a long useful life time, the opposite is correct. Importance matrix which shows comparison between recovery options with respect to each influencing factor is needed. For each item in the fuel cell stack, twenty nine comparison matrices are constructed and consequently options weights are calculated. Table 3.17 shows options comparison matrix with respect to influencing factor "item useful life time" for end plate.

Table 3.17: Options comparison matrix with respect to "item useful life time" factor for End Plate

Item: End Plate		Factor: Item useful lifetime		
	Reuse	**Recycling**	**incineration**	**Weights**
Reuse	1	5	9	**0.763**
Recycling	1/5	1	9/5	**0.153**
incineration	1/9	5/9	1	**0.085**
	CI=0.0		*CR=0.0*	

The value of the influencing factor determines the importance of an option compared to the others. The influencing factor values are shown in appendix 3-A; these values are used to conduct the importance of comparison between options and construct their comparison matrices. Regarding the "Disassembly Effort" factor, the input is usually calculated using the optimization algorithm introduced in section 3.3.2.5. For this case study, since the disassembly solution space is only one solution, there is no need to run the algorithm. The disassembly operations, disassembly time, sequence, and precedence diagram is presented in appendix 3-C.

2. Rank available options:

The rank of each available option is calculated using equation (19). The calculation is repeated for each item in the stack. Table 3.18 demonstrates fuel cells stack items (sub-assemblies and components) and their phase 1 ranked recovery options.

3. Select the best option: the best option is the option which is ranked first in the previous step. This is valid except for items whose first option is reuse. Before accepting this option as the final destiny for an item, a suggested method in section 3.2 needs to be used to verify that the sustainability index of the used item is higher than the sustainability index of a new item. The Sustainability index indicates the overall performance of a product during the use phase of its lifecycle.

Items qualified for reuse are: end plates, current collector, bipolar plate, electrical jumpers, and bolts and nuts. All these items are components assembled in the same product. Therefore, the sustainability index for each of them is similar. Therefore, the sustainability calculation is required once for only one item, and the result is applied to the rest. Table 3.19 shows the sustainability index of used end plates compared to a new one. Calculations show that used end plates are favorable over new ones. Hence, all items in the fuel cell stack qualified to be reused, without the worry of the new item outperforming the used one.

Table 3.18: Results of phase 1 recovery options ranking

Item	First Rank	Score	Second Rank	Score	Third Rank	Score
End Plates	Reuse	0.59	Recycle	0.24	Incinerate	0.17
Current collector	Reuse	0.69	Recycle	0.24	Incinerate	0.07
Gasket	Incinerate	0.50	Reuse	0.31	Recycle	0.19
Bipolar Plats	Reuse	0.60	Recycle	0.23	Incinerate	0.16
MEA assembly	Recycle	0.44	Reuse	0.41	Incinerate	0.15
Membrane	Incinerate	0.40	Reuse	0.34	Recycle	0.26
Cathode & anode catalysts	Recycle	0.48	Reuse	0.39	Incinerate	0.13
Gas diffusion layers (GDL)	Incinerate	0.42	Reuse	0.35	Recycle	0.24
Electrical jumpers	Reuse	0.68	Recycle	0.25	Incinerate	0.07
Bolts and nuts	Reuse	0.66	Recycle	0.25	Incinerate	0.08

In summary, the output of phase one is the following:

A. Items qualified for reuse are: End plates, current collector, bipolar plats, electrical jumpers, and bolts and nuts.
B. Items qualified for recycling are: MEA assembly, and cathode & anode catalysts.
C. Items qualified for incineration are: Gasket, membrane, and gas diffusion layers (GDL)

Table 3.19: Sustainability index of used and new end plate

Item	Sustainability Index (SI)
Used end plate	0.67
New end plate	0.33

These results are taken to phase 2 of the method to decide on the second level of recovery.

Phase 2 analyses:

Cost and benefit analysis is required in this phase to decide on the second level of recovery. Analysis is performed according to equations (20) to (26) using US dollars. For fuel cells stack on hand, some recovery options are not applicable to its components due to reasons related to the product as a whole and not to the component. This is either due to OEM policies or technical reasons.

A. Items qualified for reuse are: End plates, current collector, bipolar plats, electrical jumpers, and bolts and nuts.

Option 1: Resale

Although resale of a functioning stack is possible ,resale of individual components is not a valid option. This is due to technical reasons; once the stack is opened the sealing function provided by gaskets is lost, which is enough to make the stack non-reusable.

Option 2: (maintenance, service, or replacement)

This option is invalid for stack as a whole and its individual component. This is due to technical and business policy reasons: the technical reason is the same as mentioned previously in option1 while the second reason comes from the EOM business policy. According to the opinion of experts, OEM will provide incentives (most probably money value) for returning EOL stacks to specified collection points. These incentives will prevent end-users from considering any of these options.

Option 3: Refurbishing

Currently, fuel cell stacks manufacturing and development is in the hand of OEM. This puts the business for independent recoverer at a loss, making business instead of profit.

Table 3.20 shows the calculations for this option. This situation might change in the future due to technology maturity and business dynamics. Calculations are made using equation (22):

Benefit = Revenue $_{refurbishing}$ – $C_{disassembly}$ – $C_{refurbishing}$ – $C_{reassembly}$ – $C_{testing}$

Option 4: Remanufacturing

Cost/ benefit analysis shows that remanufacturing is the only economically feasible reuse option for the stack. OEM receives EOL stacks for further reprocessing which starts by stack disassembly and separating the specified five items for reusing them in new stacks. Table 3.21 shows the required calculations according to equation (23).

Benefit = Revenue $_{reman}$ – $C_{reman.}$ – $C_{disassembly}$ – $C_{reassembly}$ – $C_{testing}$ - $C_{packaging}$ - $C_{warrantee}$

Remanufacturing is a profit making option, with the exception of bolts and nuts. Disassembly cost is the main reason behind this loss. Attention needs to be paid to the fact that this disassembly effort is required to access further components, so that reconsidering disassembly cost allocation is a reasonable approach. Moreover, the total of individual benefits of remanufacturing for the five items is still profitable.

B. Items qualified for recycling are: MEA assembly and cathode & anode catalysts.

For a recycled item two scenarios are available; either full disassembly or shredding and separation. Cost/benefit calculations are made using equation (24) and (25). The MEA assembly has three components, one of which is the cathode/anode catalysts. The recycling scenario of MEA is coupled with the recycling scenario of the catalysts. Then, it is needed to determine cathode/anode recycling best scenario first. The following calculations are made:

Recycling benefit of scenario1 (disassembly) = 365- 25 = 340

Recycling benefit of scenario 2 (shredding) = 346- 2.5 – 50 = 294.5

The disassembly option makes an extra $45 over the shredding option, that is due to a higher material yield of a disassembly option. Due to the dependency between the Catalyst and the MEA, the recycling scenario selected for the catalysts applies to the MEA.

C. Items qualified for incineration are: Gasket, membrane, and gas diffusion layers (GDL)

Incineration options range between full item incinerations to complete landfilling, equation (26) is used to decide on the best option for each item. Table 3.22 shows the cost/ benefit analysis for each of the three items.

Since the membrane has hazardous materials, the incineration option is not feasible. Controlled landfilling is required. For the gasket and GDL the decision is mainly controlled by energy and landfill rate prices. Calculations shown in table 3.22 are based on 2013 prices in Michigan, USA. The calculations show the best option for a gasket as well as GDL is incineration.

Table 3.20: Cost/benefit analysis for refurbishing option.

	$C_{disassembly}$	$C_{refurbishing}$	$C_{reassembly}$	$C_{testing}$	$Revenue_{refurbishing}$	Benefit [Equation(22)]
End Plates	0.167	4.472	223.6	50	33.54	**-244.699**
Current collector	0.083	1.064	53.2	50	7.98	**-96.367**
Bipolar Plats	0.125	73.68	3684	50	552.6	**-3255.205**
Electrical jumpers	0.083	0.2	10	50	1.5	**-58.783**
Bolts and nuts	15.000	4	200	50	30	**-239.000**

Table 3.21: Cost/benefit analysis for remanufacturing option

	$C_{disassembly}$	C_{reman}	$C_{reassembly}$	$C_{testing}$	$C_{packaging}$	$C_{warrantee}$	$Revenue_{reman}$	Benefit [Equation(23)]
End Plates	0.167	6.708	0.224	0.022	0.224	2.236	22.360	**12.780**
Current collector	0.083	1.596	0.053	0.005	0.053	0.532	5.320	**2.997**
Bipolar Plats	0.125	110.520	3.684	0.368	3.684	36.840	368.400	**213.179**
Electrical jumpers	0.083	0.300	0.010	0.001	0.010	0.100	1.000	**0.496**
Bolts and nuts	15.000	6.000	0.200	0.020	0.200	2.000	20.000	**-3.420**

Table 3.22: Cost/ benefit analysis for items qualified for incineration

	Energy recovered(KW)	Rate $/KW	Landfilled weight(kg)	Landfill rate ($/kg)	Benefit equation(26)
Gasket	0.055	0.10	.01	0.025	0.0025
Membrane	NA	NA	.01	0.025	NA
Gas diffusion layers (GDL)	0.092	0.1	.01	0.025	0.0067

3.3.3.3 Discussion of results

The implementation of the proposed method demonstrates the effectiveness of the employed logic. It is found that when breaking down the decision of an EOL product recovery into two levels, the decision is an effective approach. At the first level, the decision is made based on the selection of one of three major recovery options (reuse, recycling, and incineration). At the second level, the decision is made based on the sub options found under each main option selected in the first level. This approach has drastically reduced the solution space while maintaining quality solutions.

The structure of the proposed method matches the previous logic; the method comes into two phases which are designed to address the corresponding level of the problem. The first phase of the method provides the holistic perspective of the method; it includes carefully selected factors that altogether determine the proper recovery option. These factors span the whole aspects of the EOL product recovery decision. With the aid of the AHP decision method, the first phase of the proposed method is able to include preferences of different decision makers who might be interested in the recovery decision. For example, the decision maker's preferences, who is OEM, are very obvious in the analyzed case study; the calculated weights of major criteria that affect the decisions reflect the decision maker's preferences. They are 0.460 for engineering criteria, 0.308 for business criteria, 0.170 for environmental criteria, and 0.062 for societal criteria. If the decision maker is an independent recoverer or governmental agency interested in EOL product recovery, then the previous weights would be different. Results obtained from the fuel cell stacks case study shows the following:

- The reuse option scores high with components made of metals; metals are durable and structurally stable materials. The deterioration in their physical properties is minimal; all that make items made of metals good candidates for reuse, especially when these items are maintained in a neutral environment during their use phase. For example, all components in the stacks which are qualified for reuse are metallic. They are: End plates, current collector, bipolar plats, electrical jumpers, bolts and nuts
- Components which have long useful lifetime are also good candidates for reuse; long useful lifetime makes the item suitable for a second lifespan
- Components which are structurally unstable and uneasy to handle are assigned to recycling options if they have high value material. If they havehigh heat content, then they would be assigned to incineration. Gasket, GDL, and catalysts are very thin sheets which lose their structure during the disassembly process, which makes their reuse unsuitable.
- The method selects the incineration option for fuel cell membrane which has hazardous material. This could be unwanted result. This result was discussed with a GM expert who agreed with this notion and commented, "fuel cell membrane has hazardous materials which make it unsuitable for incineration. Incineration of these hazardous materials will produce Ozone depletion gases. Controlled landfilling could be the best recovery option since these materials are not harmful in their solid state"
- The results of the calculated sustainability index for items qualified for reuse return the same results for all items in the stack. This is due to the fact that sustainability index measures the performance of used products compared to the performance of the new products during their use phase within their lifecycle. Since none of the items operate individually, the results of the sustainability index is attributed to the fuel cell stack and not to the individual components.

- In phase 2, where cost/benefit analyses are conducted, the resale and service options are identified as non-applicable options. It is important to know that a fuel cell in an auto application is still in the research and development phase. Ambitious estimations expect that a marketable model will be available in less than ten years. The absence of the product from the market and technical difficulties with current designs make this recovery options invalid. This result could change if the situation changes in the near future.
- The losses shown for the refurbishment option are due to high costs of disassembly and reassembly. Disassembly is a costly operation due to variations in the disassembled product. Variations are due to uneven flow of returned EOL products, unexpected changes made by the user to the product during its use phase, and wear and rust that could make disassembly a costly operation. On the other hand, reassembly of fuel cell stacks is currently a costly operation due to the lack of mass production and high initial capital investment.
- Remanufacturing is the only profitable option for reusing stack items. This can be explained by OEM involvement and commitment to their EOL product recovery. OEM commitment is behind the success of many product recovery cases. Xerox is a traditional example.
- The decision to landfill or incinerate the last three items in the stack is mainly controlled by prices of energy and landfill rate. This can be considered as a part of deficiency of pure cost/benefit decision models. Extra caution needs to be taken while selecting the proper option between land fill and incineration for an item.
- The assessment model proposed in this work can be integrated with the international standards (ISO 14040 and ISO 14044). These standards cover environmental assessment for the entire lifecycle; the results from this assessment can be used in the developed model to decide about the weights of the influencing factors under the environment criterion.

3.4 EOL assessment linked to active disassembly

EOL assessments which are developed in this chapter fulfill level 1 requirements of the proposed framework in section 1.5. Their main purpose is to justify the decision for incorporating active disassembly in the design of the product, which is also the subject of the assessment. Justification is based on the merits of improving corporate sustainability. OEMs are welling to get involved in A.Dis. if it improves their sustainability. The proposed assessments provide OEMs with detailed answers towards this purpose. According to the proposed framework, assessment starts with closing the loop in a product lifecycle by introducing EOL products to a second life; this is the reuse option which is detailed in section3.2. The framework starts firstly with this option because it does not consume resources to prolong product useful life. When reuse is not a feasible option, the framework suggests the next type of assessment which is detailed in section 3.3. It explores the opportunity to recover EOL products as assemblies and parts. It also gives OEM decision makers a detailed analysis for opportunities to close the loop in their product through the recovery of its components.

3.4.1 The need for disassembly

The need for incorporating A.Dis. in product design is linked to the need for disassembly. The ultimate goal of OEM is to recover their EOL product without the need to disassemble it. OEM decision makers are in front of two types of EOL recovery:

1. Whole product recovery
2. Assemblies and part recovery

Whole product recovery does not require disassembly. Hence, A.Dis. is not required. In this case the purpose of level 1 in the framework is satisfactory and no further need is required to consider A.Dis. In real life practices, EOL product reuse is found in products which the sole purpose of its ownership is the functions it provides; whereas products that provide aesthetic values beside functional values are not suitable for reuse due to low demand.

Assemblies and parts recovery involve a certain level of disassembly. The second type of assessment provides insight on the level of the required disassembly. Recovery options such as incineration and material recycling do not require substantial disassembly; partial disassembly is sufficient. In some cases, destructive disassembly like crushers and shredders are valid alternatives. Whenever partial or destructive disassembly alternatives are valid, there will be no need for A.Dis. Figure 3.10 demonstrates how incorporating A.Dis. in a product design is linked to the output of the EOL recovery assessments. A.Dis. is justifiable when there is a substantial level of disassembly involved in the recovery process. Options like maintenance, service, refurbishment, remanufacturing, and high value materials recycling usually require this level of disassembly. This type of recovery is manifested in auto and electronics.

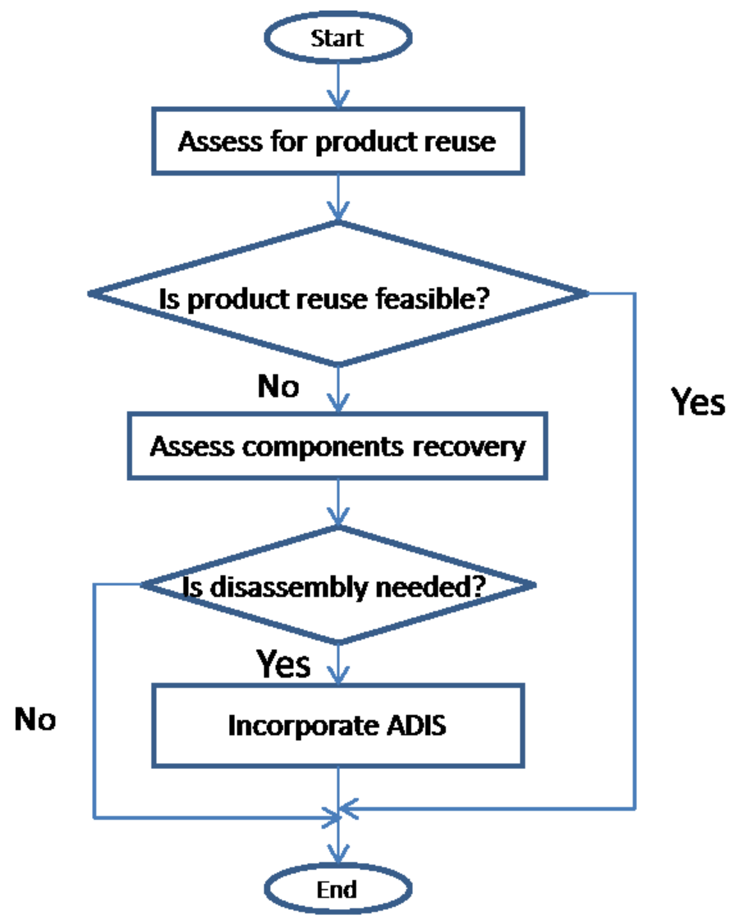


Figure 3.10: : Relating EOL assessments to A.Dis.

3.4.2 The need for active disassembly

Product designers want to consider A.Dis. in their design under the following circumstances:

1. EOL assessments show a need for EOL product disassembly. Then A.Dis. can be consider to achieve the following objectives:

a) Improve current feasible recovery opportunity. Low rate of return or payback period can be improved by reducing costs associated to manual disassembly when it is replaced by A.Dis.
b) Qualify EOL items for recovery options with higher value than current assigned ones. Options that would not be feasible without A.Dis.

2. OEM top management decide to incorporate A.Dis. in their product design as a strategic decision based on their strategic future planning. Reasons behind such a decision cannot be captured by the EOL assessments, since they are designed to capture current situations, and not predicting or planning future.
3. Obligatory Disassembly. Partial or complete disassembly of an EOL product may be obligatory due to environmental or safety concerns. For example, some components may contain hazardous materials that need to be disassembled and isolated from other components before shredding or incineration.

Based on one or more of the mentioned situations above, product designers may want to consider A.Dis. The proposed framework suggests to them to look for readily available solutions found in the active joint catalogue located in appendix 4-A or A.Dis. literature. Should they find that insufficient, or if they want to design their active joints for their own product, the next chapter leads to this target; design methodology is developed to innovate and design active joints.

4 ACTIVE JOINT DESIGN METHODOLOGY[3]

4.1 Introduction:

Active joint is an essential requirement for joining parts that use active disassembly. It is essential for the EOL product disassembly, since disassembling parts becomes an important process prior to product recovery. The technique involves using an active joint which can be disassembled using a triggering field that can initiate simultaneous disassembly of many products having the same joints. Design of such joints requires substantial level of invention and a systematically driven design process. The purpose of this chapter is to provide a design methodology that systematically guides and helps product designers in generating inventive working design solutions for active joints that will/could be used in their products. The Methodology development is approached from the perspective of two well recognized design approaches: systematic design (Pahl and Beitz, 1996), which gives the developed methodology its systematic nature, and the TRIZ approach (Altshuler, 1984), which adds the inventive feature to the methodology. Methodology validation and implementation is explained and demonstrated in chapter five.

4.2 Need for design methodology

Design was considered an art more than an engineering work. During the 1970s, researchers and practicing designers recognized the need for establishing engineering design theories and methodologies (Tomiyama *et al*., 2009). The need for engineering design methodologies to facilitate the design process is justified through the expected outcome of having such methodologies. Teegavarapu (2009) lists the following purposes of having engineering design methodologies:

a) Quality solutions: design procedures set by a design methodology facilitate complete inclusion of design requirements. tThis ensures that the final solution fulfill these requirements; which in turn, leads to a quality solution which satisfies

[3] This is outcome of joint research

the customer's requirements with a reduced design cost due to the consistency expected from using a design methodology.

b) Creativity and intuition: using a design methodology reduces the routine activities and work that usually consume a designer's attention; this gives the designer less effort and more time to focus on the tasks that add value and creativity to the design.

c) Design reuse and automation: Design methodology facilitates proper design documentation for future reference and reuse them for similar products. Design documentation forms a knowledge database of design theories, models, requirements and solutions which can be used to automate parts of the design process.

d) Collaboration and management: design task can be handled effectively and efficiently when it is governed by a design methodology that can facilitate breaking down the task into manageable subtasks between teams and their individuals.

e) Teachability and learnability: establishing design theories and methodologies facilitate the teaching and learning process of engineering designs in the academic and practical environment. It is easier to teach and learn a methodology rather than a person experiencing it in an art.

4.3 Assessment of current design methodologies

Design methodologies include a wide spectrum of methodologies found in different disciplines; engineering design methodologies, and specifically mechanical engineering design methodologies are the focus of this work. In this section, methodologies related to product design are discussed. Finger and Dixon (1989[b]) categorize mechanical design methodologies into six categories; the proposed methodology in this work fits the prescriptive methodologies category. Hence, prescriptive models are the subject of assessment presented in table 4.1. Prescriptive design methodologies are ones that advise or prescribe techniques, procedures, guidelines, and rules that assist product designers in their design process. Finger and Dixon (1989[a]) identify two purposes of prescriptive methods: to prescribe "how" a design process ought to proceed and "what" attributes design solutions ought to have. Table 4.1 exhibits a non-exhaustive list of well-established design methodologies known for design research community and used in industrial practices. These methodologies are selected from a longer list compiled by

Tomiyama *et al*., (2009). Methodologies with limited applications and less presence in the literature are not considered in this work.

Table 4.1 : Design methodologies assessment. Compiled from (Tomiyama et al., 2009)

Design method.	Method.'s application	Strengths	Weaknesses
Axiomatic design	Products and systems	Solution found will meet design requirement	May be difficult to find solution; biases designer; reasonable traceability
Characteristics-properties modeling (CPM)	Product	Able to follow up with large list of product characteristics and required properties	No priority reference can be given to properties or characteristics
Concurrent engineering	Product development	Negotiation and collaboration during product development	Less support for design process
Design for x (DFX)	Targeted objective	Systematic in addressing targeted objective	Time and effort consuming; contradiction between different design objectives
Design decision-making methods,	Alternative selection	Efficient in evaluating and selection among design alternatives	Does not support generating design alternatives; sensitive to uncertainty.
Design structure matrix (DSM),	Product or system	Efficient in presenting relation between design solution components	Time consuming; require multi-disciplinary knowledge.
Failure mode and effect analysis (FMEA),	Product/system design improvement	Predicting failure mods and avoiding its effect	Require team of experts; data availability limits feasibility of method's calculations
Pahl and Beitz (systematic design)	Product	Systematic management of design; allows trade off; logical sequence of design process	Difficult to quantifying attributes accurately and consistently; little traceability
Quality function deployment (QFD)	Quality deployment during product	Systematic procedures of handling information; ensure the transfer of	Sensitive to data quality and availability;

	development	quality requirements throughout lengthy product development process	substantial work load is required to complete method requirements
Taguchi method	Product and process design	Mathematically and empirically addresses factors affect design solution performance	Requires known relationships between design parameters and product performance.
Total design of Pugh	Product, systems, subsystems	Systematic methodology for concept selection	The selection process is subjective and depends on the reference alternative.
TRIZ	Product, systems, subsystems	Provide designers with tools for invention and concept generation; provide analytical methods for problem formulation and modeling	Local focus on specific problem rather than complete product solution; lacking of systematic procedures that guide and manage product design

4.4 Process of developing a design methodology

The development of an engineering design method does not follow a systematic method; literature review in this work could not locate any such method. Also, literatures of existing design methodologies do not reveal how the developers develop these methodologies; whether they use a method or their own intuition and experience. Tomiyama *et al*. (2009) show, through a survey of design methodologies, that a developers' background and experience contributes to the development of their methods and shapes its final structure. The need for a systematic method for developing design methodologies was studied for the first time by Teegavarapu (2009). The study refers the nonexistence of such method to three reasons. First, design methods are required by multi disciplines in engineering; hence, a generic systematic method that can be used in all engineering disciplines guiding the development of their individual methods would be a challenge. Second, lack of standards, techniques, and procedures to test and assess the efficiency and effectiveness of the proposed design method challenges the development of a design method. Existence of standards helps a method developer build test his/her method and build confidence in the development process. Third, design methods develop over a long period of time; sometimes by more than one developer. This creates the experience and the intuition of the developer, a main contributor to the development process, and renders the use of rigid systematic procedures. Teegavarapu (2009) attempted to bridge this gap by providing a systematic method for developing an engineering design methodology; figure 4.1 shows the method. The method carries a lot of resemblance with Pahl and Beitz's systematic design methodology; it consists of seven steps, six of which can fit under Pahl and Beitz's method.

Analogous to task planning and clarification in Pal and Beitz's methodology, Teegavarapu's method suggests the following four steps: *First*, Problem definition starts with identifying the objectives of the intended design methodology to be developed. It is recommended at this step that the developer states a hypothesis which guides the development process. *Second*, literature survey is conducted to explore the existence of design methods that could serve the objectives specified in previous step. Literature outside the field is recommended to be surveyed to explore possible ideas and techniques that could be used in building the intended methodology. Once the surveyed methods are identified, their characteristics, constructs, logic, strengths and weakness are documented for further analysis and possible integration to build the intended method. *Third*, benchmarking of proposed methodologies with identified ones in the previous step is conducted. The purpose of benchmarking is to identify the strengths of a proposed methodology over previously existing ones and avoid their shortcomings. *Fourth*, requirements elicitation step is conducted to ideally quantify requirements identified in previous steps. A More detailed list of requirements is expected at this step; requirements regarding a method's representation capabilities, performance, quality, and functional requirements are detailed and listed.

The *fifth* step is concept exploration, which requires a method developer to explore literature in depth based on the list of quantified requirements in the previous step. A Morphological matrix can be used to assist in gathering and combining ideas that lead to concepts generation. Once this concept is selected, the *sixth* step starts; the developer needs to build the constructs of the method where the type and objectives of the method determines the information flow, algorithm logic, and processes to be performed by each construct. It is recommended to test and validate construct before starting to build the next one. The method refers to this type of validation as intrinsic testing, which validates the method's constructs individually. The *Final* step requires extrinsic validation of the proposed method as a whole. Method validation is the evidence that shows the effectiveness and efficiency of the proposed method; without validation, no confidence can be built in the method and consequently designers would not prefer to use it.

To the best of the author's knowledge, Teegavarapu's method is the only one found in literature that can be used to guide the development process of a design methodology. It will be used to guide the development of the design methodology proposed in this work. The next section shows the development of the proposed methodology.

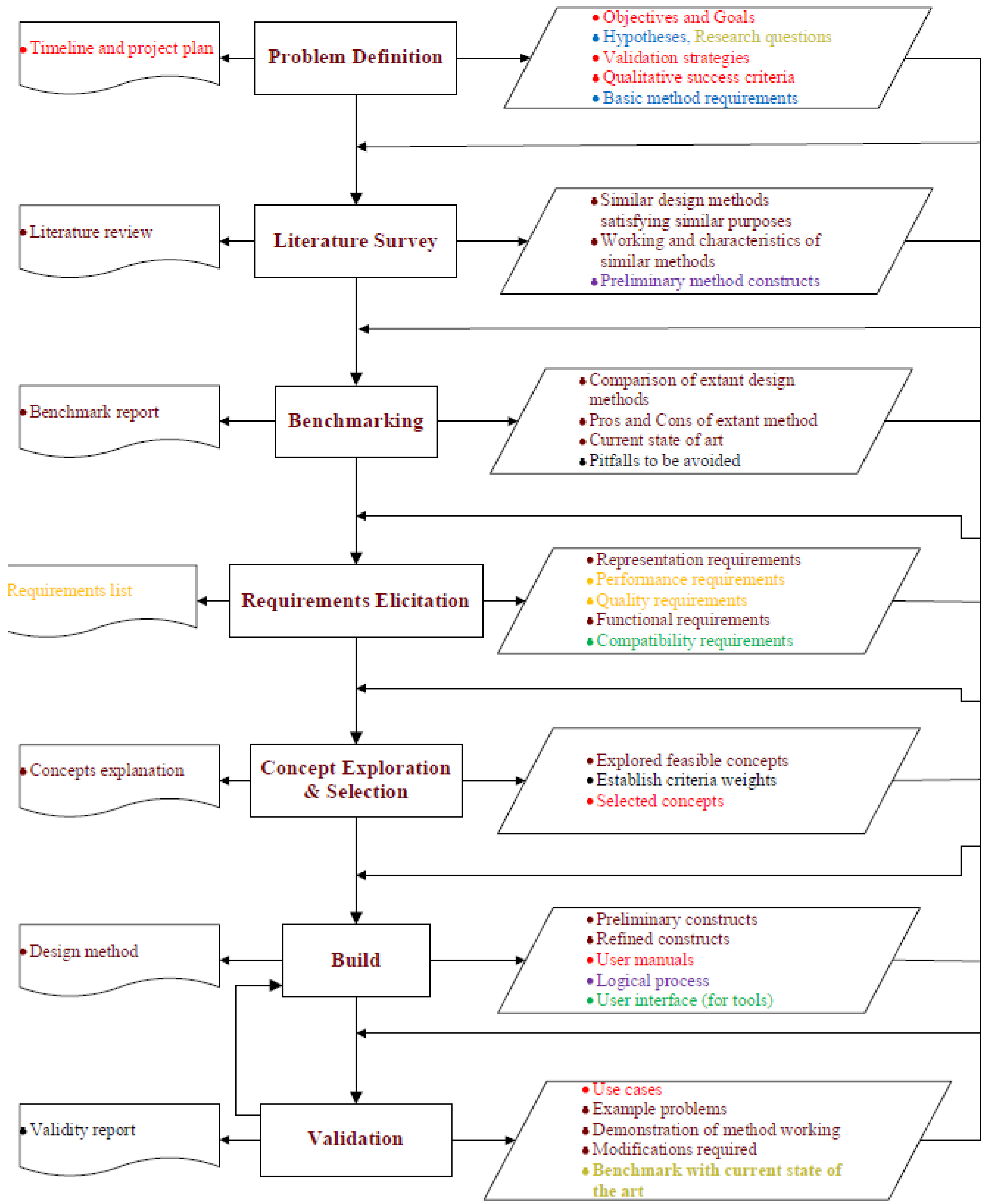


Figure 4.1: Process of developing a design methodology. Source: (Teevagarapu, S, 2009)

4.5 Proposed methodology development

The development process consists of seven major steps. The output of each step is required by its subsequent step; so the output quality is cumulative and so is the quality of the developed methodology. The validation step at the end ensures the quality of the developed methodology. If the developed methodology does not satisfy the quality requirements stated in step number four, then the process needs to be run again with more clarification and depth. This, generally, complies with the iterative nature of the design as a process.

4.5.1 Problem definition

During the product design process, designers select appropriate joining methods to join and assemble product components from well-established and known joining methods to product designers; the more the coverage the better. Active Joints are not well known to most product designers, and are not well established either. This is due to their new emergence and dependence on the development achieved in the fields of smart materials and adaptive structures. Active Joints are theoretically traditional joints with one extra feature, which is the ability to disassemble using a triggering field.

Active structures, which are designs that have active joints, are defined by the ASME committee on Adaptive Structures & Material Systems Committee (ASMS) as "adaptive structures consisting of smart materials having geometry or characteristics that can be remotely or automatically changed to respond to internal and external stimulation".

Active Joints are defined as "joints consisting of material having geometrical or characteristics that can be remotely or automatically changed to respond to internal or external stimulation to produce disjoining (disassembly) action enough to release the joined components".

The Design of these types of joints will be the main objective of the envisioned design methodology, which needs to be systematic to guide the design process, and at the same time, be creative and inventive. Usually, design methodologies cover one and miss on the other. To address the specific nature of active joints, the proposed methodology has to provide designers with reference to a body of knowledge capable of bridging the gap in their knowledge of physical principles. It should be employed directly or combined with each other to generate working concepts suitable for active joints.

4.5.2 Literature survey

Based on the problem definition, a thorough and directed literature survey is done in this step. The survey is directed toward engineering design methodologies suitable for product designs and able to demonstrate a systematic way of addressing a design task. Another direction of search is engineering design methodologies which demonstrate a considerable level of invention and creativity in providing engineering solutions and demonstrates its abilities in generating new ideas and working concepts.

The assessment of current design methodologies conducted in section 4.3 is used at this stage to direct the literature survey. The assessment shows that the following design methodologies demonstrate a reasonable level of systemization.

Axiomatic design is a systematic method of translating customer attributes into final product parameters. The method depends on the theory of axioms; two design axioms make the theoretical foundations of the method. One to maximize functional requirements uncoupling and another to minimize information content (Nam Suh, 2001). These two axioms do self-validation for the method, in other words, the designs generated using the method and satisfying both axioms are necessarily valid and good designs. The method has five constructs called domains: customer, functional, physical, and process domain. Mapping between the functional domain (what is required) and the physical domain (how to fulfill requirements) is constructed through a design matrix. This construct is usually found in many design methodologies (linking functional requirements to physical design solution attributes).

Pahl and Beitz's systematic design is a systematic methodology of guiding and managing the product design process. The methodology consists of four constructs (Pahl *et al.*, 2007), namely, task planning and clarification, conceptual design, embodiment design, and detail design. These four construct with their internal processes are enough to systematically guide the design process and help designers generate a working concept for their proposed design solution. The Task planning and clarification phase is crucial to a method's success in providing design solutions that fulfill the intended requirements. It provides the means to identify properly and rigorously functional requirements.

QFD is a systematic method of translating customers' requirements into product structure and components covering a customer's functional requirements (Akao, 1990). The method has developed since its first publication. Currently, the method has many constructs that can be used collectively or individually. Quality deployment is the core construct of the method which maps the functional requirements into physical attributes of a proposed solution.

For creativity and invention, the following methods are identified:

TRIZ is defined by Altshuler (1984) as the theory of the solution of inventive problems. TRIZ's methodology is concerned with solving a problem in an inventive nature. The method's main purpose is not product design, but it provides innovative solutions for concept generations required in the design process. TRIZ can provide creative and inventive solutions that help product designers meet the functional requirements without trade-off.

FMEA is an analytical method that can be used during the product design process to determine possible product failure modes and innovatively avoid them early in the product design stage (Tomiyama *et al*., 2009). The method can be used to optimize and improve proposed design solutions and lead to innovative solutions which satisfy requirements with minimal possible failure.

4.5.3 Benchmarking

The literature surveyed in the previous step is used to conduct benchmarking analysis between the envisioned methodology and the state of the art methodologies. Table 4.2 shows the benchmarking. The purpose of benchmarking is to assess the features over which a method excels over its competitors; also to avoid the bits and falls of competitive methods.

Table 4.2: Benchmarking proposed methodology with state-of-art design methodologies

Design methods	**Focus on active joint**	**Support innovation**	**Systematic**	**Influence designer preferences**	**Validation**
The proposed method	Yes	High	High	Medium	Through examples
Axiomatic design	No	Low	High	High	Through examples
Pahl and Beitz	No	Medium	High	Medium	Through examples
QFD	No	Low	Medium	High	Through examples
TRIZ	No	High	Low	Low	Through examples
FMEA	No	Medium	Medium	Medium	Through examples

4.5.4 Requirement identification

The developed design methodology has to adhere to generic requirements to be fulfilled by any design method other specific requirements that make the methodology efficient and effective in addressing its core function, namely active joints and adaptive structure design and innovation. Three groups of requirements can be identified:

a) Functional requirements:

1. Design active joint: the main function of the methodology is to guide and help designer design active joints able to perform their functions in the intended product.
2. Generate inventive concepts for active joints: active joints design requires a considerable level of creativity and invention, and new inventive working concepts for active joints.

b) Performance requirements:

1. Systematically guide the design process: the methodology needs to perform the design in a predictable, traceable, and well structured

procedure. The Method’s construct interact systematically enough to communicate their input and output between teams involved in the design process.

2. Effective and efficient in supporting invention: the methodology is required to support invention effectively by providing innovative design solution, while using available resources efficiently.

c) Quality requirements:

1. Use and produce logical data: methodology’s constructs are required to process quality data to produce quality output.
2. Does not impose preferences on designers: producing quality design solutions require a methodology that does not limit a designer creativity or designer preferences.

4.5.5 Concept exploration and selection

The identified requirements in the previous step clarifies y the need for a design method conceptually cored around two features: Systematic guidance and supporting invention. As intuition, the concepts that might lead to the intended design methods can be explored using the literature of current design methodologies; and inspired by their approaches, addressing these two features. Pugh matrix shown in table 4.3 is used to explore possible concepts for building the intended methodology.

Table 4.3: Explore possible concepts using Pugh matrix

	Weight	Means				
Criteria for being systematic		**Datum:** QFD	Pahl and Beitz	Axiomatic design	TRIZ	FMEA
Requirement: a). 1	9	0	++	+	-	-
Requirement: b) .1	5	0	++	++	-	S
Requirement: c) .1	7	0	+	s	s	+
Total: (Systematic criteria)		**0**	**35**	**19**	**-14**	**-2**
Criteria for being Inventive						
Requirement: a) .2	9	0	+	+	++	+
Requirement: b) .2	5	0	-	s	++	+
Requirement: c) .2	3	0	s	s	+	s
Total: (Inventive criteria)		**0**	**4**	**9**	**31**	**14**

Legend: s = 0 point, + = 1pont, ++ =2points, - = -1point, -- = -2 points

Based on the Pugh matrix analysis, the following two approaches can be tested:

a. have one method inspire development of the intended method
b. Combine more than one method to produce one coherent approach for developing the method.

Exploring the approach in section (a) shows that there is only one method that shows satisfactory performance in the two sets of criteria (systematic and inventive); axiomatic design methodology scores 19 for being systematic and 9 for being inventive. Other methods show polarity tendency; i.e., each method excels in one feature, not in both. This concept is compared to the one which results from approach (b). This approach suggests conceptualizing the intended method based on two or more existing methods; Pahl and Beitz's method is superior in being systematic (score 35) but not as good in being inventive (score 4). TRIZ is the opposite; it shows high competency in being inventive (score 31) and scores badly in being systematic.

It is obvious that the second approach is more reasonable; a method that benefits from the strengths of the other two methods, while avoiding their weaknesses would be better than a method that takes strengths and weaknesses of one method. Based on this argument, the development of the intended method is cored around the characteristics and strength of the selected design methodologies; Pahl and Beitz will provide the systematic approach, while TRIZ will provide the inventive feature of the proposed method.

4.5.6 Building methodology constructs

4.5.6.1 Approach

The two design methodologies, systematic and TRIZ, are hybridized and form the basis of the developed method. The overall structure of the methodology is inspired by the structure of Pahl and Beitz's methodology, which provides a very systematic way of addressing a design task. This is very obvious in its logic and data flow and the interaction between its design phases; it is the backbone of the proposed methodology. This backbone holds and correctly positions the proposed methodology's peripherals (methodology constructs), see figure 4.2.

The inventive nature that is required in this methodology is proposed with the intention of being fulfilled using constructs that are adapted and modified from the TRIZ Methodology. TRIZ is rich with methods and tools that support invention. Both analytical and knowledge based tools are used, which consistently prove their ability in solving inventive problems. The Problem solver (designer) needs to know how to select and use the proper tool of TRIZ. The developed tools are built to facilitate the designer's job to perform this task. The Designer needs to use only one methodology at a time without worrying about the details of other methods. eEach construct in the methodology is carefully modified and devoted to serve its core purpose; i.e., design inventive active joint. Details of building each construct in the methodology are explained in the following section.

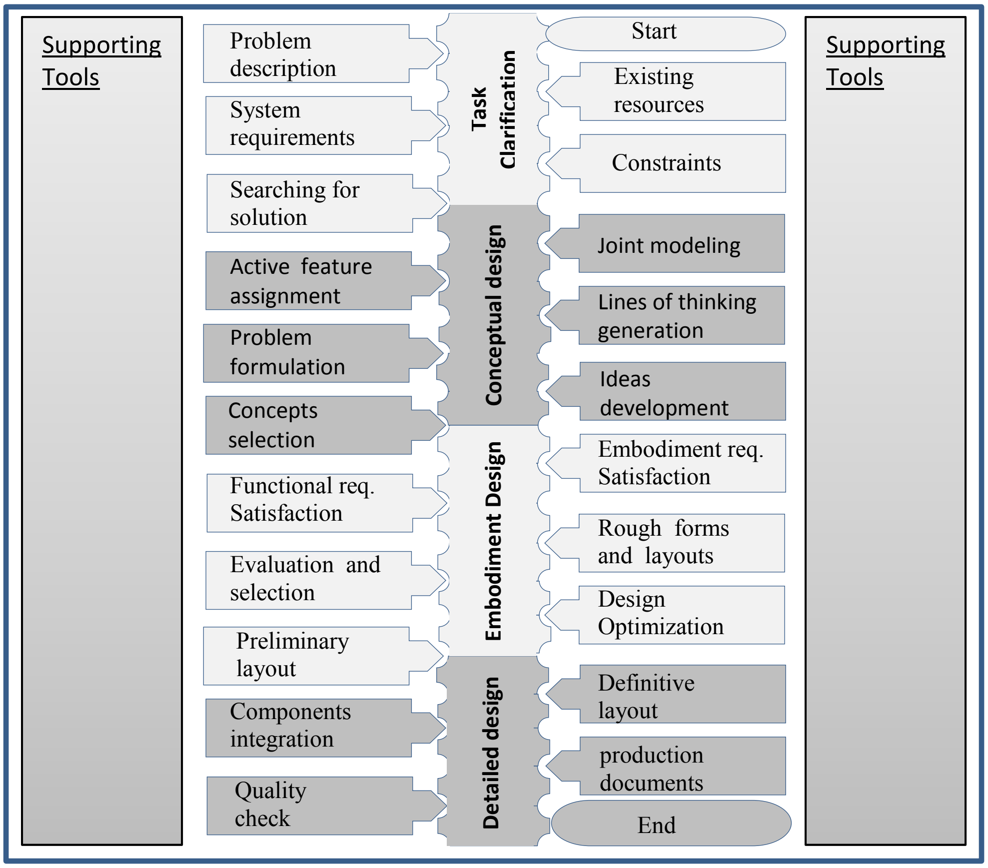


Figure 4.2: Methodology structure

4.5.6.2 Methodology construction

The methodology is structured in four systematic design phases, inspired by Pahl and Beitz's methodology. they are: design task clarification phase, conceptual design phase, embodiment design phase, and finally detailed design phase. These design phases systematically guide the design process of active joints and help the designer translate the required active joint features into a final product (active joint) that completely satisfies its intended use. Each design phase consists of carefully selected and built constructs, which together, perform the tasks of an active joint design. The logic, information, and sequence flow is shown in the methodology flow diagram Figure 4.3

Phase 1: Design task clarifications

This phase is considered as a foundation for the next phases. The quality of data and information acquired for this phase is crucial to the quality of the generated concepts and their final design solutions. This phase has the following constructs:

P1C1. Design task title and description:
Construct's purpose: the purpose of this construct is to give identification to the design task at hand. It also supports the internal and external communication between the design team members and other interested parties by providing unique references to the task. These references are brief, but are descripted enough to identify the task.

Construct's benchmarking: this construct is a typical construct that can be found in most design methodologies. For example, Pahl & Bietz's method uses project or product names to refer to the design task.

Construct's input/output: the input for this construct comes from the designer's initial understanding of the design task; the output is a succinct title with a brief description.

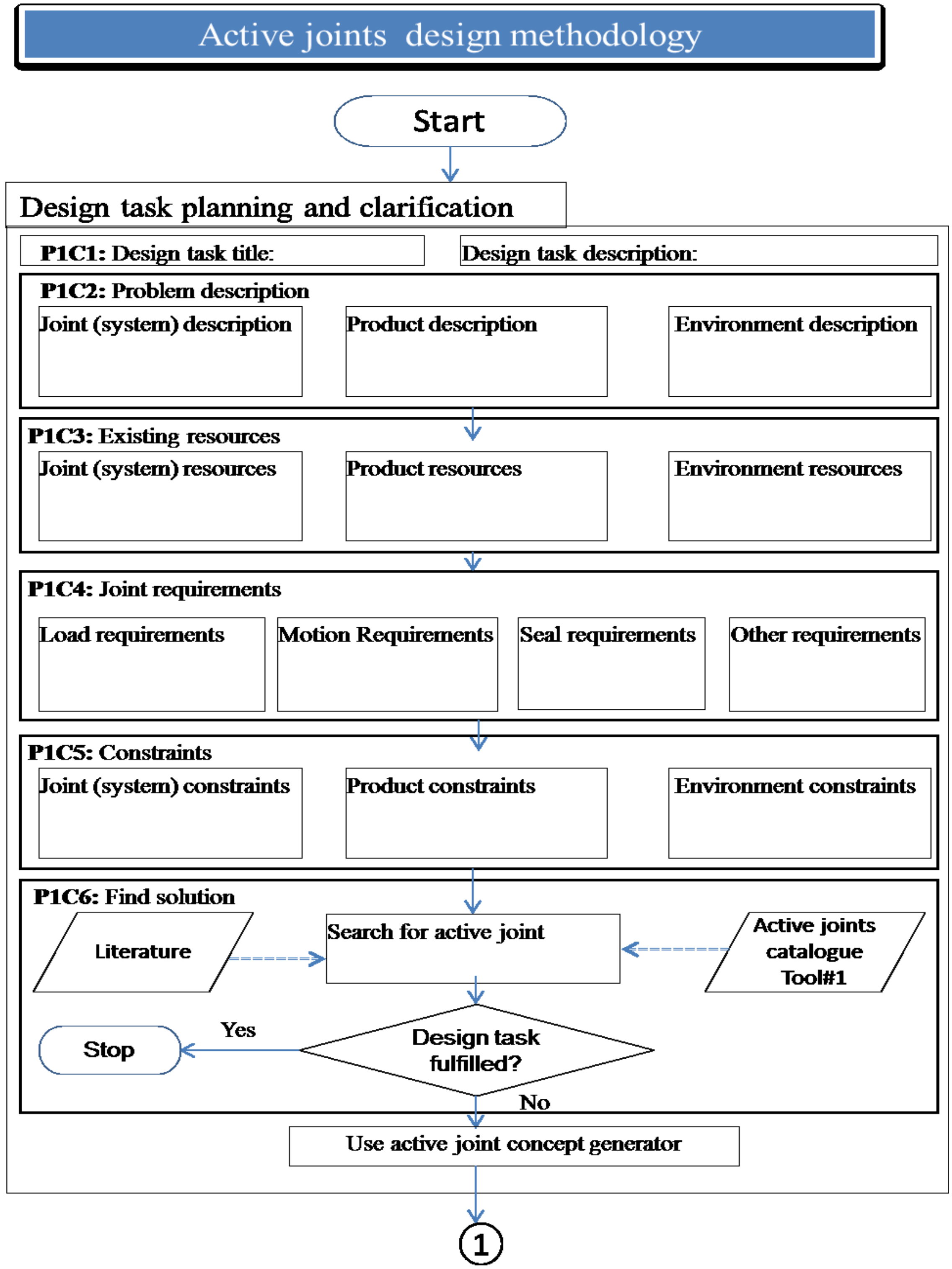
Construct's development: the development of this construct is minimal. iIt is divided into two steps; first, the title, and second, the description.

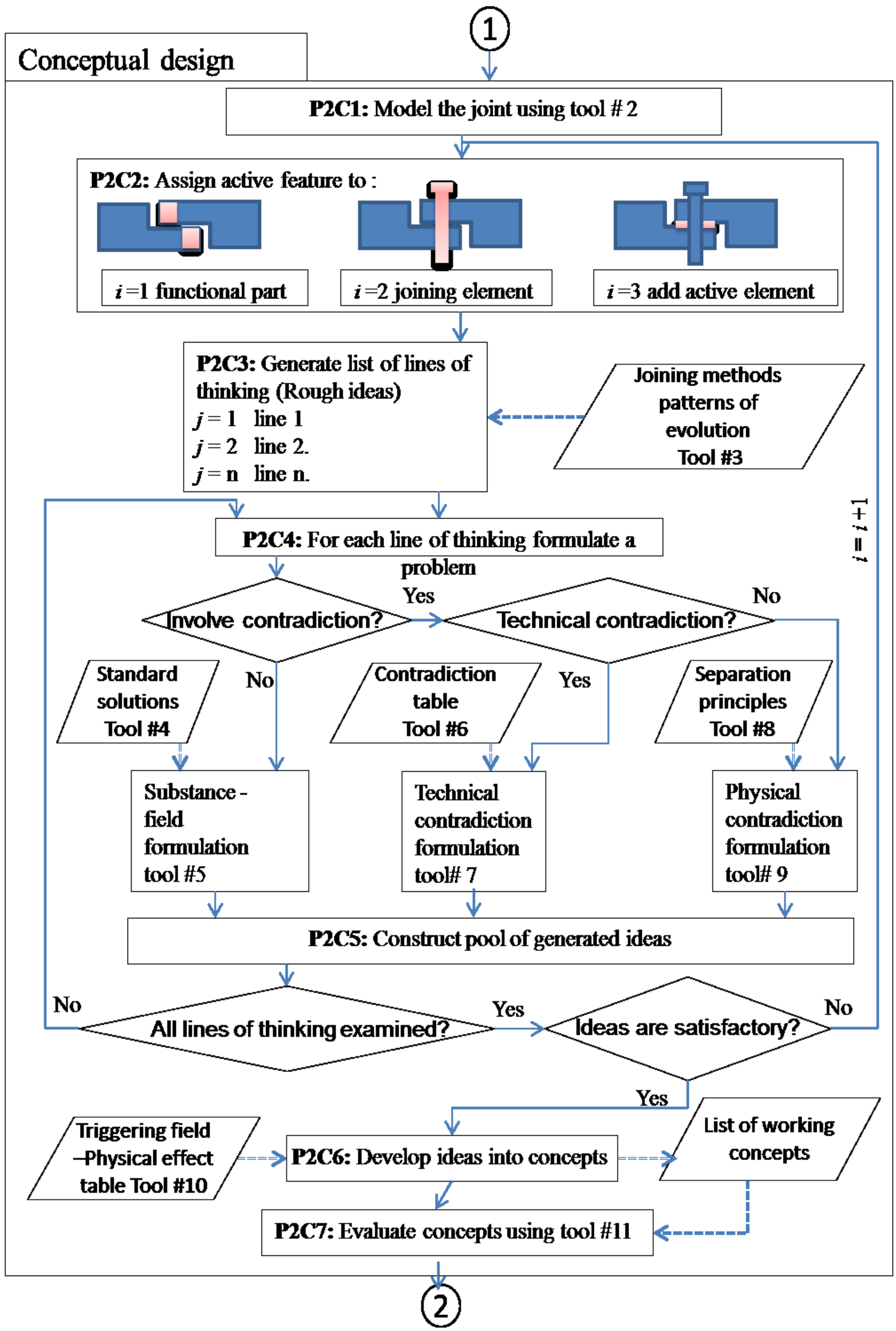
P1C2. Problem description:
Construct's purpose: the purpose is to provide the designer with a detailed description of the joint, the product in which the joint will fit, and the work environment for both joint and product.

Construct's benchmarking: many problem solving methods have this construct in different formats. A QFD list of customer requirements can be considered to this end. A customer domain in the axiomatic design serves the same purpose.

Construct's input/output: information gathered from market surveys, field tests, experts' opinions, and analysis of similar products are consider the input information for this construct. The gathered input can be documented in many formats; a fishbone diagram is one of them. The output is a detailed description that describes the design problem of the intended joint.

Construct's development: it is developed based on TRIZ's point of view. TRIZ looks at systems as multi-level structures: subsystem, then system, and finally supper system. The active joint is considered as a technical system which is the subject of the design task. Product is the super system. Finally, the working environment determines the working condition of the active joint and the product. At this stage of the design, the active joint is not known yet; hence, joint description could be very abstract. On the other hand, product and environment are known and defined; hence, clear description is possible at this stage.


Active joints design methodology
Start
Design task planning and clarification
P1C1: Design task title:
Design task description:
P1C2: Problem description
Joint (system) description
Product description
Environment description
P1C3: Existing resources
Joint (system) resources
Product resources
Environment resources
P1C4: Joint requirements
Load requirements
Motion Requirements
Seal requirements
Other requirements
P1C5: Constraints
Joint (system) constraints
Product constraints
Environment constraints
P1C6: Find solution
Literature
Search for active joint
Active joints catalogue Tool#1
Stop
Yes
Design task fulfilled?
No
Use active joint concept generator
1


1
Conceptual design
P2C1: Model the joint using tool # 2
P2C2: Assign active feature to :
i =1 functional part
i =2 joining element
i =3 add active element
P2C3: Generate list of lines of thinking (Rough ideas)
j = 1 line 1
j = 2 line 2.
j = n line n.
Joining methods patterns of evolution Tool #3
i = i +1
P2C4: For each line of thinking formulate a problem
Involve contradiction?
Yes
Technical contradiction?
No
Standard solutions Tool #4
No
Contradiction table Tool #6
Yes
Separation principles Tool #8
Substance - field formulation tool #5
Technical contradiction formulation tool# 7
Physical contradiction formulation tool# 9
P2C5: Construct pool of generated ideas
No
All lines of thinking examined?
Yes
Ideas are satisfactory?
No
Yes
Triggering field –Physical effect table Tool #10
P2C6: Develop ideas into concepts
List of working concepts
P2C7: Evaluate concepts using tool #11
2

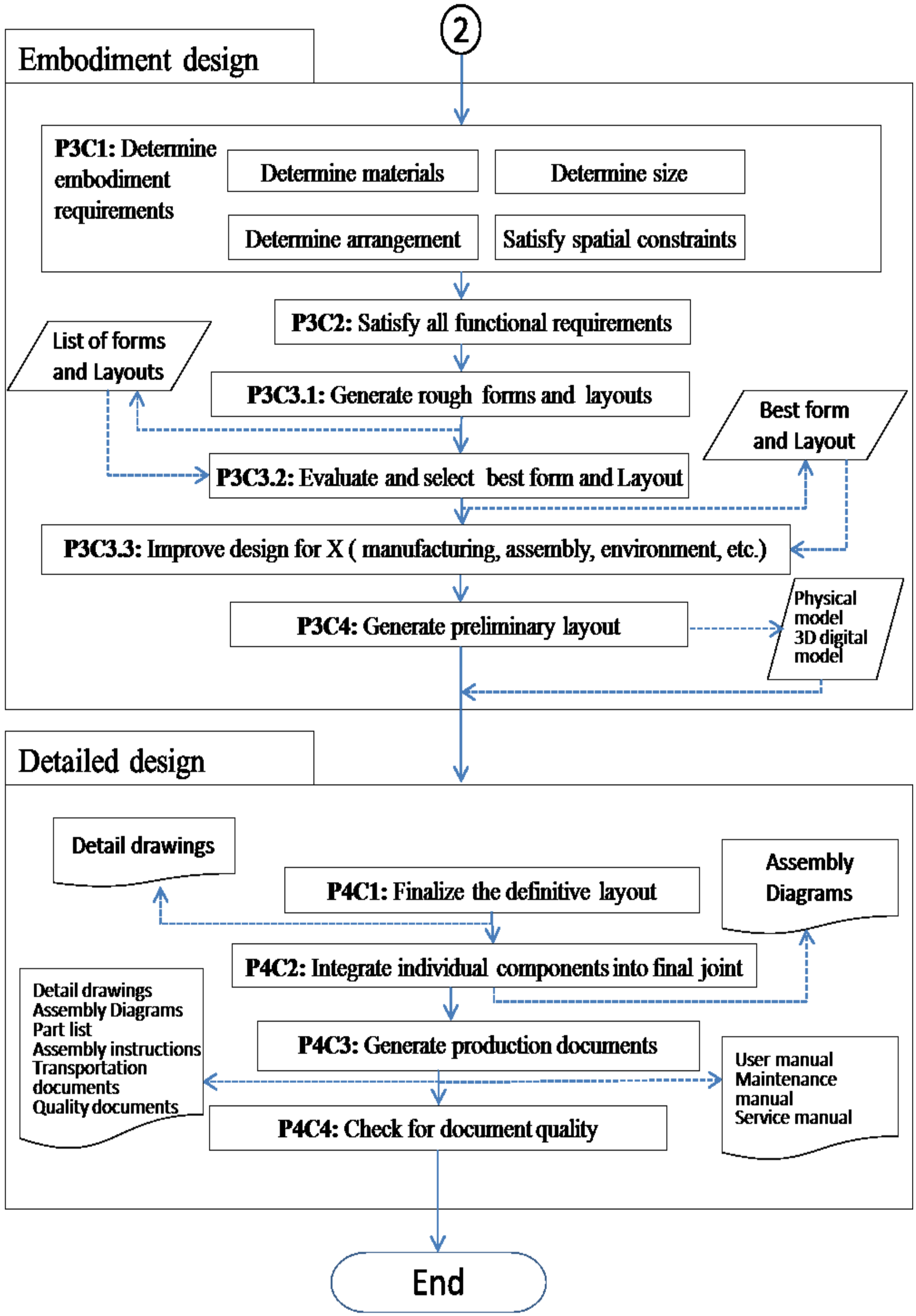


Figure 4.3: Methodology flow diagram.

P1C3. Existing resources

Construct's purpose: the more resources the designer has, the more ideas and concepts that can be generated. A TRIZ-based list of resources is helpful to inspire the designer and widen his/her scope of thinking.

Construct's benchmarking: similar constructs are found in many TRIZ methods. The ideation of TRIZ uses similar constructs called "available resources" that can list system and environment resources.

Construct's input/output: input for this construct may use, in addition to other sources, output from construct P1C2; i.e., first phase (P1)-second construct (C2). The output is a list of resources found in the system (joint), product, and their environment.

Construct's development: this construct is to explore all possible resources related to joints, products, and their environment. The types of resources required by this construct are specified by TRIZ; they are explained in table 4.4.

Table 4.4: Type of resources considered in construct P1C3

Resource	For all super system components (Joint, Product, Environment)
Substance resources:	Properties related to components material and shape
Field resources:	All sources and forms of energy; Ex. Mechanical, electrical, magnetic, thermal, etc.
Space resource:	Unoccupied space; natural or artificial voids; constant or variable empty space
Time resource:	Time before, during, and after performing an action
Information resource	Information transmitted by or through the system

P1C4. System (active joint) requirements

Construct's purpose: to identify functional requirements for the intended active joint

Construct's benchmarking: Functional requirements in axiomatic design, QFD, Pahl and Beitz's, and ARIZ's methodologies are all typical parallels to this construct.

Construct's input/output: input could be sought from construct P1C2, list of customer requirements, industry technical standards, applicable laws and regulations, and product developer expertise. The output is a detailed list of functional requirements that should be fulfilled by the active joint.

Construct's development: this construct is made of four major groups of functional requirements: load, motion, disassembly, and other requirements. These groups include all functional requirements which an active joint should fulfill during its use cycle and during its EOL product disassembly. Table 4.5 is suggested to collect and document active joint functional requirements.

Table 4.5: Functional requirements

	Direction				**Direction**			**Other requirements**
Loading Req.	X	Y	Z	**Motion Req.**	X	Y	Z	A. During use life
Compression				Linear				1.Reliable and safe
Tension				Rotational				2.Function under multi environments
Shear								3.Does not harm product esthetic value
Torque								B. During end-of-life product disassembly
Bending moment				Sealant requirements		Yes	No	4. Does not cause parts damage
Torsion				Insulation requirements		Yes	No	5. Disassembled by triggering field

P1C5. Problem constraints

Construct's purpose: the purpose is to keep the designer aware of limitations imposed on his/her solution space by adhering to constraints on the joint, product, and environment.

Construct's benchmarking: design constraints are addressed directly by all design methodologies, as in the ideation of TRIZ and QFD, or implicitly as in axiomatic design.

Construct's input/output: the chain effect should be considered while identifying input information for this construct; the product imposes constraints on the joint, and the environment imposes constraints on the product and the joint. Construct P1C2, list of customer requirements, industry technical standards, applicable laws and regulations, and product developer expertise are all sources for input information. The output is a detailed list of joint, product, and environment constraints. An example is shown in figure 4.4.

Construct's development: this construct consists of three components: 1) constraints directly related to the technical system (active joint), which is the subject of the design task, 2) constraints related to the super-system (product), and 3) constraints related to the environment.

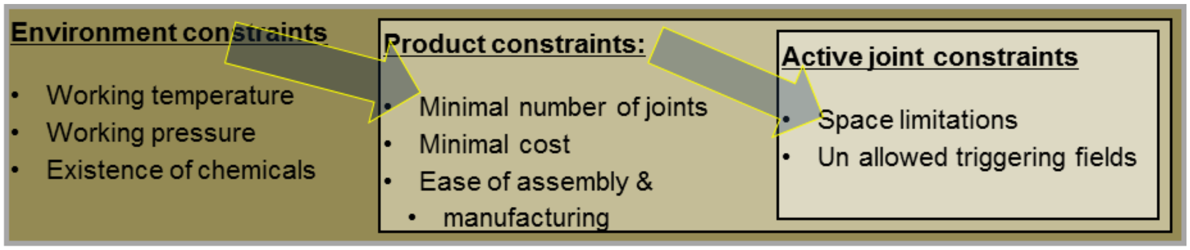


Figure 4.4: Example of problem constraints and their chain interaction

P1C6. Finding a solution

Construct's purpose: the purpose is to find an existing solution which satisfies the design problem.

Construct's benchmarking: Pahl and Beitz's method requires this construct.

Construct's input/output: Information gathered in constructs P1C2, P1C3, P1C4, and P1C5 are inputs for this construct. Existing literature and active joints catalogue (tool #1 found in appendix 4-A) are the main source for finding existing design solutions. The output of the construct is one or more design solution candidates.

Construct's development: literature is the main source for locating existing design solutions. To facilitate this task, this methodology provides a catalogue which lists existing active joints, their physical principles, and their triggering fields. The Designer is encouraged to check the catalogue developed in appendix 4-A

Phase 2: Conceptual design

P2C1. Active Joint modeling using tool # 2

Construct's purpose: the purpose of this construct is to model joint functions and their interaction using a specific terminology, which will be used later on in the methodology to present the joint in different formulations. The purpose of multi formulations is to generate multi ideas.

Construct's benchmarking: in the field of software engineering modeling language, such as structured analysis and design techniques uses IDEF0 as function modeling tool, which is similar in its purpose to the suggested tool.

Construct's input/output: the required information for this construct can be imported from the output of P1C2 and P1C4 constructs. The output is a diagram that shows joint functions and their interactions presented in language, and are specified in tool #2, which is shown in figure 4.5

Construct's development:

The development of this construct is inspired by the substance field method from TRIZ. Identification and classification of joint functions and their interactions are used to give a better understanding of the joint. Opportunities for solution and even improvements can be explored using the model. Figure 4.5 shows the development of the tool and its constituents. Functions are modeled in three types:
Wanted function: a required function the joint has to provide.
Unwanted function: it could be a consequence, or a result of the wanted function, or a function imposed by the environment.
Introduced function: a function that is added purposely to eliminate or reduce the consequences of the unwanted function; it is usually not required by the joint.
The interactions between functions are of two types: the first type of interaction is when one function generates another function or is needed by the other function: the second type is a function that eliminates the effect of other function.
P2C2. Active feature assignment
Construct's purpose: the purpose is to explore every opportunity for including the active function in the joint. This exploration is done in a systematic approach, which considers design optimization in terms of minimizing the number of components in the product.

Construct's benchmarking: the Design For Assembly (DFA) methodology suggests minimizing the number of components in a product by eliminating or combining parts. DFA is similar to this construct in its objective.

Construct's input/output: this construct receives input from P1C3, P1C4, P1C5, and P2C1 constructs. The output of this construct is a systematic guidance that helps the designer to the priorities of incorporating the active disassembly feature in the joint.

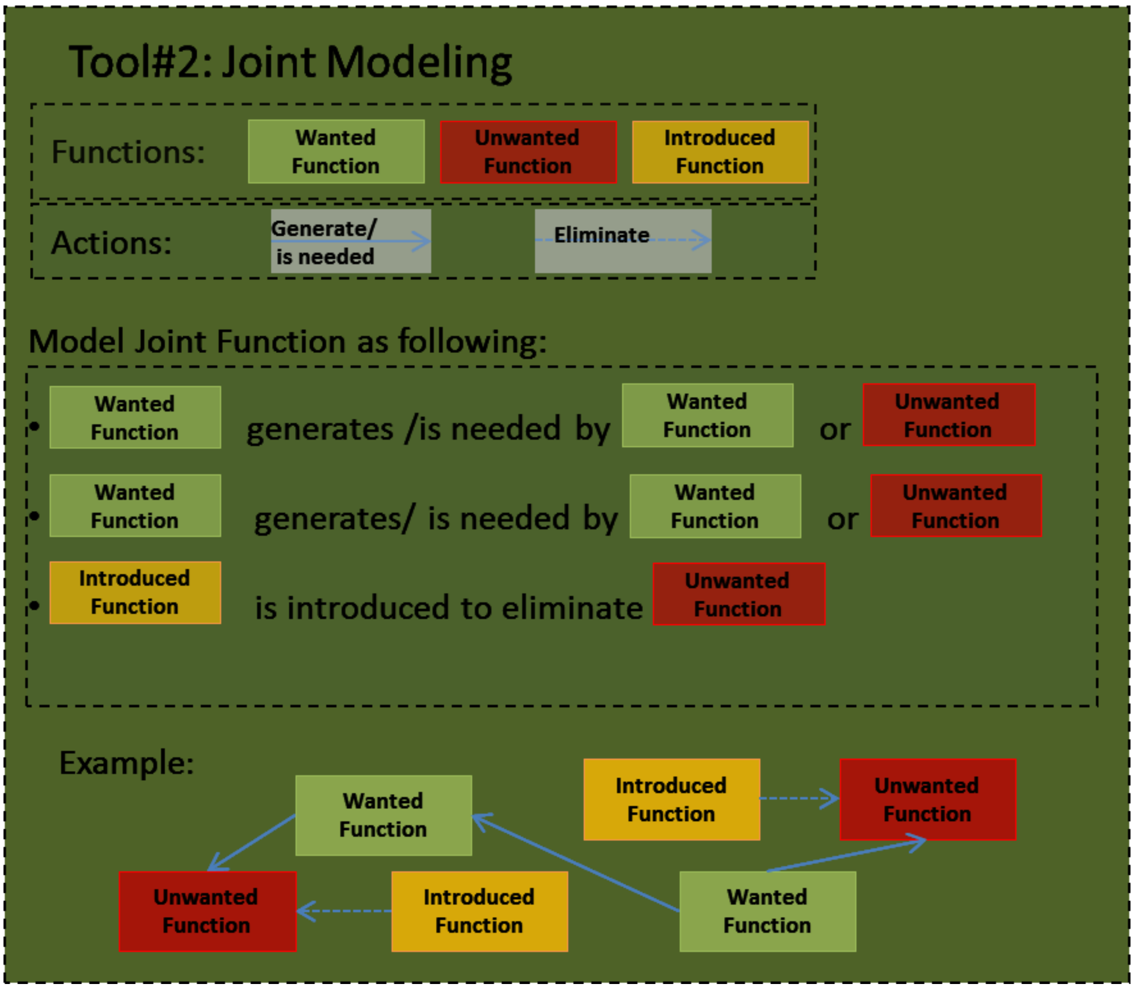


Figure 4.5: Tool # 2: Joint functions modeling.

Construct's development: The construct exhibits the three possible cases of incorporating active disassembly features in an active joint design. These cases are prioritized according to the DFA methodology. First, the designer is encouraged to eliminate joining elements and assign the joining function to the joined parts, while simultaneously assigning the active disassembly feature to the functional parts. An example of this is to replace screws with integral snap fits which could be actively disassembled as well. Second, if the elimination of joining elements fails, active disassembly feature is assigned to the joining element. Last, a new element is added to the joint which has the active disassembly feature. Since this choice increases the product number of components, previous choices should be exploited before considering it. Choices are summarized in figure 4.6.

P2C3. generating lines of thinking

Construct's purpose: the purpose of this construct is to work as starting base for ideas to be generated later in the methodology. It synthesizes information from previous constructs to generate lines of thinking, which turn into rough ideas.

Construct's benchmarking: this construct can be compared to patterns of evolutions and standard solutions found in TRIZ's methodology.

Construct's input/output: P1C2, P1C3, P1C4, P1C5, P2C1, P2C2, and tool #3 provide input information for this construct. The output is a list of generated crude ideas, which requires further analysis to qualify for being an idea that might evolve into a concept.

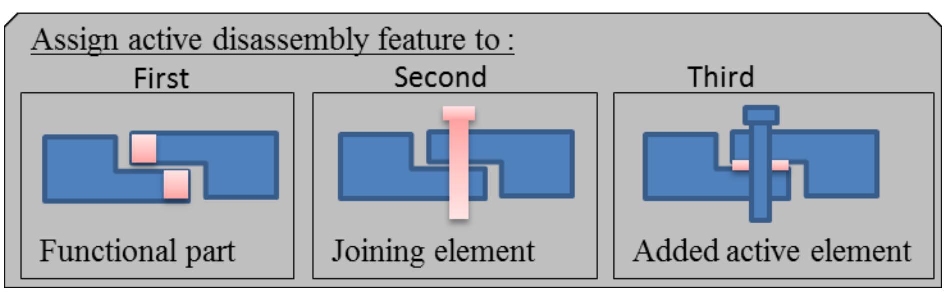


Figure 4.6: Active disassembly feature assignment

Construct's development: The construct uses tool #3, shown in figure 4.7, to help the designer set lines/directions of thinking for generating rough ideas that might evolve into more developed ideas, which are good enough to generate concepts for active joints. Tool

#3 provided patterns of evolution in the joining methodology; these patterns are derived based on a combination between two sources of information:

1.TRIZ technical patterns of evolution

TRIZ patterns of evolution specify eight patterns that govern the evolution of any technical system. These patterns are direct observations of TRIZ inventor regarding the development of technical systems, he noticed through the analysis of thousands of patents that technical system evolve in specific directions, they were called laws of evolution and lately patterns of evolutions. They appear in the left side of tool #3.

2. Cladistics-based Classification of joining methods

Cladistics is a method of classification which groups taxa hierarchically into discrete set and subsets (Kitching *et al.* 1998). Although its application is well known in the field of biology, Elmaraghy *et al.* (2008) show novel implementations to study the relationship between products and their manufacturing systems. Ziout and Azab (2012) use cladistics to classify existing joining methods and to assess their future evolution. The results obtained from joining methods of the classification tree are shown to the right side of tool #3. This construct synthesizes the generic TRIZ patterns with specific cladistics-based results to obtain specific patterns of evolution about joining methods.

Generating lines of thinking starts by identifying active disassembly feature assignments in P2C2. Then, for each pattern of evolution in tool #3 and input from tool #2, designers can suggest a line or multiple lines of thinking; also, input from constructs identified previously need to be considered. Generated lines are documented for future reference and listed for further development.

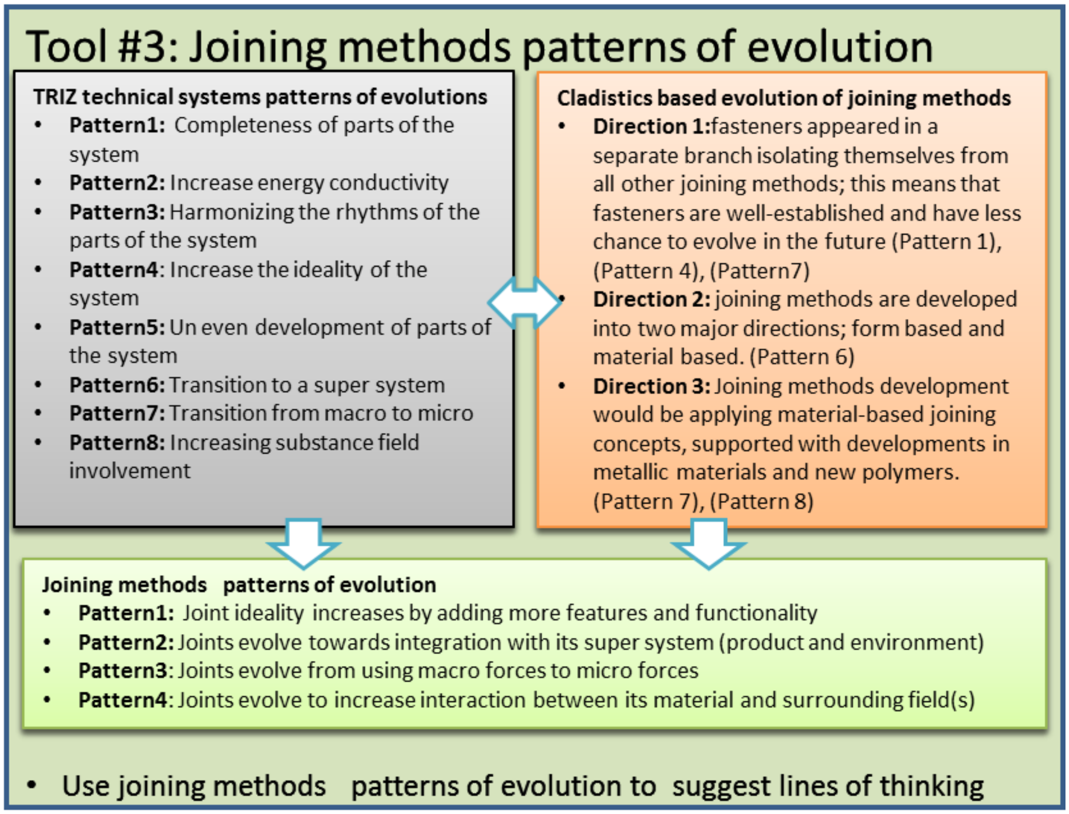


Figure 4.7: Derivation of joining methods patterns of evolution

The expected output of this construct is a list similar to the one shown in figure 4.8 below

Input: P1C2, P1C3, P1C4, P1C5, P2C1, P2C2, tool#3

Pattern	Generated Lines of thinking
Using Pattern1	Line 1:
	Line 2:
Using pattern2	Line 1:
Using pattern3	NULL
Using pattern4:	Line 1:
	Line 2:
	Line 3:

Figure 4.8: P2C3 output form

P2C4. Problem formulation:

Construct's purpose: the purpose of this construct is to take lines of thinking generated in construct P2C3, and take further steps towards concept maturity. The ultimate purpose is to transfer lines of thinking into mature ideas.

Construct's benchmarking: this construct is comparable to mathematical problem formulations, such as the ones found in operations research. It uses problem formulation tools which are modified from TRIZ tools.

Construct's input/output: the main input is the list of generated lines of thinking in previous construct. The construct also considers and uses information collected in the task clarification and planning phase. The output of this construct is a list of ideas which have the potential to be developed into concepts.

Construct's development: Three major TRIZ problem formulation methods are used after being modified to suite the active joint design problem. They are: A) substance-field formulation modified into tool #5, B) technical contradiction formulation modified into tool # 7, and C) physical contradiction formulation modified into tool # 9. Tool #5 depends on the knowledge based on tool #4 and how it provides the ideas. Tool #7 depends on tool #6 for ideas generation. Tool #9 depends on tool #8 to generate ideas for solving the problem. The selection of the proper tool depends on the problem itself; the basic rule for method selection is the contradiction rule, which has two basic forms, technical contradiction and physical contradiction. The rule is explained in figure 4.9. Tool #5 is used when the problem does not have contradictions, while tool #7 is used for formulating problems with technical contradictions. Tool #9 is for formulating problems that have physical contradiction; the selection logic is explained in figure 4.3. The development of each tool is shown below.

Contradiction rule:

A. Technical Contradiction: Addition/improvement of joint function/feature deteriorates another wanted function/feature.

B. Physical contradiction: Joint feature is wanted simultaneously into two opposite values; (long & short)

Figure 4.9: Contradiction rule

A. Substance-field formulation using tool #5

This method formulates the joining problems graphically by presenting joint substances and their interaction. At this stage of idea generation, attention should not be paid to the substance material or form, since this could limit the designer's creativity and ability to generate more number of ideas.

Tool #5 is developed to graphically model the joint on hand. The tool uses standard symbols found in the TRIZ methodology to perform problem modeling and formulation. Figure 4.10 exhibits the tool symbols and method development. Symbols are used according to their meaning in the TRIZ methodology. Substance is a term that means any object regardless of its degree of complexity; it could be one item or many. Action is the effect that one substance has on the other, while interaction is a mutual effect between substances. Field is any form of physical field, such as: electrical, magnetic, mechanical, heat, etc. More examples with details can be found in appendix 4-A. The concept of field is extended in this method to include any form of energy transformations. The symbols are used to model the joint, its substances, fields, and their interaction as shown in the modeling section of tool #5. The final step to generate ideas for possible concepts is to seek solutions for formulations resulted from the modeling section and documented in the problem formulation section of the tool. Solutions can be sought using tool #4, which is obtained from (TRIZ standard solution) and modified to suite active joint problem. The standard solutions in tool #4 start from solutions that require minimum change to the system, to more change in intensive solutions. The user is recommended to start searching for possible solutions from the beginning of the table shown in tool #4, which is located in appendix 4-B.

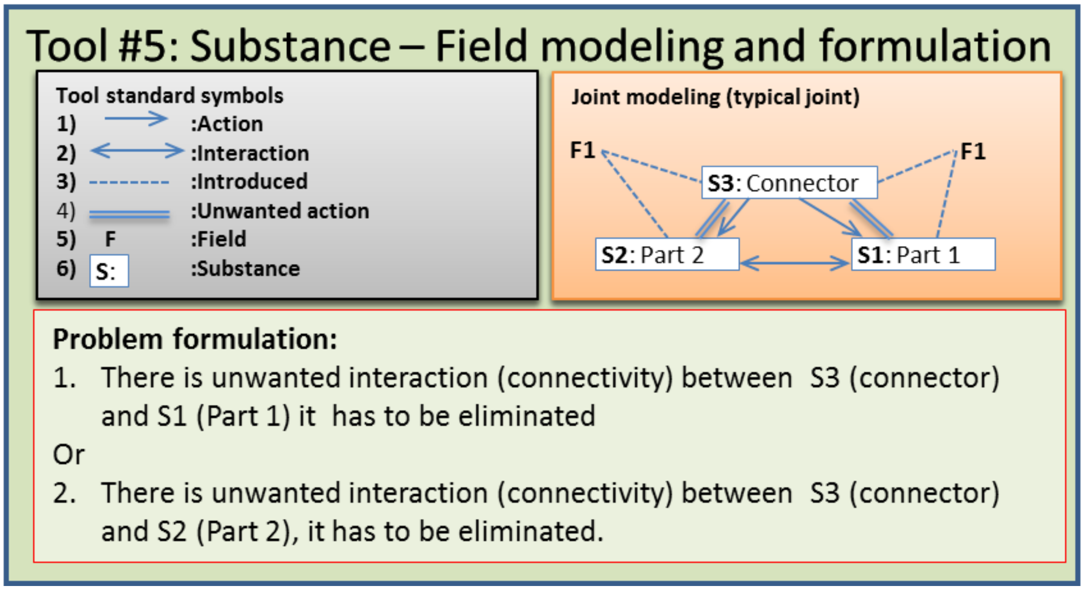


Figure 4.10: Tool #5: Substance – Field modeling and formulation

B. Technical contradiction formulation using tool # 7

The origin of this tool comes from the fact that improving or introducing a function or a feature to a system causes deterioration in performance of other features or functions in the system. The purpose of this tool is to resolve this contradiction. TRIZ methodology identifies 39 technical parameters that can be found in any technical system; some of which could be contradicting. In regards to the problem of joining method, 24 parameters out of the 39 were found applicable. Table 4.7 lists the applicable parameters and describes them. The forty inventive principles developed in the TRIZ methodology are used to resolve contradictions between engineering parameters. The contradiction table consists of improving parameters listed vertically, along with deteriorating parameters listed horizontally; this is shown in appendix 4-C. This table is used to identify the proper inventive principles that can be used to solve the contradictions. The intersection between horizontal parameters and vertical parameters gives the identification numbers of the suggested inventive principles. A complete list of inventive principles and their explanation is shown in appendix 4-C. Technical contradiction formulation is carried out according to tool #7 shown in figure 4.11.

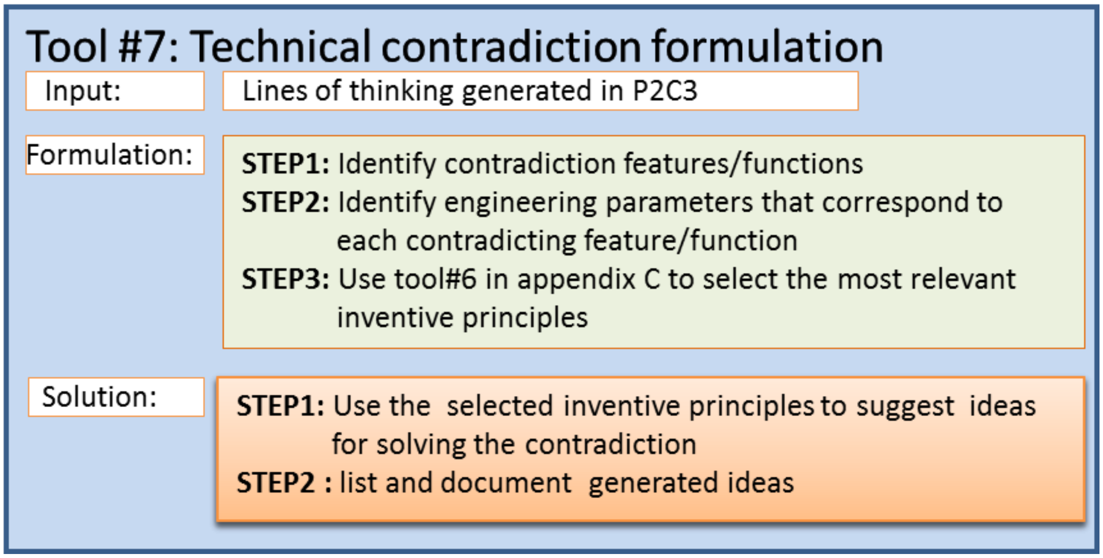


Figure 4.11: Tool #7: Technical contradiction formulation

C. Physical contradiction formulation using tool # 9

If the line of thinking requires the presence of contradicting values of a physical feature, then tool #9 (shown in figure 4.12) is used to formulate a problem in the physical contradiction domain. The physical contradiction rule presented in figure 4.9 is the primary understanding to the concept of physical contradiction. In addition to that, simultaneous existence and absence of a feature function, substance, or a field is also considered a physical contradiction. The TRIZ methodology provides four separation principles for solving physical contradiction; they are presented in table 4.6.

Table 4.6: Tool #8 Separation principles

Tool #8: Separation principles		
#	**Separation principle**	**Explanation**
1	Separation in time	have the contradicting values happen in different points of time
2	Separation in space	have the contradicting values happen in different points of space
3	Separation of whole into parts	divide the system so that contradicting values happen in different parts
4	Separation upon presence of condition	have the one contradicting value happen upon the presence of a condition while the other values happen during its absence

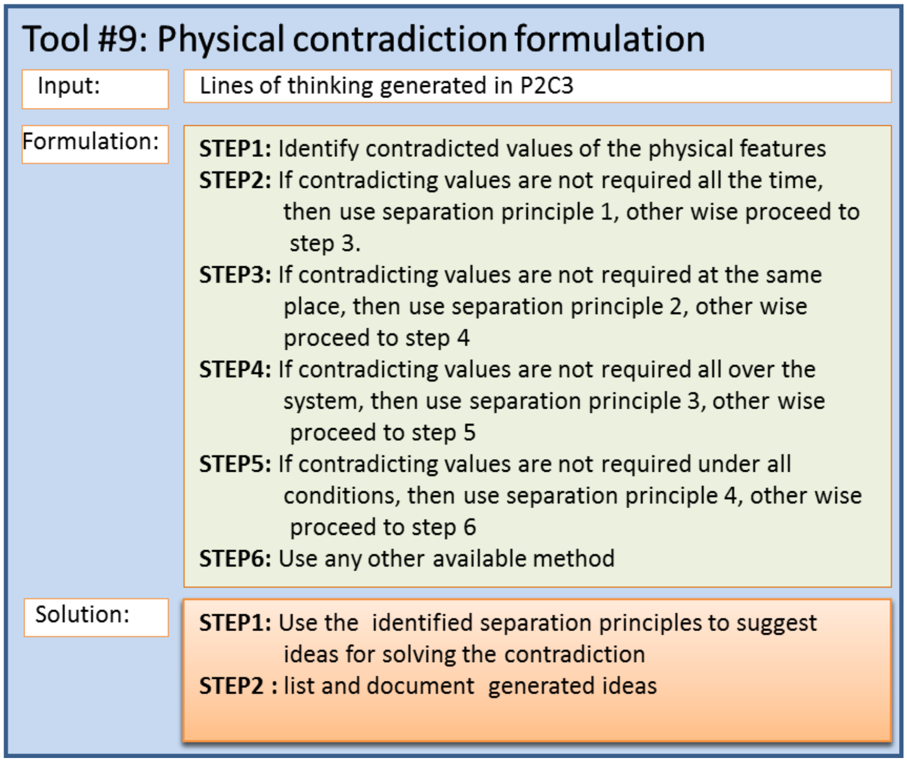


Figure 4.12: Tool #9: Physical contradiction formulation

Table 4.7: Contradiction engineering parameter applicable to joint problem modified from (http://www.triz-journal.com/archives)

#	Parameter Name	Description
1	Weight of moving object	The mass of the object, in a gravitational field. The force that the body exerts on its support or suspension.
2	Weight of stationary object	The mass of the object, in a gravitational field. The force that the body exerts on its support or suspension, or on the surface on which it rests.
3	Length of moving object	Any one linear dimension, not necessarily the longest, is considered a length.
4	Length of stationary object	Same.
5	Area of moving object	A geometrical characteristic described by the part of a plane enclosed by a line. The part of a surface occupied by the object. OR the square measure of the surface, either internal or external, of an object.
6	Area of stationary object	Same
7	Volume of moving object	The cubic measure of space occupied by the object. Length x width x height for a rectangular object, height x area for a cylinder, etc.

8	Volume of stationary object	Same
9	Force	Force measures the interaction between systems. In Newtonian physics, force = mass X acceleration. In TRIZ, force is any interaction that is intended to change an object's condition.
10	Stress or pressure	Force per unit area. Also, tension.
11	Shape	The external contours, appearance of a system.
12	Stability of the object's composition	The wholeness or integrity of the system; the relationship of the system's constituent elements. Wear, chemical decomposition, and disassembly are all decreases in stability. Increasing entropy is decreasing stability.
13	Strength	The extent to which the object is able to resist changing in response to force. Resistance to breaking .
14	Temperature	The thermal condition of the object or system. Loosely includes other thermal parameters, such as heat capacity, that affect the rate of change of temperature.
15	Use of energy by moving object	The measure of the object's capacity for doing work. In classical mechanics, Energy is the product of force times distance. This includes the use of energy provided by the super-system (such as electrical energy or heat.) Energy required to do a particular job.
16	Use of energy by stationary object	same
17	Power	The time rate at which work is performed.
18	Loss of Energy	Use of energy that does not contribute to the job being done. See 19. Reducing the loss of energy sometimes requires different techniques from improving the use of energy, which is why this is a separate category.
19	Loss of substance	Partial or complete, permanent or temporary, loss of some of a system's materials, substances, parts, or subsystems.
20	Loss of Information	Partial or complete, permanent or temporary, loss of data or access to data in or by a system. Frequently includes sensory data such as aroma, texture, etc.
21	Loss of Time	Time is the duration of an activity. Improving the loss of time means reducing the time taken for the activity. "Cycle time reduction" is a common term.
22	Quantity of substance/the matter	The number or amount of a system's materials, substances, parts or subsystems which might be changed fully or partially, permanently or temporarily.
23	External harm affects the object	Susceptibility of a system to externally generated (harmful) effects.
24	Object-generated harmful factors	A harmful effect is one that reduces the efficiency or quality of the functioning of the object or system. These harmful effects are generated by the object or system, as part of its operation.

P2C5. Generated ideas pooling and synthesizing

Construct's purpose: the purpose of this construct is to maintain a list of generated ideas, which result from all formulation methods used in P2C4.

Construct's benchmarking: Brainstorming sessions and the Delphi method use similar construct to maintain generated ideas and serve as a trigger for new ideas.

Construct's input/output: the input of this construct is the summation of outputs from tools #5, 7, and 9. The output is a unified list of all generated ideas.

Construct's development: In addition to the list of ideas, this construct watches for exploitation of all lines of thinking generated in P2C3. It also checks for the quality and level of satisfaction by considering the chance of these ideas to be developed into a working concept in the next construct. If the generated ideas are not satisfactory, the process is repeated while considering choice number 2 in construct P2C2. The same applies to ideas generated in the second round; if it is not satisfactory, the third choice in P2C2 is considered.

P2C6. Ideas development

Construct's purpose: the purpose is to develop the generated ideas into working concepts

Construct's benchmarking: Pahl and Beitz's design methodology uses similar construct in the conceptual design phase of the methodology; the construct is called "Searching for working principles"

Construct's input/output: list of ideas generated in P2C5 is the input for this construct, while the output is a list of working concepts.

Construct's development: for each listed ideas in P2C5, the construct uses tool #10 (located in appendix 4-D) to choose a triggering field and possible physical effects that can be developed into an active joint. At this step of the concept generation, it is recommended to investigate the possibility of combining ideas found in P2C5 to produce more matured ideas. It is essential to keep in mind that information found in tool #10 is a continuously growing data base where users can use it at any point of time; yet, they need to consider new discovered and invented triggering concepts after the last update of the database.

P2C7. Concepts evaluation and selection using tool #11

Construct's purpose: the purpose is to provide designers with a tool to evaluate obtained working concepts before taking them to the embodiment design phase.

Construct's benchmarking: Pugh matrix is comparable to this construct.

Construct's input/output: construct inputs are the concepts developed in P2C6. It also uses information from P1C3, P1C4, and P1C5. The output is a list of ranked concepts.

Construct's development: the construct uses the concept of systems ideally defined in the TRIZ methodology. The same analogy is applied to the selection of the most ideal concept. Table 4.8 details the evaluation process.

Table 4.8: Concept evaluation and selection tool

Tool #11: Concept ideality			
Concept	Useful Functions	Harmful functions	Concept ideality $I = \frac{\sum Useful\ functions}{\sum Harmful\ functionsa}$
Concept 1	a_{11}	b_{12}	I_1
Concept2	a_{21}	b_{22}	I_2
Concept (n)	a_{n1}	b_{n2}	I_n

Phase 3: Embodiment design

The constructs of the embodiment design phase are similar to what is found in Pahl and Beitz's. This phase starts with embodiment requirements identification.

P3C1. Embodiment requirements identification

Construct's purpose: the purpose is to identify and document embodiment design requirements.

Construct's benchmarking: This construct is found in Pahl and Beitz's methodology

Construct's input/output: construct inputs are the concepts developed in P2C6. The output is a list identified requirements.

Construct's development: the construct has four sets of requirements that need to be identified and assigned values to it. They are materials, size, arrangements, and spatial constraints.

P3C2. Functional requirement satisfaction

Construct's purpose: the purpose is to maintain compliance with functional requirements identified earlier in the methodology; identified embodiment requirements in P3C1 should not violate functional requirements

Construct's benchmarking: This construct exists in Pahl and Beitz's methodology

Construct's input/output: construct inputs are the functional requirements identified in P1C4. The output is a list of unsatisfied requirements.

Construct's development: each functional requirement is checked against the embodiment parameters identified in P3C1.

P3C3. Generating and evaluating rough forms and layouts

Construct's purpose: the purpose is to generate many forms and layouts for the selected concept and evaluate them according to their ability to satisfy the functional requirements.

Construct's benchmarking: This construct exists in Pahl and Beitz's methodology.

Construct's input/output: construct inputs are the items identified in P3C1. The output is one or more forms and layouts.

Construct's development: The forms and layouts can be made using sketches and prototypes.

P3C4. Preliminary layout generation and improvement

Construct's purpose: the purpose is to generate a preliminary layout and perform improvements and enhancements.

Construct's benchmarking: This construct exists in Pahl and Beitz's methodology.

Construct's input/output: construct input is the selected rough layout in P3C3. The output is one layout that will be considered for the next phase in the methodology; i.e., detailed design.

Construct's development: The layouts can be presented in a physical model or three-dimensional digital model.

Phase 4: Detailed design

Detailed design phase starts with the definitive layout. It is carried out using a computer aided design and manufacturing software. They are capable of producing all or some of the following detailed design outputs:

- Details drawing
- Assembly drawings
- Parts list or Bill Of Materials (BOM)

Detailed design also should provide other documents such as: packaging and transportation instructions, quality test instructions, user manual, service and maintenance manual, and safety instructions.

4.5.7 Validation

Validation is the last step in the design methodology development. It gives confidence to the usefulness of the methodology and demonstrates its applicability. Chapter five is devoted to the purpose.

5 METHODOLOGY VALIDATION AND APPLICATION[4]

5.1 Introduction:

Knowledge validation is a subject of debate between different schools of thought (Seepersad *et al*., 2005). Similarly, validation of engineering methods does not have a well-established and cross-the-field accepted validation process. The Institute of Electrical and Electronic Engineering (IEEE) defines validation as “conformation by examination and provision of objective evidence that the particular requirements for a specific intended use are fulfilled” (IEEE, 1998). The definition is termed around the ability of a model or method to fulfill its intended purposes. Although the definition is clear, the validation process is not. Olewnik and Lewis (2003) pointed out that the validation process depends on the type of model or method that needs to be validated. Two types of model validations were identified:

1. Validation of descriptive models: Engineering research usually use analytical models built around the mathematical modeling of reality. Then the validation of these models is how much they are reasonably accurate in representing reality. In other words, their validation is to measure and quantify a method’s results and their deviation from reality. These types of methods can be experimentally validated. Experiments are designed and conducted to measure the results obtained from applying the model in order to solve the intended problem within the model pre specified limitations and assumptions. The collected results are compared to real life outputs. Statistical analysis can be used to deduce inferences about the model’s validity.

2. Validation of prescriptive models: due to the complicatedness of prescriptive methods, their validation is a difficult task. Usually these methods are evaluated using their pragmatic value. Quantitative analysis are not enough, if not impossible, to validate prescriptive models. That is due to subjective elements impeded in them. In addition to that, their output is not unique and can be judged differently; so they cannot be strictly described as right or wrong.

[4]This is outcome of joint research

5.2 Engineering design methodologies validation

Frey and Li (2004) argue that no design method can be expected to guarantee a particular benefit in every single implementation of the method since there are many factors that affect the success of the output design.

Frey and Dym (2006) suggest the analogy between validation of clinical methods and engineering design methodologies. Based on their analogy, a design method can be validated using its outcomes (quality, profitability, warrantee, claims, safety, etc.) through the use of the following evidences:

a) Field validation of design method: the acceptance and popularity of the method in its field.

b) Simulation of design method.

c) Theoretical decisions (statistical analysis, decision science, cognitive science, etc.).

Olewnik and Lewis (2003) propose three criteria for design method validations. For a method to be valid it must:

a) Be logical

b) Use meaningful reliable information.

c) Do not bias or influence designer’s preferences.

The importance of previous criteria for a design method cannot be underestimated. Yet, it can be argued that these criteria do not necessarily guarantee a methods effectiveness required by IEEE definitions.

Validation square is a widely accepted framework for design method validation. (Seepersad *et al*., 2005) demonstrate the use of validation square. Figure 5.1 shows the components of a validation square. The purpose of a validation square is to build confidence in a design method with respect to an intended purpose. The validation process can be broken down as the following:

a) Theoretical Structural Validity: the following is evaluated

1. Evaluate construct validity: literature can be used as a benchmark for evaluating the structural components of the method.

2. Evaluating method consistency: to build a confidence in the way the constructs are assembled in the method. Information flow between constructs indicates this consistency.

b) Empirical Structural Validity (evaluating the example problems): to build a confidence in the suitability of examples that is used to verify the method. The example problems need to be similar enough to the intended problems, and use data sufficient to support a conclusion.

c) Theoretical Performance Validity: evaluating the usefulness of a method beyond the example problems. This generalization can be induced based on the confidence built throughout the validation process (part a, b, and d).

d) Empirical Performance Validity:

1. Evaluating usefulness of method for some example problems: the outcomes of the method can be evaluated in terms of their usefulness.

2. Prove usefulness is linked to the use of the method. This can be achieved through demonstrating the contribution of each individual construct to the final solution.

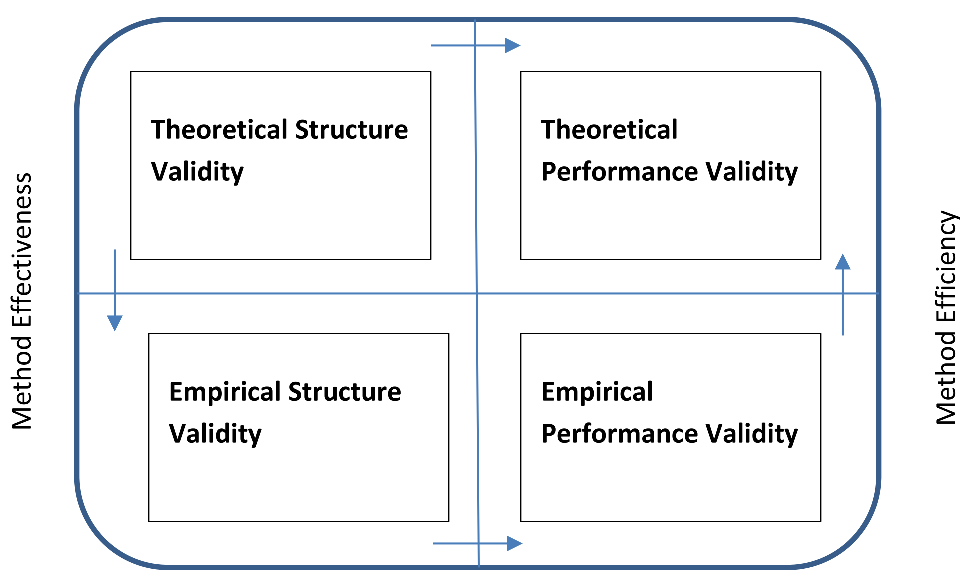


Figure 5.1: Validation Square. Modified after (Seepersad *et al*., 2005)

5.3 Methodology validation

The Validation square is used to validate the proposed design methodology in chapter four. The Validation square is selected due to the fact that it includes most of the validation criteria, a method in which literature would have. It is also suitable for prescriptive methodologies. Since the active joint design methodology is one of them, the following types of validations are investigated:

Empirical Performance Validity: Two types of validation are used to validate the imperial performance of the developed methodology:

Type 1: Methodology's usefulness in solving example problems. Case study 1 in section 5.4 demonstrates the usefulness of the methodology. through its application to a real life problem in medical applications where joining, and later on disassembly of live elements is required. Innovative active joint is developed.

Type 2: Prove of usefulness is linked to the use of the methodology. Case study 2 in section 5.5 demonstrates how effectiveness of the proposed active joint is linked to the use of the methodology. Safety system in the automotive application, which already has active joint implemented in its design, is redesigned using the methodology. Comparisons made between the two solutions show that the use of the methodology has improved the effectiveness of the solution.

Empirical Structural Validity, evaluating the example problems:

The problems used to verify the methodology need to be relevant; i.e. they are within the scope of the methodology. His type of validation is to prove this relevance. The example problems need to be similar enough to the intended problems. Example problems in case study 1 and 2 are problems that require active joints to assemble and disassemble two or more components. This is exactly the intended use and the purpose of the developed methodology.

Theoretical Structural Validity:

This type of validity is shown in the development process of the methodology. Theoretical structural validity requires construct validity and methodology consistency. Construct validity is demonstrated through the benchmarking between constructs in the methodology and similar constructs in other engineering design methodologies. Benchmarking is done in the methodology development section in chapter four. The second requirement, which is methodology consistency, is demonstrated through the information flow between its construct. The methodology development section in chapter four demonstrates the information flow between the different constructs. It shows how the output and input of methodology constructs are related and linked to the final output.

Theoretical Performance Validity:

This is to evaluate the usefulness of a methodology beyond the example problems. This generalization can be achieved through future implementation of the methodology.

5.4 Case study 1: Validation and application in joining live elements

5.4.1 Purpose of the case study

The purpose of this case study is to demonstrate type 1 of the empirical performance validation of the developed methodology. It demonstrates the usefulness of the methodology through design and innovation of active joints which can be used to join fractured bone. It uses A.Dis. to disassemble the joining element from the bones.

5.4.2 Design task planning and clarification

The design task planning and clarification phase are accomplished through the following constructs:

P1C1: design task title giving and description: For this case study, a proper design task title is: SCFE active joint design. The task can be described as a design and innovation of active joint for joining Slipped Capital Femoral Epiphysis (SCFE).

P2C2: Problem description: Slipped Capital Femoral Epiphysis is a disjoint condition that affects the hip. The tip of the thigh bone, called femur, disjoins and slips backward and forward. SCFE is the most common orthopaedic hip dislocation affecting children and adolescents. Orthopaedists relate SCFE to mechanical and constitutional factors (Loder *et al*., 2000). An Obese child's weight exerts sheer stress that cannot be sustained by rapidly grown femur cells, which eventually cause the slip. The main objective of a SCFE treatment is to stop any further slippage and help the slipped part to re-join to the main thigh bone (Tan *et al*, 2007).

Surgical operation is needed to reposition the slipped bone to the main thigh bone and maintain its position by applying permanent compression; this continues until the growth plates heal. This treatment is called "in situ pinning" (Loder *et al*., 2000), in which a single or multiple screws are placed across the growth plate to attach the slipped bone to the thigh bone. Three to six months is the average recovery time for a SCFE surgery.

The in situ pinning uses cannulated shaft screws with a threaded end. The screw diameter ranges between 4-8 mm, and the length of the threaded part is between 10-20mm. It can be made of stainless steel or titanium. Many designs are suggested and patented (Gruber *et al*. 1995, Synthes, 2012).

Surgeons recommend screw removal after the slipped joint heals. This practice is due to many reasons. Reese *et al*. (2004) referred this to the pain over the site of the screw head, while Warner *et al*.(1994) mentioned trochanteric inflammation, possible future fractures due to stress riser effect, and neoplasia (tumour growth) due to theoretical long-term corrosion caused by the implanted screws .

Screw removal has many implications; a part of these implications is related to the screw itself, while other implications are due to the environment (bone growth around the screw). Warner *et al*. (1994) explain their experience with cannulated screws implanted for operations made between 1990 to 1994: Five patients out of six who returned for screw removal had complication with at least one screw. Screws were difficult to move and resisted high rotational torque and were often stuck. The screws were cut and left in situ.

Complications continue to be encountered during screw removal. Tan, *et al*. (2007) report failure in SCFE screw removal; initial attempts removed 10mm of the screw before it would get stuck in the bone and the screw head would get stripped. A survey of forty patients was conducted by Ihme, *et al*.(2009). It shows that 30% of screw removal required open surgery while part of the screw, or even the whole screw, remained in situ in 40% of the cases. Surgery time for screw insertion was 51 minutes, while removal time was 91minutes, on average. These results reflect the complications encountered during screw removal. A recent survey conducted by Oburu *et al*. (2012) shows results of 51 children who went through screw removal; with 9.8% of the cases had complications.

P1C3: Identify existing resources. Three sets of resources can be identified; joint, product, and environment. The joint is made of fractured bones and cannulated screws. Both of them can be considered as a resource for a problem solution. The generative feature of the bone and its ability to grow is considered as a resource. Strength and rigidity of the screw is a potential resource for solving the problem.

The human body is the product which contains the joint. Many resources can be identified; body temperature, chemistry, immune system, and enzymes are potential resources that can contribute to the innovation of required active joints. Since the joint is completely isolated from external environment, no related resources can be identified.

P1C4: Identify joint requirements. The joint is required to deliver the following:

1. Load requirements:
   - Tension and compression forces: the joint is required to take tension and compression forces in X, Y, and Z directions. The magnitude of these forces depends on the body weight.
   - Torsion and moment load: the joint is required to take moments perpendicular to the joint axes. Due to the physical shape of the SCFE, no torsional load is required.
2. Motion requirements: the joint is required to give zero displacement in all directions, and no deflections in case of bending.
3. Other requirements:
   - Be reliable and safe
   - function under human body environment

- Does not cause harm for the patient
- Does not cause bone damage during EOL disassembly
- Can be disassembled by triggering field

P1C5: Identify Constraints. The following constraints are applicable to the intended joint;

- Joint assembly and disassembly has to be done in an operation room under medical settings.
- Assembly and disassembly time is to be kept minimal.
- Joint materials are subjected to medical approval before implanting in the human body.
- Joint geometry (dimension and shape) is constrained by the hip geometry; joint has to be contained within the body.

P1C6: Search for a solution. The designer is encouraged to search the active joint catalogue (tool #1) and literature for an existing solution.

A. Search for a solution using the active joints catalogue (tool #1in appendix 4-A):

An existing active joint that is located under biologically-triggered joints in Appendix 4-A has similar applications. The joint is made of bioadsobable screw, which is made out of a material that degrades in living tissues by hydrolysis into alpha-hydroxy acids, which are metabolized by the body (Bioretec.com, 2013). This alternative of metal screws would be an evolutionary solution to this problem if it satisfies all joint requirements. The low flexural strength of these screws makes it unqualified to replace metallic screws in application where bending resistance is required, such as fixing SCFE problems.

B. Search for a solution using literature:

The solutions, which are found in literature, do not use A.Dis. in their designs. For the sake of completeness, they are listed below:

- Gruber, *et al*. (1995) used a screw with a hexagonal head to increase the coupling between the male hexagonal head and the female socket used to remove the screw. An 8.0mm screw was used to test the solution over 10 patients. All screw removals went without reported complications. The authors did not mention the applicability of the solutions at different screws diameters, nor did they justify the selection of a 8.00mm screw. Though the suggested solution is logical and shows competency in solving the problem of crew head stripping, further investigation is needed to prove that no new complications exist; for example, the new head design does not cause discomfort to the patient due to the shape and extended length of the screw head.

- Cannulated screw retraction apparatus is developed by Graser (1999) to extract fractured or stuck screws in the bone. This solution helps extract the screw once complications are encountered, but does not solve the root cause of the problem.
- The Industry also addresses this problem by providing a specially-designed screw to increase the coupling between screw heads and screwdrivers. Synthes, an international instruments and implant manufacture, exhibits in their 2012 product technical guide an internally threaded screw head purposefully designed to increase the coupling and overcome excessive torsional forces during screw removal (Synthes, 2012).

All previous solutions, other than bioadsorbable screws, address the symptoms of the problem without solving the problem's root cause. They focus on increasing the coupling between the screw head and screwdriver to overcome large friction and sheer forces between the screw surface and the dense newly grown bone. These solutions have many disadvantages which make active joints a better solution. Since there is no existing solution that satisfies all requirements, the design task continues to the conceptual design phase in the suggested method.

5.4.3 Conceptual design:

The purpose of this phase is to generate concepts that can be developed into embodiment designs and eventually into final active joints for the intended application.
Implementation appears in the following seven constructs.

P2C2: Use tool #2 to model the joint. The purpose of tool #2 is to provide the designer with a better understanding of joint functions and their interaction. Equation 27 describes the existing joint in a static condition (before the screw start moving). It describes the equilibrium state, where the applied force ($SF_{Applied}$), in static condition, is equal to the summation of static friction forces (F_S) between the screw and bone, and cutting force (F_c) exerted by the screw threads on the bone.

$$SF_{Applied} = F_s + F_c \qquad (27)$$

In dynamic condition: the static friction forces change into dynamic friction forces, while cutting forces remain the same. Due to the reduction in dynamic friction force, applied force (DF_{Applied}) is lesser than the static one. Assuming there is no acceleration, equation 28 describes the equilibrium state.

$$DF_{Applied} = F_d + F_c \qquad (28)$$

The existing joint can be functionally modelled using tool #2 based on the above understanding. Figure 5.2 shows functions delivered by the joint during its use phase and disassembly phase.

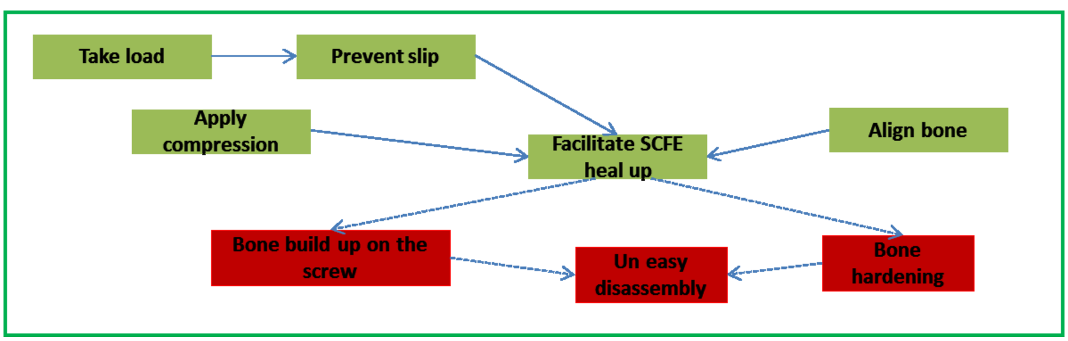


Figure 5.2: SCFE screw joint functions model using tool #2

P2C2: Assign active feature to Functional part, joining element, or added element.

This construct suggests starting with a functional part as carrier for the active feature that will be incorporated in the joint. The functional parts in the SCFE joint are the fractured bones. The designer has no access to modify these parts. The next choice, according to the flowchart in figure 4.3, is to assign the active feature to the joining element, which is the cannulated screw. This option is taken to the next construct.

P2C3: Generate list of lines of thinking (rough ideas). Patterns of evolution for joining methods identified in tool #3 are examined to create lines of thinking. Lines of thinking direct the designer to potential starts for new ideas. While examining patterns of evolutions, the designer also needs to consider the output of previous constructs. Pattern 1 suggests adding new features to the joint. This can lead into two lines of thinking: one is to add active feature to prevent bone hardening, the other is to add active feature to prevent bone build up. Pattern 2 has limited potential; it is impossible to integrate the joint with the body. Pattern 3 suggests using micro forces instead of macro forces; body tissues have to provide these micro forces, which is something beyond the designer's access. Pattern 4 suggests increasing the interaction between joints material and its surrounding. Potential line of thinking can go in the direction of adding material that interact with a field to ease screw disassembly. Lines of thinking are documented in the form shown in figure 5.3 and are taken to the next construct.

Input: P1C2, P1C3, P1C4, P1C5, P2C1, P2C2, tool#3

Pattern	Generated Lines of thinking
Using Pattern1	L1: Add active feature to the joint to prevent **Bone hardening** L2: Add active feature to the joint to prevent **Bone build up on the screw**
Using pattern2	NULL
Using pattern3	NULL
Using pattern4:	L5: Add active feature to the joint so it interact with a field to ease screw disassembly.

Figure 5.3: Documentation of generated lines of thinking

P2C4: Formulate lines of thinking in terms of TRIZ problem formulation. The generated lines of thinking in previous constructs are taken into a higher level of ideation. Each line of thinking could lead to one or more ideas; these ideas can be developed further using a TRIZ tool based on the logic shown in figure 4.3.

Line 1 can be formulated as following:

Bone hardening happens during the healing process; L1 suggests eliminating bone hardening or making the bone soft. Bones need to be hard for healing up and need to be soft for ease of disassembly. This leads to physical contradiction.

The logic in the method flow chart is applied to select the proper problem solving method. Physical contradictions can be solved using tool #9. The solution is shown in figure 5.4.

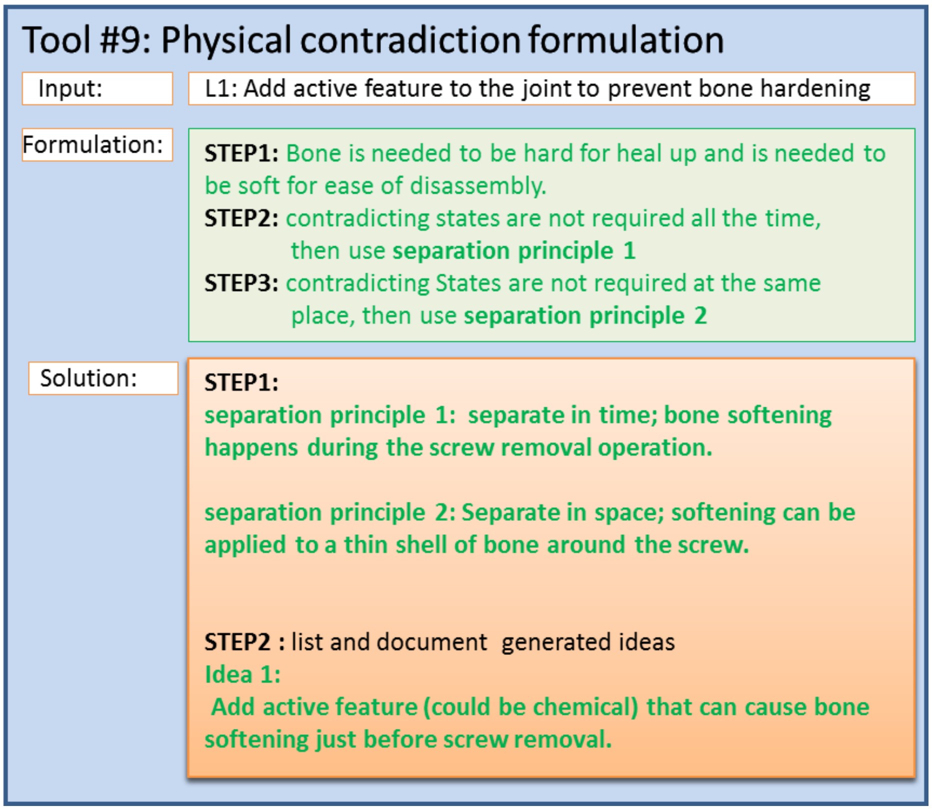


Figure 5.4: Development of line of thinking into idea

The remaining lines of thinking go through the same procedures. The generated ideas are taken to the next construct.

P2C5: maintain a list of generated ideas. The ideas generated in previous constructs are listed and documented. Moreover, possible merging and synthesis between ideas is explored. The generated ideas are listed below.

Idea1: Use material around the screw head and its unthreaded shank, which can respond to a field which can change the material parameter in order to ease disassembly.

Idea2: Add active feature (could be chemical) that can cause bone softening just before screw removal.

P2C6: Develop generated ideas into concepts. The purpose of this construct is to develop the generated ideas in previous constructs into working concepts.

For Idea 1: use active material around the screw head and its unthreaded shank. With consulting with triggering field – physical effect table tool #10, the following fields are selected:

- Biological field; it is proposed to activate a destruction of a material that can be biologically metabolised by enzymes.
- Magnetic field; it is used to control the starting time of the biological reaction

The proposed design is conceptually demonstrated in figure 5.5. An advantage of this solution is that the enzyme's activation is a controlled process which could be initiated by a surgeon at the beginning of the removal operation. Many activation mechanisms do exist; one of them is magnetic steel beads technology. Magnetic beads are micro beads made of polystyrene with magnetic particle impeded inside. Enzymes can be attached to these magnetic beads. A magnetic field is then used to collect and trap these beads, which helps keep attached enzymes away from the targeted collagen. The activation process is triggered by an opposite external magnetic field that should be capable to release and free the attached enzymes. The freed enzymes then are designed to attack and destroy the collagen layer.

For idea2: the use of a chemical inside human body is potentially not a successful concept.

P2C7: Evaluate concepts. Since only one concept is generated, there is no need for evaluation. The concept is selected for further development.

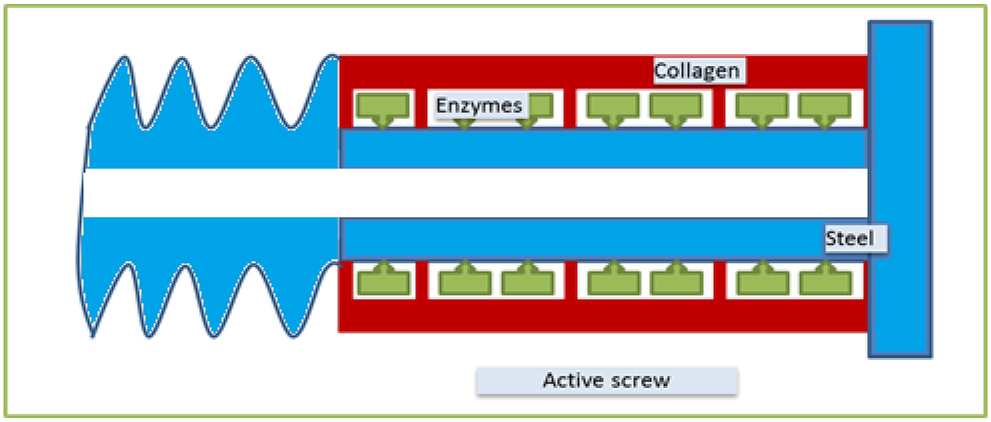


Figure 5.5: Conceptual design for proposed solution- Screw cross sectional view

5.4.4 Embodiment and detailed design

The embodiment design of the developed concept is detailed below:

P3C1: Determine the embodiment requirements.

1. Materials: this design can use, for the screw material, a grade of stainless steel or titanium currently approved for use in the human body. For the outer surface of the screw, current industrial collagen can be used; Although, it needs to be tested and approved for use in the human body. The thin layer between the collagen and the steel can be made out of enzymes characterised based on the used collagen.
2. Size: The size of this embodiment design is comparable to the size of current screws used in the same application. A range up to 8 mm in diameter is needed.
3. Arrangement: The arrangement is shown in figure 5.5
4. Spatial constraints: the Collagen layer and the enzyme layer should be within the range of the threaded part of the outer diameter.

P3C2: Satisfy all functional requirements.

1. Force requirements: The proposed design satisfies force requirements specified in section construct P1C4
2. Displacement and orientation requirements: It does not allow displacement in any direction; hence, it maintains the required orientation.

3. Safety requirements: It does not give access to unauthorized disassembly during the use phase.

P3C3.1: Generate rough forms and layout

Layout is presented in figure 5.5

P3C3.2: Evaluate and select the best layout

One layout is generated and selected

P3C3.3: Improve design for X:

1. Design for manufacturing: possibility of using standard engendering materials instead of special medically approved ones could be investigated.
2. Design for assembly: the proposed design keeps previous design features related to ease of insertion and application.

P3C4: Generate preliminary layout

A 3D digital model is presented in figure 5.6, which demonstrates the final form and layout of the concept.

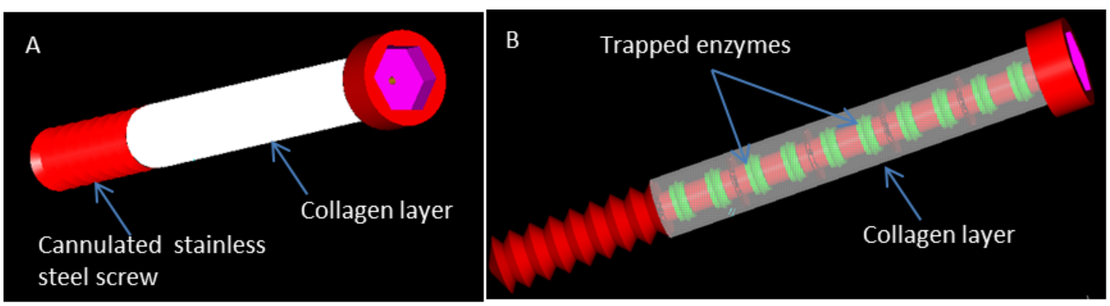


Figure 5.6: Embodiment design of the proposed active screw, A: 3D view, B: Transparent view

5.4.5 Detailed design:

Once the definitive layout of the embodiment design is finalized, the production document can be generated based on the CAD model presented in figure 5.6. Detailed drawings, assembly diagrams, part lists, and assembly instructions can be generated using the CAD system. Detailed design of the generated concept is not the focus of the future work of this dissertation.

5.4.6 Case study discussion

In this case study, a novel solution is introduced to solve a real life problem encountered in removing bone joining screws at their EOL. The concept of A.Dis. is used to develop active screw that facilitates the removing process without encountering problems with the existing types of screws. Although the cost of active screws developed in this case study will be larger than the existing one, the cost should not be a limiting factor when it comes to ease of operation with a human body.

The attempt to take this invention to the manufacturing and product realization stage faced a series of lab test and validations that regulate products intended to be used within the human body; the tests could take years before the product gets approved; yet, opportunity for implementation in other applications might exist.

5.5 Case study 2: Validation through automotive safety system application

5.5.1 Purpose of the case study

The purpose of this case study is to demonstrate type 2 of the empirical performance validation of the developed methodology. It demonstrates the quality of a proposed solution that is linked to the use of the methodology. The Air bag module mounted in a steering wheel assembly is redesigned by incorporating A.Dis. The usefulness of the output solution is compared to a previous design which also used A.Dis. By conducting comparison between the two designs, it was possible to validate the purpose.

5.5.2 Design task planning and clarification

P1C1: design task title and description: For this case study, a proper design task title is steering wheel airbag active joint design. The task can be described as a design and innovation of an active joint for an EOL airbag in a steering wheel assembly.

P1C2: problem description. Currently, dismantlers deploy unused airbags of EOL vehicles that release more harmful gases into the atmosphere. Airbags (especially ones that have been used for more than 30 years), along with seatbelts petitioner contain Sodium Azide (for generating the gas to fill airbags during deployment). In 2005, Oregon Legislature passed House Bill 2507, which requires that airbags to be removed from vehicles before it is wrecked or dismantled. Dismantling facilities face a hard time to disassemble airbag modules from vehicles. They would rather deploy the airbag in place instead of removing it and disassemble it into parts for reusability purposes.

Airbags are just like other mechanical components: they have a limited lifespan. Moreover, the concern about the ability of protecting the vehicle occupants in a crash has been growing. Thus, improving the airbag disassembly process and procedures serve three purposes: reusability, recyclability, and maintenance of the un-deployed airbag modules. Restraint systems in the automotive industry require maintenance as needed. However, currently, auto dealers' maintenance practices require replacing the entire module and the used one to be sent to EOL specialized facilities. Those facilities perform open-air deployment which increases the risk of releasing more gases into the atmosphere; in turn, it reduces the opportunity to reuse expensive and healthy materials. Japan's Automobile manufacturers deploy unused airbags at the EOL vehicles without taking the advantage of re-using the module even partially. Deploying unused airbags release Sodium azide gas (NaN3) in the air.

A study shows that a batch of airbags were fed into the shredder, it was found that only 50% deployed. More alarmingly, due to the material difference of the steering wheel assembly (die-cast and steel), the airbags were equally spread between the resulting materials due to the fact that non-ferrous waste was still manually treated. As an outcome, an unacceptable situation arises. Operators need to become in contact with live detonators which cause a safety threat to their lives (Jones, 2003).

The disassembly burden of an air bag in the instrument panel (IP) module is assessed in a joint work conduct by Ramadan *et al.* (2009). Kroll's chart (Kroll *et al.* 1996) has been established to calculate the disassembly efficiency. After completing the disassembly process of the airbag module using the above chart, the efficiency has been calculated and found as low as 20%. To ease the disassembly process by reducing the time for disassembly, reduce the number of required tools to take the module apart, and to increase the overall efficiency rating, new design concepts are generated to improve the design.

Additional DFD processes were conducted to evaluate the DFD efficiency for the new proposed design. Using the same equation to calculate the DFD efficiency, the new result is an improvement; although, not significantly. The DFD efficiency increased to 24%.This low DFD efficiency suggests that A.Dis. has been used. Although the disassembly analysis was carried out for the IP air bag, result are applicable to steering wheel air bags as well.

P1C6: Search for a solution. The designer is encouraged to search the active joint catalogue (tool #1) and various literatures to find an existing solution.

A. Search for a solution using active joints catalogue (tool #1in appendix 4-A): After referring to tool #1, no suitable joints were found.

B. Search for a solution using literature:

The Disassembly of the steering wheel air bag was studied by Jones (2003). The study shows the need for air bag disassembly at vehicle EOL. Due to the manual effort involved in an air bag disassembly, an A.Dis. solution is proposed. The "Hot Probe" A.Dis. technique was developed by Jones (2003). A Shape Memory Alloy (SMA) collar is heated using a hot probe. The heat causes the collar to unroll and releases the airbag assembly. The concept is illustrated in figure5.7.

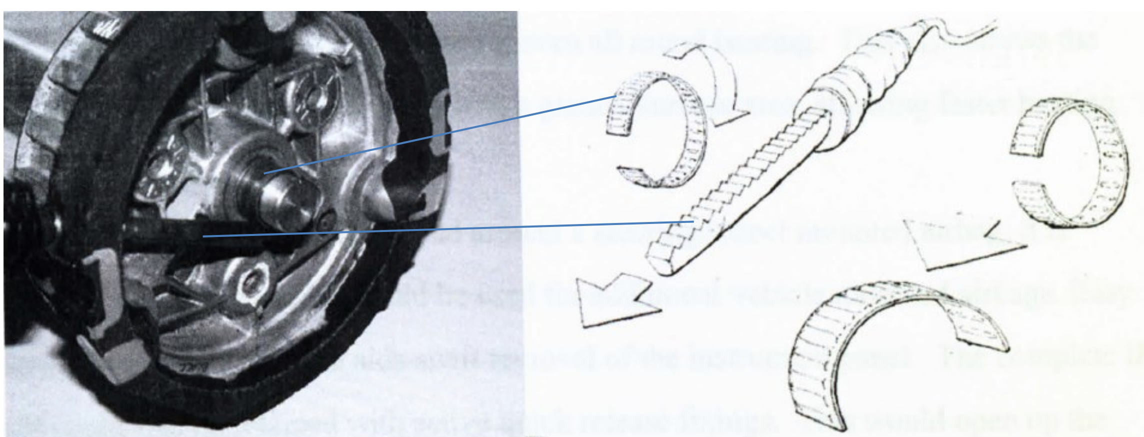


Figure 5.7: Hot probe A.Dis. technique for steering wheel airbag. Source: (Jones,2003)

A hole is drilled in the side of the steering wheel hub; a hot probe is inserted and engaged with an/the SMA collar. The toothed profile of the probe and the collar maximize the engagement and reduces heating time, which is between 5-10 seconds. A Toothed profile is also needed because there is no visual access to the collar.

Since the purpose of this case study is to test the solutions provided by the methodology against previous solutions, searching for a solution will not stop at this point. Searching for a new solution will proceed to the next design phase.

5.5.3 Conceptual design

P2C2: Use tool #2 to model the joint. The methodology starts the conceptual phase by modelling the joint's functions using tool #2. The intended joint is between the airbag module, steering wheel hub, and steering column. This joint has two wanted functions and one unwanted function which are modelled in figure 5.8. They are:

Wanted function1 (mount): To mount the airbag module to the steering wheel hub and steering column.

Wanted function2 (locate): to locate the module in the centre of steering wheel hub.

Unwanted function1: limit access during disassembly.

Mount function requires forces Fx, Fy, Fz in the X, Y, and Z direction respectively.

Locate function requires zero displacement in the X, Y, and Z direction

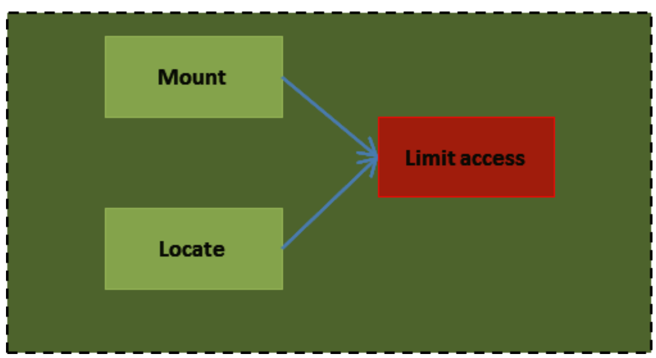


Figure 5.8: Joint functions model

P2C2: Assign active feature to Functional part, joining element, or added element.

To reduce part count in the final product, the methodology assigns active disassembly features firstly to a functional part or parts. Three functional parts are identified in this case study: steering column, steering wheel hub, and airbag module. Due to the functionality and specification of these parts, assigning active disassembly features to them is not a feasible option. The second option is to assign the active feature to the joining elements. The last option is to add new active element to the joint. The second and third options are investigated in this case.

P2C3: Generate list of lines of thinking (rough ideas). Based on joint functional modelling in step, active feature assignment in step 2, joining methods patterns of evolution in tool #3, and considering the following:

- Wanted functions need to be maintained
- Unwanted function need to be resolved
- Active disassembly feature is assigned to joining element.

Lines of thinking are generated and demonstrate in the following table:

Table 5.1: Generated lines of thinking

Pattern of evolution	Generated line of thinking
Pattern 1	L1: Add more features to the joint
pattern 2	L2: Add more integration between airbag module, steering wheel, and steering column (design changes may be needed)
pattern 3	L3: Use joining forces at the micro level
pattern 4	L4:make use of surrounding fields

P2C4: Formulate lines of thinking in terms of TRIZ problem formulation. For each line of thinking generated in the previous step, further development is carried out using appropriate TRIZ innovation tool.

L1: Add more features to the joint which can be developed further into the following idea:

Idea 1: A feature can be added to the joining element that makes it able to engage and disengage the joining action based on an external trigger.

Since there is no contradiction involved in this idea, the substance field formulation tool #5 is selected. The problem is modelled as illustrated in figure 5.9, which shows an unwanted action between the airbag module and the steering column during the disassembly process. Idea1 is introduced to eliminate this unwanted interaction.

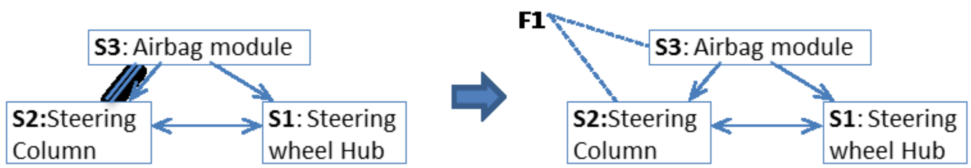


Figure 5.9: Substance-Field formulation for airbag joint

L2: Adding more integration between parts:
Since this line of thinking requires design changes to the whole assembly, which is beyond the purpose of this example, no further development to this line of thinking will be carried out.
L3: Use joining forces at micro level:
Idea2: Join the airbag module to the steering wheel hub and the steering column, or either one of them, using joining forces at micro level; for example ., adhesive forces at molecular level. At this point, the idea can be presented as follows: Active adhesive can be used to join the assembly and can be actively disassembled using heat. This idea involves contradiction with safety concerns regarding using heat as a trigger. Based on this contradiction, the problem can be formulated using tool #9.
Physical contradiction: the joint is heated to activate joint disassembly. Meanwhile, the joint cannot be heated due to possible unwanted airbag deployment.
L4: Introduce material that can be activated by a surrounding field:
Idea3: the airbag module can be joined using adhesive which can be disassembled using fields other than heat;. cooling or chemical media are examples of good alternatives. This idea involves technical contradictions that can be formulated using tool #7.
Technical contradiction: reducing the joining adhesive force using proposed media causes time loss during the disassembly process.
P2C5: maintain a list of generated ideas. The purpose of this step is to document generated ideas and to investigate possible synthesis between them which may lead to new ideas. Table 5.2. portrays a new idea, idea 4, which can be synthesized by combining the strengths of previous ideas in a new idea, which says: a surrounding field (e.g., magnetic field), can be employed to disengage a joining element that joins the airbag module to the steering column.

Table 5.2: list of generated ideas

Generated ideas:
Idea 1: A feature can be added to the joining element that makes it able to engage and disengage the joining action based on external trigger.
Idea2: Join airbag module to steering wheel hub and steering column, or possibly to one of them, using joining forces at micro level, e.g. adhesives forces at molecular level. At this point, idea can be presented as follows: Active adhesive can be used to join the assembly and can be actively disassembled using heat.
Idea3: Airbag module can be joined using adhesive which can be disassembled using fields other than heat, e.g. cooling or chemical media which does not harm the Airbag.
Idea4: a surrounding field, e.g. magnetic field, can be employed to disengage a joining element that join airbag module to steering column.

P2C6: Develop generated ideas into concepts. At this step, ideas listed in step 5 are further developed into working concepts. Idea1 and Idea4 have a similarity; both ideas can together develop into a working concept. While ideas 2 and 3 are similar, they can develop into other working concepts.

Concept1:

This concept is built around the idea of adding active features to the joint to make it responsive to a triggering field. The concept is developed over the following steps:

- First: the joint is separated into two joints; one is between the steering wheel hub and the steering column, while the other one is between the airbag module and the steering wheel hub. A.Dis. is needed for the second joint, unlike the case of the first one.
- Second: traditional bolts can be used to join the steering wheel hub and steering column. This will keep the current joining method without change.

- Third: an active joint is needed to join the airbag module to the steering wheel hub.
- Fourth: using tool #10 (Triggering field – physical effect), magnetic field is selected to provide triggering magnetic force. This force is responsible for A.Dis. of "smart-made", especially design joints between the airbag module and the steering wheel hub. Figure 5.10 demonstrates the concept.

This concept uses mechanical interlocking between the assembled parts (P1, and P2). P3 and P4 provide the mechanism to achieve the interlocking feature. P4 makes upward and downward motions, while P3 makes inward and outward movements. When P4 is in its upward position, P3 will be in its inward position. When P4 is in its downward position, P3 will be in its outward position. During assembly, P3 prevents relative movements between P1 and P2. This is maintained as long as P4 stays in the upward position. When A.Dis. is required, external magnetic force is remotely applied to P4, which is made of martial responsive to magnetic force. This force makes P4 move downwards, and P3 move outwards, causing P1 to be released.

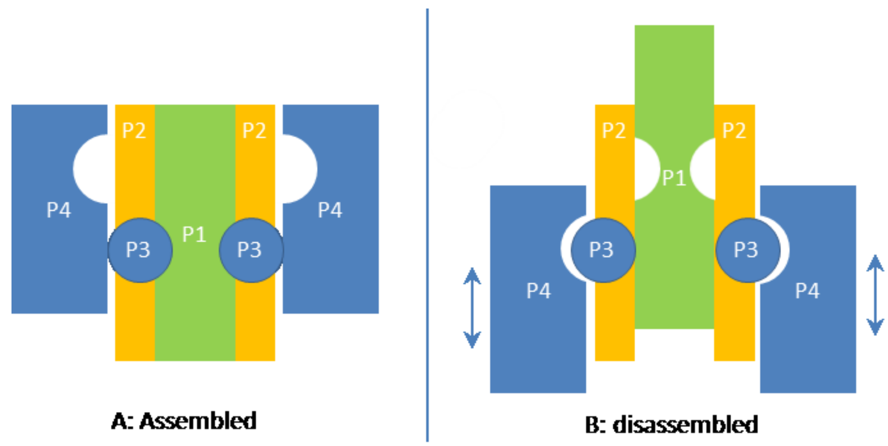


Figure 5.10: "smart-made" active joint for concept1

Concept2:

This concept is built around the idea of using active adhesive, an adhesive which loses its bonding capability under the influence of a triggering field. Idea 2 suggests the use of heat as a triggering field which is easy to apply and effective in de-bonding many current types of adhesive; hence, no new adhesive needs to be developed. Meanwhile, heat could cause damage or deployment to the airbag. Idea 3 suggests the use of a field that does not cause harm to the airbag. If idea 2 and idea 3 are combined together, then a new challenging idea would be to use heat without harming the airbag. This idea has physical contradictions that can be solved using tool #9 and tool #8. This contradiction has been formulated in step 4, which states that the joint is heated to activate joint disassembly meanwhile, the joint cannot be heated due to possible unwanted airbag deployment.

Based on tool #9, concept 2 can be developed in the following steps:

STEP1: Identify contradicted values of the physical features.(Existence and absence of heat)

STEP2: If contradicting values are not required all the time, then use the separation principle1; otherwise, proceed to step 3.

(It is required all the time, proceed to step 3)

STEP3: If contradicting values are not required at the same place, then use separation principle 2; otherwise, proceed to step 4.

(It is not required at the same space, then use the separation principle 2 in tool #8)

STEP4: Principle 2 suggests separation in space. Heat is needed to melt the adhesive, but it will transfer to the air bag due to its physical contact with the adhesive. Using principle 2, a physical separation between the air bag and the adhesive will solve the contradiction; then concept 2 can be said as following:

An active joint between the air bag module and the steering wheel hub can be achieved by heat triggered assembly after adding a thermal insulator between the air bag module and the steering wheel hub. The insulator will be glued to the air bag model from one side and to the hub from the other side. The concept is modelled in figure 5.11. Using triggering field-physical effect table tool #10, the external heat source is induction heating using electromagnetic field that heats the hub material, which is currently conductive material. This heat melts the adhesive between the hub and the insulator. The airbag is protected by the insulator.

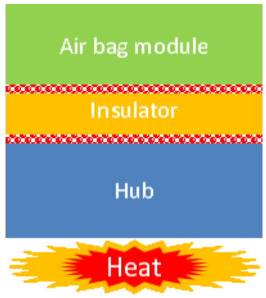


Figure 5.11: Concept 2 heat activated joint

P2C7: Evaluate concepts. Evaluation identifies the best concept which is taken to the embodiment and detailed design phase. In this case study, the generated concepts in the previous section can be evaluated using tool #11. For the sake of demonstrating the usefulness of the methodology, all concepts are developed into embodiment designs.

5.5.4 Embodiment and detailed design

Embodiment design of concept 1:

P3C1: Determine the embodiment requirements.

1. Materials: P1, P2, and P3 can be metal or polymers which satisfy load and displacement previously determined. P4 has to be ferromagnetic material.
2. Size: due to the space limitation, the overall size of the joining element can be ½" in diameter and 1" in height, assuming it is a cylindrical shape.
3. Arrangement: two joining elements are needed;, each element has two coaxial cylinders with a set of beads trapped between the two cylinders. A spring is needed to maintain the outer cylinder in engaged position. See figure 5.10 and 5.12.
4. Spatial constraints: The joining element is attached to the hub from inside. P1 is attached to the air bag module, it approaches the assembly from the top.

P3C2: Satisfy all functional requirements.

1. Force requirements: This joint can sustain forces in X,Y, and Z directions.
2. Displacement and orientation requirements: It does not allow displacement in any direction, and hence, it maintains the required orientation.

3. Safety requirements: It does not give access to unauthorized disassembly during the use phase.

P3C3.1: Generate rough forms and layout

Layout is presented in figure 5.10

P3C3.2: Evaluate and select the best layout

For demonstration purposes, only one layout is generated and selected

P3C3.3: Improve design for X:

1. Design for manufacturing: Standard engendering materials and items can be used for this application.
2. Design for assembly: Top-down insertion is sufficient to assemble the airbag to the hub.
3. Design for environment: Easy to disassemble elements (active joints), made of recyclable materials.

P3C4: Generate preliminary layout

A 3D digital model is presented in figure 5.12 which demonstrates the final form and lay out of the concept.

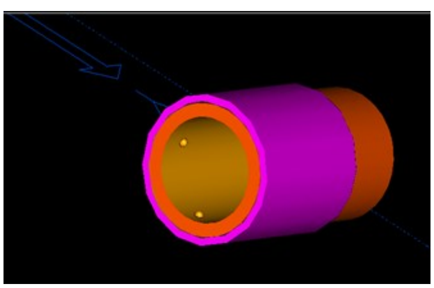


Figure 5.12: 3D digital model of embodiment design 1

Detailed design:

Once the definitive layout of the embodiment design is finalized, the production document can be generated based on the CAD model presented in figure 5.12. Detailed drawings, assembly diagrams, part lists, and assembly instructions can be generated using NX software. Detailed design of the generated concept is not the focus of the future work of this dissertation.

Embodiment design of concept 2:

P3C1: Determine the embodiment requirements.

1. Materials: Hub material has to be ferromagnetic material compatible with induction heating; mild steel is selected. Adhesive material can be a glue that loses its joining capability at 100 $C^{0.}$ The insulator material can be ceramic so that it prevents heat transfer and provides forces and displacement requirements.
2. Size: The maximum size of the joint is limited by the bottom dimension of the hub.
3. Arrangement: Adhesive layer is spread inside the hub, while the insulator is located at the top of the layer. Another layer of adhesive is applied to the top of the insulator. The air bag module is then set at the top making a permanent joint. See figure 5.11.
4. Spatial constraints: The insulator has to take the shape of the steering wheel hub.

P3C2: Satisfy all functional requirements.

1. Force requirements: This joint can sustain forces in X,Y, and Z directions.
2. Displacement and orientation requirements: It does not allow the displacement in any direction; hence, it maintains the required orientation.
3. Safety requirements: It is a permanent joint; it can be disassembled either destructively or using A.Dis.

P3C3.1: Generate rough forms and layout

Layout is presented in figure 5.13 below

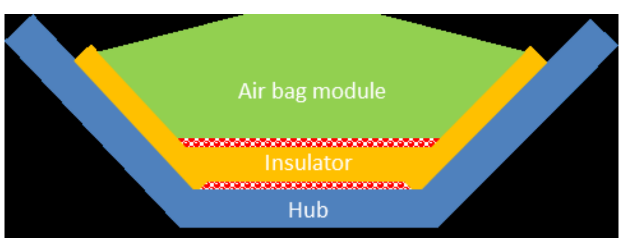


Figure 5.13: layout of embodiment design 2

P3C3.2: Evaluate and select the best layout

Only one lay out is generated and hence, it is selected.

P3C3.3: Improve design for X:

1. Design for manufacturing: Standard engendering materials and items can be used for this application.
2. Design for assembly: Top-down insertion is sufficient to assemble an airbag to the hub.
3. Design for environment: Easy to disassemble elements (active joint); made of recyclable materials.

P3C4: Generate preliminary layout

A 3D digital model is presented in figure 5.14 which demonstrates the final form and layout of the concept.

5.5.5 Detailed design:

Once the definitive layout of the embodiment design is finalized, the production document can be generated based on the CAD model presented in figure 5.14; detailed drawings, assembly diagrams, part lists, and assembly instructions can be generated using NX software. Detailed design of the generated concept is not the focus of the future work of this dissertation.

Using the active joint design methodology developed in this research, two designs are generated to fulfil the requirements of A.Dis. in automotive application. The next section will discuss these results compared to the previous A.Dis. design.

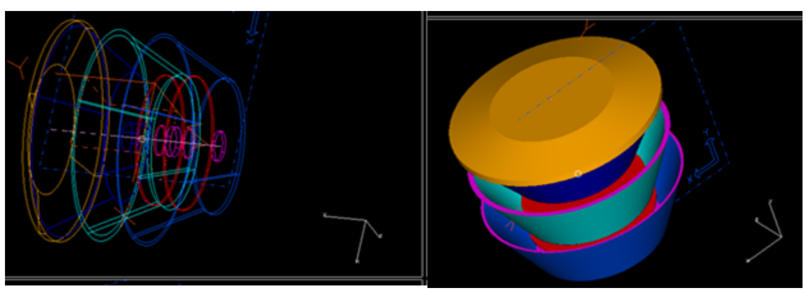


Figure 5.14: 3D digital model for embodiment design 2

5.5.6 Case study discussion and conclusions

Applying a real life problem illustrates usefulness and rigorousness of the methodology. It is found capable in fulfilling the A.Dis. requirements; two design solutions are invented. Comparison between solutions generated using the methodology, and previous existing solutions show the advantage of the generated solutions. Table 5.3 demonstrates the comparison. Seven criteria are used to evaluate the solutions. The pros and cons of each solution are investigated. The previous A.Dis. design is found easy to assemble, but not easy to disassemble. A hole is needed to be drilled in the hub, and then a hot probe is blindly inserted with the hope of making engagement from the first time with an SMA collar; otherwise, trial and error or 'feel' is used to make the engagement. Safety concerns also exist with this method of trigger application; if heat is brought close to the air bag, it might lead to unintended deployment. This endangers a worker's safety. To the contrary, this concern is not found in the second design solution. Although, it uses heat as a trigger, thanks to the methodology's tool that solves such contradiction and at the same time leads to innovative solution.

As of the downside of the proposed designs, they might render service and maintenance of the parts joined by these types of joints.; This is due to the fact that active joints need the assigned trigger to initiate the disassembly, which might not be within the reach of service workers.

Table 5.3: Comparison between developed solutions and previously existing one

	Criteria	**Design 1**	**Design 2**	**Previous solution**
Pros	Ease of assembly	High	High	High
	Ease of trigger application	High	Medium	low
	Applicability in similar applications	Medium	Medium	Medium
Cons	Accidental triggering during use phase	Low	Medium	Medium
	Level of human involvement	Low	Low	High
	Accidental deployment during A.Dis.	Low	Low	High
	A.Dis. time	Low	High	Medium
Solution ideality	$I = \sum(\text{pros})/\sum(\text{cons})$	8/4 = 2	7/7= 1	6/10 = 0.6
Legend: High = 3, Medium = 2, Low = 1				

In conclusion, the following features in the methodology have impacted the quality of the generated solutions:

- Functional modelling of the joints give more thoughts and directions for possible solutions. The designer becomes aware of which functions can be assigned to which elements in the joint so that A.Dis. can be easily achieved.
- Joining patterns of evolution facilitate ideas generations; this leads to a large reserve of ideas that might develop into working concepts.
- Three TRIZ based tools are found useful in developing crude ideas into working concepts. Versatility of these tools enables the designer to handle a large spectrum of ideas involving contradicting requirements. Solving contradictions usually leads to innovative working concepts. In this case, study 2 innovative concepts are generated.
- Triggering field and physical effect tool #10 facilitates a designer's job for selecting potential A.Dis. triggers suitable for working concepts in hand.
- Finally, the systematic nature of the methodology lets its users end up with a quality solution each time they apply it.
- Combining A.Dis. with manual or automated disassembly could also improve the feasibility of recovery process. For example, automated separation for parts which have been actively disassembled could be an economical solution; in other cases manual separation could be more economical.

6 DISCUSSION AND CONCLUSION

6.1 Discussion

At the heart of this dissertation, active disassembly is presented as an enabler for a product closed loop lifecycle. The role of the EOL product recovery, its requirements to achieve a closed loop product lifecycle, and its achievement in sustainability has been demonstrated. Product ease of disassembly is an enabler to achieve a closed loop in product lifecycle. Traditional disassembly methods are proved unfeasible for most recovery options in many products. Active disassembly is an emerging product disassembly method, which uses external triggers to initiate remote disassembly of active joints which are purposefully impeded in a product.

Review for A.Dis. literature and practices was conducted. The review identified deficiencies and gaps in A.Dis. Identified gaps showed that the decision to incorporate active disassembly in a product design lacks comprehensive sustainability assessment that justifies it. Moreover, once a decision is taken to incorporate A.Dis., it is not an easy task to design an active joint capable of providing A.Dis., considering the substantial level of scientific knowledge and innovation required to design such type of joints.

To bridge the identified needs, a framework consisting of two levels was proposed. The first level of the framework was devoted to justifying the decision to incorporate A.Dis. in product designs. To this end, two assessment models were developed: firstly, reuse for EOL product as a whole is assessed. According to the proposed framework, products that qualified for reuse did not need disassembly, and hence, did not need A.Dis. Secondly, recovery of EOL product assemblies and parts is done. Disassembly effort is identified through an embedded algorithm in the model, and hence, a need for A.Dis. is justified. The second level of the proposed framework provides design methodology, which is the first of its kind that fulfill the need for both rigorous design and innovation of active joints required to enable A.Dis. The methodology, through its TRIZ-based constructs, supports the creativity required to generate inventive ideas and concepts for active joining, while the systematic design backbone relies on provides structure and ensure rigorousness.

6.1.1 EOL recovery assessment models

The development and implementation of the model proposed to assess reuse opportunity for EOL products showed the following results and observations:

- Reuse of EOL product after its first cycle of use is a problem that needs to be closely examined. Economical, environmental, and societal component of sustainability have to be analyzed before introducing EOL product into another cycle of use.
- This research, through a field survey, found that the importance of each of the three sustainability aspects are not equal and case dependent. Matter of fact, it depends on the decision maker's preferences. The model presented in this research solved this need by providing decision makers with a flexible sustainability assessment tool, which covers the quantitative and qualitative aspects of the problem, and at the same time provides variable weights to reflect special circumstances of each case.
- In this model, indicators which are rated as important by surveyed experts are considered in the development of the model. Six indicators are selected for both the economical and environmental components of sustainability. Only three indicators are identified as important for societal aspect of EOL product reuse. This shows that there is room for investigating more indicators that could be important to the society but not yet to the decision maker.
- The indicators used in the model development were selected based on a field survey, which was quite precise and effective in selecting the most related and influential indicators. The selection is based on preferences and experiences of experts in the field. That in turn distinguished this model from previous ones and helped resolve a valid concern about the cut offs and criteria for considering a specific indicator
- EOL product recovery is characterized by unavailability, scarcity, and qualitative nature of the data. These are issues proven to be crucial for correctness and usefulness of the final decision to be arrived at. AHP employed approach tackled this problem by incorporating experts' qualitative judgments.

- On the negative side though, the developed model quantify EOL product reuse in a single scalar number, where it becomes hard to track the contribution of each performance variable to the computed sustainability index.
- The model's sensitivity and limitation studies were performed for the case study at hand. The analysis showed that the improvement in environmental performance of the new machine cannot outweigh the advantages of the used one, especially when it comes to savings of local jobs and capital investment. This showed the ability of the model to reflect a decision maker's preferences. To illustrate, in the employed case study, environmental aspect was not a real concern; hence, it was not really accounted for in the implementation of the developed model.

According to the proposed framework, EOL product which is not qualified for reuse is taken to the next EOL recovery assessment. Development and implementation of the assessment model to recover EOL product as assemblies and parts is showed the following results and observations:

- The model's development showed that EOL product recovery is a complicated process; it involves considerations of many factors that come from different fields motivated by interests of different stakeholders. Not only are the number of factors large, but the interaction between these factors is substantial. The model was built based on a holistic approach, which tackled the problem without sacrificing any details.
- This research benefited from reviewing previous methodologies, i.e., it built on their strengths and avoided their weaknesses. It successfully developed and implemented a holistic assessment model for decision making of EOL product recovery options.
- The use of PESTEL analysis helped in identifying the most influencing factors amongst a large number of them. AHP equipped the proposed framework with the ability to consider different decision maker preferences and deal with both quantitative and qualitative aspects of the available data.
- Disassembly planning algorithm was integrated with the model. It helped in evaluating disassembly effort and identifying the need for A.Dis.

- Cost/benefit analyses, found in the second phase of the method, addressed the economical details which were needed to decide on the second level of recovery option.
- Validity and usefulness of the proposed methodology was demonstrated through the fuel cell case study. The model was found capable of considering a decision maker's preferences, providing correct and meaningful decisions, and highlighting potential uses of A.Dis.
- Moreover, the lack or inexistence of some data is accommodated by the model through estimates and judgments made by the expert, thanks to implemented AHP approach.
- The results obtained from the case study were insightful and recommended to be used by fuel cells stack designers, manufacturer, possible future independent recoverers, and other interested parties in fuel cell industry.
- The model implementation showed that substantial effort for data gathering and analysis is needed. The analysis effort is proportional to the number of items in the product at hand. For products which have large number of items the methods become tedious and time consuming.
- Results stressed the role of product disassembly in recovery process. Reduction in disassembly effort, or ultimately eliminating it, would qualify the disassembled item to a better recovery option or improve current option feasibility.

6.1.2 Active joint design methodology

The need for A.Dis. was identified based on results obtained from developed EOL recovery assessment models. The second level of the proposed framework provided a design methodology specifically developed to fulfil this need. The following insights and results were observed:

- Active joint design methodology was developed to fulfill the need for a methodology that provides quality active joint solutions, facilitates designer creativity, and communicates design outputs to other members involved in design and development of active joint and product design.

- To fulfill the previous requirements, two characteristics were built into the developed methodology, namely consistency (structure) and innovation. Being systematic was achieved through following the four phases of systematic design, each phase consisted of constructs which guided designers throughout the design process. The methodology was also characterized by its support for designer creativity. TRIZ-based constructs provided this feature, by providing innovative problem solving techniques which showed the ability to generate innovative ideas and concepts for active joints
- Developed patterns of joining methods evolution contributed to the novelty of the developed hybridized design methodology, and hence, the obtained solutions; they set directions for generating new ideas and consequently increased quantity and quality of generated ideas.
- A set of tools were developed and integrated with the methodology. They guide and help the designer perform tasks required by the methodology. Active joint catalogue, triggering fields-physical effects table, and joining method patterns of evolutions are a few examples.
- The methodology ability to communicate with other design methods, tools, and software was considered during its development. Data and fact finding methods can contribute to phase 1 of the methodology. PLM tools can contribute to phase 3 and phase 4 of the methodology.
- To maintain the methodology structural validity, the methodology's constructs were benchmarked with similar constructs found in well-established engineering design methodologies
- To prove the methodology's ability to provide quality solutions, a case study of joining live tissues in human body was used. Innovative design for an active screw was developed through the suggested methodology.
- A case study of safety systems in automotive application was used to validate the methodology's imperial performance. The steering wheel airbag, which has been already equipped with active joint to disassemble the EOL airbag, was also redesigned using the developed methodology. Comparisons between proposed and

previous designs demonstrated the ability of the methodology to produce better solutions than previous ones.

6.1.3 Significance

This research contributed to the engineering knowledge by pushing the envelope of a newly emerging product disassembly method. The research's contributions, and their significance to the field of A.Dis. and sustainable product design, are summarized below:

- A novel design framework to assist with closing the loop in a product's lifecycle is introduced. This framework is the first of its type in addressing the requirements for incorporating A.Dis. in product design
- The new assessment model specifically devoted to assess an EOL product reuse was presented. Reuse of EOL products in another use cycle was considered as the optimal recovery option from a sustainability point of view.
- The use of PESTEL analysis is novel to an EOL product recovery assessment. Based on this novel use, sustainability metrics were derived and used in the assessment model for EOL recovery. These metrics are also beneficial, not only for product designer and developer, but also for other stakeholders who have interest in EOL product recovery
- The new holistic model is developed to assess EOL product recovery into assemblies and parts. This model is based on a novel set of influencing factors based on the PESTEL analysis. The model presents a novel match between decision making tools used in the model and the previously two identified level of recovery.
- The design methodology is important to the product designer and also joining methods developers. The developed methodology is expected to promote the use and adoption of A.Dis. in the product design after designers have a design methodology dedicated for active joint innovation. It is also expected that the methodology will be provide a foundation for paradigm in joining methods, namely active joining.
- This research adds three active joining elements to the current library of active joints. These active joints can be used in similar applications and will inspire design and innovation of new active joints that might use similar concepts.

6.2 Conclusions

The following conclusions were made:

- Active disassembly is a potential candidate to replace manual disassembly and simultaneously boost the feasibility of EOL product recovery.
- The developed framework did successfully guide the decision of incorporating A.Dis. in the product design. The framework starts with satisfying sustainable design requirements with minimal use of resources. EOL product reuse is tested at first; only unqualified EOL products are taken to the lower level of recovery; i.e., recovery of assemblies and parts. The framework ends with a design methodology for active joints to fulfill the need for identified A.Dis. in previous EOL recovery assessments.
- The first assessment model was found accurate in addressing the EOL product reuse problem. It showed a complete match with industrial practice. The second assessment model showed superiority over similar models found in the literature. 90% matching with industrial practice was achieved, compared to 46% -86% in other models.
- EOL recovery terminologies discrepancies were found within literature and between literature and industrial practices. They were identified and unified.
- The research also provided rational classifications for existing recovery options and provided meaningful clear cut distinction between these options.
- PESTEL analysis and AHP as a decision means as well as cost/benefit analysis they found to be successful tool in allocating the best recovery option for each assembly and part in the EOL product at hand. The model also identified where active disassembly is needed.
- The design methodology developed in this research is found to be essential in the innovation and design of active joints.
- The proposed design methodology demonstrated a better quality solution over previous ADis designs. This conclusion was obvious from results obtained from implementing the methodology at an application which was previously designed for A.Dis. The methodology showed rigorousness in quality and quantity of generated design solutions. Results showed how this research improved the closed loop lifecycle of EOL products considered in the case studies; recovery opportunities were

identified, and active joints were designed. Hence, higher recovery value was achieved. This positive impact is linked to the implementation of the proposed framework.

- The three novel active joints developed in this research provide evidence to usefulness of the developed methodology. It will shift the focus from material-based active joints to structure-based joints, as well as joints based on combinations of both.

6.3 Assumptions and limitations

It should be noted that in applying the developed models the following assumptions and limitations should be noted:

- Globally sold product: Globally sold product may not fully benefit from the results obtained by EOL assessment models, since this assessment would vary from region to another due to the difference in influencing factors values.
- Decision maker preferences: The model may lose its holistic value in situations where environmental and societal factors are of no importance to the decision maker. If this is the case, then pure cost benefit models would be more reasonable.
- Shredding and separation technologies: New efficient separation technologies and cost effective shredding methods will affect the results of an EOL assessment models to the point that it makes A.Dis. unwanted.
- Incidental A.Dis.: Unwanted A.Dis. during the use phase of the product life remains a safety concern in many applications. Possibility of unwanted activation should be assessed before incorporating ADis in product design
- Triggering fields and physical effects limitations: Limited number of triggering fields and physical effects suitable for A.Dis. challenge the adoption and considering A.Dis. by many designers and product developers.
- Customer perception: ADis implementation may restrained by customer perception. Although safety may be guaranteed by the design, customers may hesitate to have product equipped with A.Dis. and not suite products.
- Tools update: Some tools developed in the active joint design methodology require continuous update. Fail to do so may result in tools obsolescence.

6.4 Future work

Based on the knowledge obtained in this research the following future research directions can be recommended:

- The reverse implementation of EOL recovery assessment models can be explored. The proposed models are used to identify appropriate recovery options for an existing product. The model's ability to identify product design based on predetermined recovery options needs further research.
- It was stated earlier in this dissertation that EOL recovery assessment is a lengthy process and requires considerable effort. This effort can be automated using a software tool that facilitates data input (through user friendly interfaces) to carry out the analysis through an automated algorithm; preferably publically available through the web. Also, it would be beneficial to integrate a knowledge base tool that accumulates the knowledge of large numbers of EOL recovery examples; this knowledge can be used to provide recommendations on the major influencing factors that highly contribute to the selected recovery option for an item. It also could include recommendations on design features and could suggest changes.
- Further research is needed to explore the concept of multi triggers active joint. This concept will improve the safety concern associated with unwanted A.Dis. during the use phase.
- The envelope of A.Dis. can be expanded by exploring applications other than EOL disassembly. Possible applications can be assembly and disassembly of adaptive structures, Micro Electro Mechanical Systems (MEMS), holders for irregular shape work-pieces. Also A.Dis. applications in process industry is seen as a promising field to explore.

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8 APPENDICES

Appendix 3-A: Input data

(Source: Interviews with GM fuel cell expert, Dr. Atwan, M.)

Influencing factors	unit	End Plates	Current collector	Gaskit	Bipolar Plats	MEA assembly	Membrane	catalysts	Gas difusion layers (GDL)	Electrical jumbers	Bolts and nuts
		Value	Value	Value	Value	Value	Value	Value	Value	Value	Value
Item useful life time	Year	100	100	2	2	2	2	2	2	100	100
Technology/design cycle,	Year	20	100	10	5	2	2	2	2	100	100
Wear-out life	Year	15	5	2	2	3	3	3	3	5	10
Standard or interchangeable item	Yes/No	No	No	No	no	No	No	No	No	No	Yes
Number of components	Integer No.	2	2	2	2	1	1	2	2	2	4
Product architecture, Level of integration	Modular/integrated	integrated	Integrated	Integrated	Integrated	Integrated	Integrated	Integrated	Integrated	Integrated	integrated
Disassembly effort	Time(s)	20	10	5	15	20	10	15	15	10	240
Materials separateability	% by weight	100%	100%	NA	100%	100	100	100	100	1	
Investment costs	H,M,L / recovery option	M, L, NA	M,M,NA	L	H,M, NA	H, L,L	NA,NA, L	H, L,L	NA,NA, L	M,M,NA	M, M, NA
Recovery process cost	H,M,L / recovery option	M,H, NA	L,L,NA	L	H,M, NA	H,L,L	NA,NA, L	H, L,L	NA,NA, L	L,L,NA	H, L, NA
New item value	Monetary unit	22.36	5.32	26.85	368.49	1904.6	493.6	652.44	522.25	1	20
Used item value	Monetary unit	4.472	1.064	5.37	73.698	380.92	98.72	130.488	104.45	0.2	4
Lost sale in primary market	No. of units/time unit	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Core location	Km	25	25	25	25	25	25	25	25	25	25
Collection cost	Monetary unit	100	100	100	100	100	100	100	100	100	100
Demand volume	No. of units/time unit	80000/year	80000	80000	80000	80000	80000	80000	80000	80000	80000
Cost of legal compliance	Monetary unit	0	0	0	0	undefined	Undefined	0	0	0	0
Regulations on recycled quota	Yes/No	Yes	Yes	No	Yes	No	No	No	No	Yes	Yes
Energy yeild	Kw/recovered item	NA	NA	0.05	NA	0.142	Na	NA	0.092	0	NA
Material Yield	% by weight	100%	100%	0	90%	20%	0	40%	0	100%	100%
Liquid and solid waste impact	H,M,L / option	L,H,NA	L,H,NA	NA,M,L	L,H,NA	NA,M,L	NA,NA,L	NA,M,L	NA,M,L	L,H,NA	L,H,NA
Air emissions impact	H,M,L / option	L,H,NA	L,H,NA	NA,H,H	L,H,NA	NA,H,H	NA,NA,L	NA,H,H	NA,H,H	L,H,NA	L,H,NA
Hazardous material contents	% by weight	0	0	0	0	20%	60%	0	0	0	0
Reason for discard	Fail, obsolete, outdated	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail
Purpose of ownership	Functional, aesthetic, both	Functional	Functional	Functional	Functional	Functional	Functional	Functional	Functional	Functional	Functional
Consumer opinion toward used product,	Favour, neutral, against	Neuttral	Neuttral	Neuttral	Neuttral	Neuttral	Neuttral	Neuttral	Neuttral	Neuttral	Neuttral
Damages/benefit to human health	Damage, neutral, benefit	Neuttral	Neuttral	Neuttral	Neuttral	Neuttral	Neuttral	Neuttral	Neuttral	Neuttral	Neuttral
Society involvement in recovery programs	Success rate	High	High	High	High	High	High	High	High	High	High
Green party pressure	Yes/No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Appendix 3-A: Input data

Fuel cell Cost data

(Source : James, B., and Kalinoski, J.A., (2010).

Item	Cost of item(US$)
End Plates	22.360
Membrane electrolyte assembly (MEA):	
1. Gas diffusion Layer (GDL)	522.250
2. Anode and cathode catalyst	652.440
3. Membrane	493.600
Bipolar plates	368.400
Gaskets	26.850
Current collectors	5.320
Electrical jumpers	1.000
Bolts	20.000

Appendix 3-B: Calculated global weights of influencing factors

Influencing factors	Local weights	Global weight
Item useful life time	0.185866	0.042772084
Technology/design cycle,	0.355064	0.081708353
Wear-out life	0.32193	0.074083423
Standard or interchangeable item	0.071158	0.016375027
Number of components	0.023687	0.005450891
Product architecture, Level of integration	0.042294	0.009732883
Disassembly effort	0.75	0.172591996
Materials separateability	0.25	0.057530665
Investment costs	0.583897	0.033857129
Recovery process cost	0.218912	0.012693558
New item value	0.111327	0.006455262
Used item value	0.055614	0.003224757
Lost sale in primary market	0.030251	0.001754095
Core location	0.104729	0.002609713
Collection cost	0.258285	0.006436106
Demand volume	0.636986	0.015872802
Cost of legal compliance	0.75	0.168660882
Regulations on recycled quota	0.25	0.056220294
Energy yeild	0.833333	0.035371193
Material Yield	0.166667	0.007074239
Liquid and solid waste impact	0.258285	0.032889054
Air emissions impact	0.104729	0.013335858
Hazardous material contents	0.636986	0.081111382
Reason for discard	0.636986	0.033010904
Purpose of ownership	0.258285	0.013385266
Consumer opinion toward used product,	0.104729	0.005427459
Damages/benefit to human health	0.785391	0.008140364
Society involvement in recovery programs	0.148815	0.001542427
Green party pressure	0.065794	0.000681934

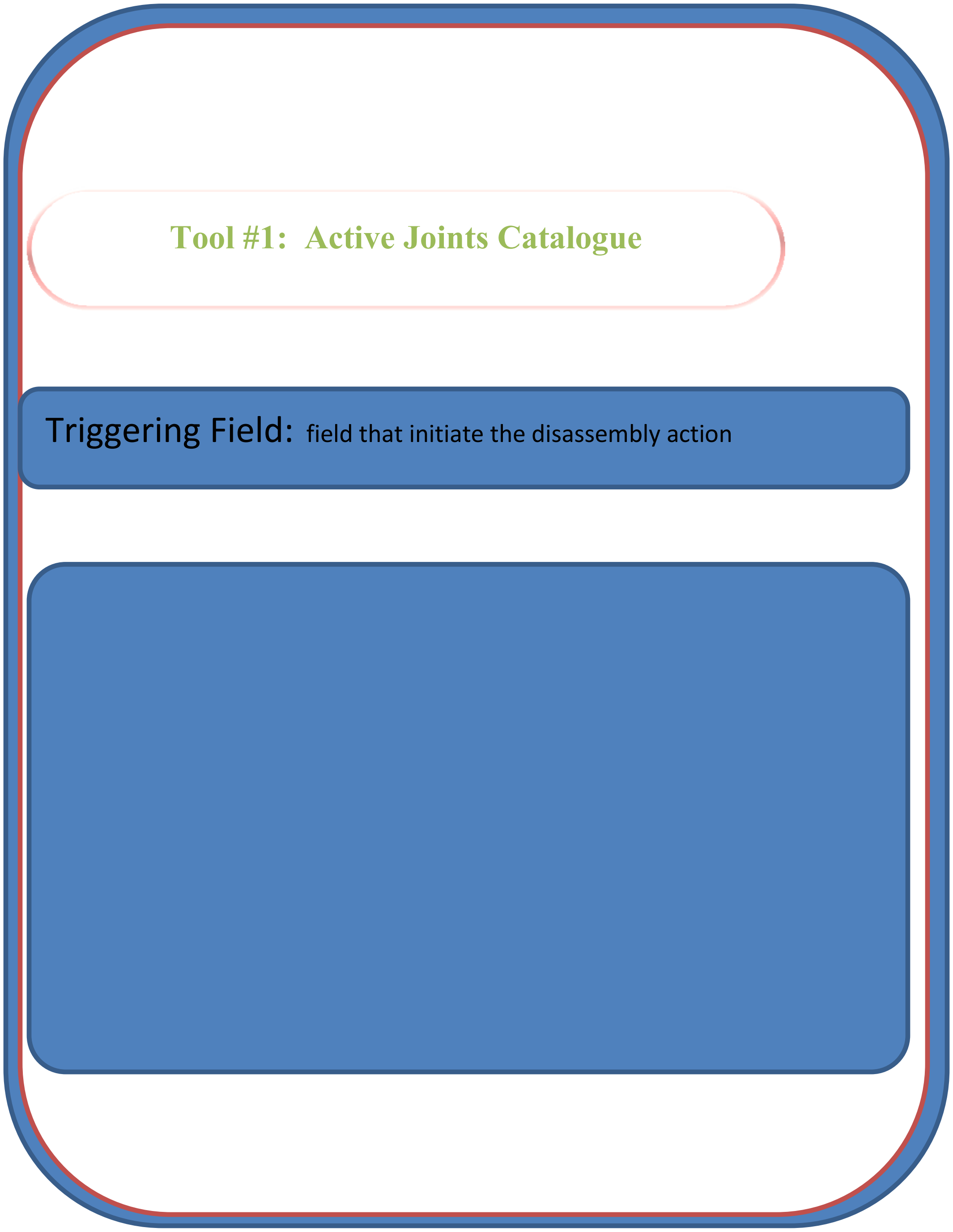
APPENDIX 3-C: Disassembly operations data for fuel cells stack

(Source: GM fuel cell expert, Dr. Atwan, M.)

operation I.D. #	**Operation Description**	**Disassembly time (s)**
1	Un plug Electrical jumpers	10
2	Unscrew end plate bolts	240
3	Removing End Plates	20
4	Removing Current collector	10
5	Removing Bipolar Plats	15
6	Removing Gasket	5
7	Removing MEA assembly	20
8	Removing Gas diffusion layers (GDL)	15
9	Removing Cathode & anode catalysts	15
10	Removing Membrane	10

Disassembly precedence diagram of fuel cell stack, operations 3-10 are identical for remaining cells in the stack.

Appendix 4-A: Tool #1: Active Joints Catalogue



Triggering Field: Thermal source: Lui *et al.* (2012)

Joint Title: The active decapitated head joint

Physical Effect:

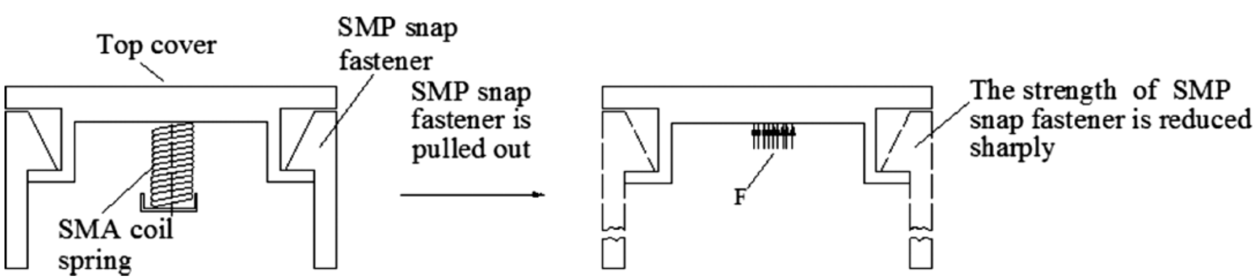
Shape memory polymers

Active disassembly concept:

When heated to the trigger temperature, these materials will exhibit plasticity, and the strength reduces sharply to about 1/64 of that at ambient temperature. This effect cause fracture to the joining element which leads to joint disassembly.

Joint description

Active disassembly devices such as SMP snap fasteners, screws or rivets need to be triggered in the appropriate temperature field. Their strength will reduce by several orders of magnitude near the trigger temperature, when they can be broken and separated by the force and deformation provided by the SMA driving part (such as SMA coil springs, ribbons or tubes) when triggered. The failure mode is usually by breakage of the active disassembly devices. (see figure below)



SMP snap fastener is softened and pulled out by the SMA coil spring

Triggering Field: Thermal Source: Chiodo and Ijomah (2012)

Joint Title: Shape Memory alloy/polymers (SMA/SMP) joints

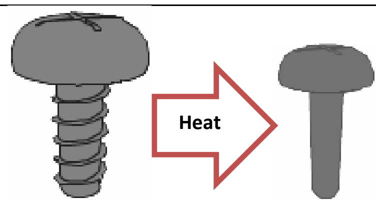
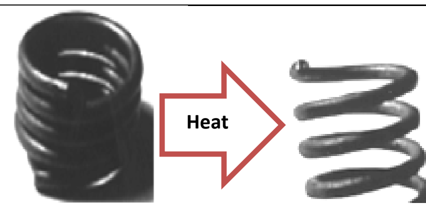
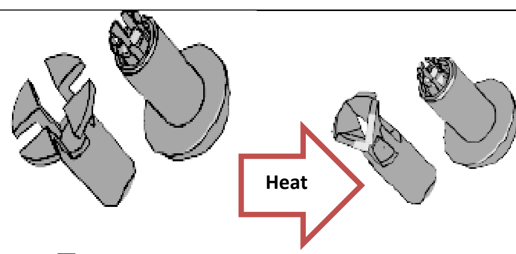
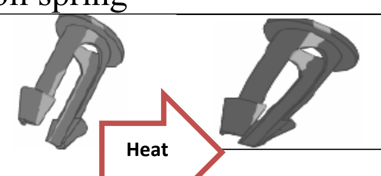
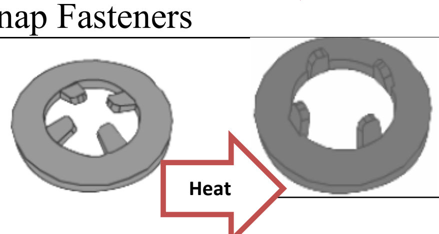
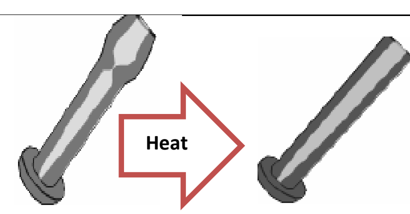
Physical Effect:

A SM is an alloy or that can remember two different shapes; one at low temperatures, and one at a much higher temperature. This transformation in shape is due to the rearrangement of crystal structures within the material.

.**Active disassembly concept:**

The joint is heated to temperature above its triggering temperature Tg, causing joint to revert back to their originally formed "trained" shape, triggering a release.

Joint description: There are different forms of SMA/SMP active joints

 Screws	 Coil spring
 Snap Fasteners	 Snap Fastners
 Clamping washer	 Rivet

Triggering Field: Chemical Source: Neubert H., (2000)

Joint Title: Water-soluble fasteners

Physical Effect:

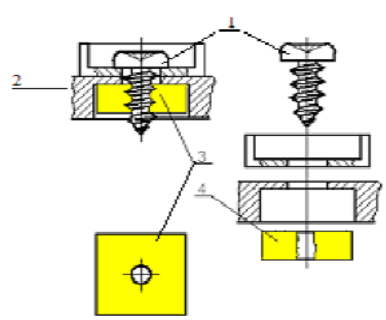
Water solves starch material

Active disassembly concept:

A screw nut system is used to join parts; the nut is made of starch- based material which is soluble in water

Joint description:

Two kinds of material are used: Methyl Cellulose (MC) and Carboxy Methyl Starch (CMS).These connections are soluble in water to the extent that they can lose its function as a fastener.



1) Regular screw, 2) housing, 3) water-soluble element in use, 4) water-soluble element after partially dissolving in water

Triggering Field: Chemical Source: Suga and Hosoda (2000)

Joint Title: Hydrogen storage alloy

Physical Effect:

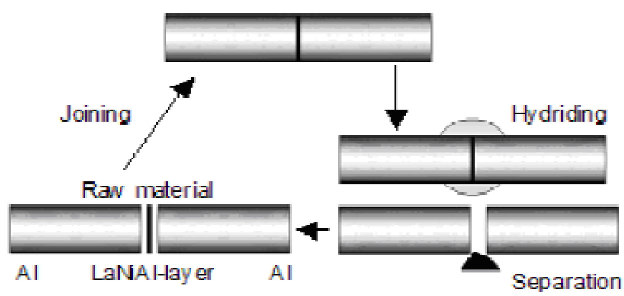
Hydrogen absorption cause metal embrittlement

Active disassembly concept:

Al- LaNiAl alloy joint actively disassembled by Hydrogen embrittlement

Joint description:

Al- LaNiAl alloy joint bonded by surface activating bonding method can be de-bonded using hydrogen absorption phenomenon. The bonding layer can collapse in a media containing hydrogen under pressure of 3 MPa at room temperature.



Triggering Field: Mechanical Source: Willems *et al.* (2007).

Joint Title: Pneumatic Snap fit

Physical Effect:

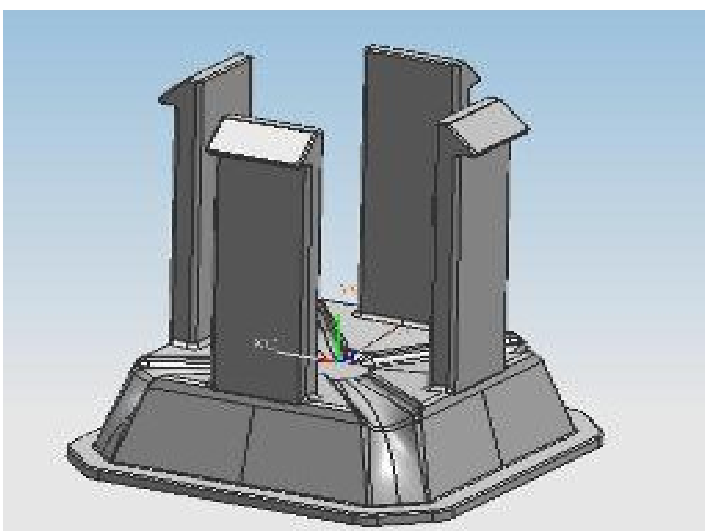
Pressure cause deformation

Active disassembly concept:

Snap-fit that can be actively disassembled using high ambient pressure

Joint description:

The proposed design used a pressure load of 50 Bar to produce 1.57mm displacement which is needed to disengage the snap-fit. Further improvement was done by the team to reduce the pressure needed to activate the disassembly process. Using the lever action it was possible to reduce the pressure from 50 bars to 7 bars.



Triggering Field: Electrical
Source: (General Motor Co., 2005. US patent 6973701B2)

Joint Title : Magnetic polymer fastener

Physical Effect:

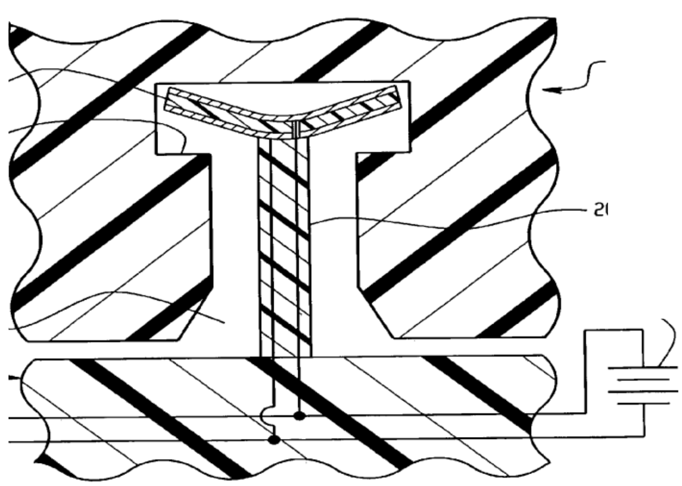
Electrical field makes metallic ions in a polymers change their location in the polymer

Active disassembly concept:

Change in electric field direction makes an ionic polymer change its shape from straight to concave or to convex based on electrical field direction. This shape change provides disassembly action.

Joint description

A releasable fastener system made of ionic polymer metal that mechanically locks and unlocks the joint due to the effectof an electrical current



Triggering Field: Magnetic
Source: General Motor Co., (2004). US patent 6742227B2)

Joint Title: Magnetic hook loop fastener

Physical Effect:

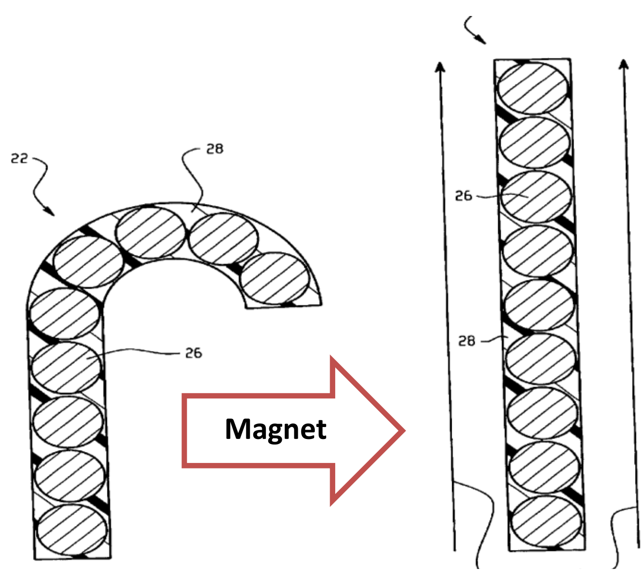
Magnetic field applies force on magnetic material

Active disassembly concept:

In a hock and loop system the hock changes it shape to straight due to the effect of magnetic field causing disassembly of the system.

Joint description

A releasable fastener system comprises of hook portion and loop portion. The fastening occurs when loop and hook portions are pressed together. Disassembly can be done manually or actively by magnetic field that changes the shape of magnetic material of the loop.



Triggering Field: Light

Joint Title

Physical Effect:

Active disassembly concept:

Joint description

Triggering Field: Biological
Source:
http://www.bioretec.com/products/pro_orthotrauma/activascrew.php

Joint Title: Bio absorbable screw
Physical Effect:

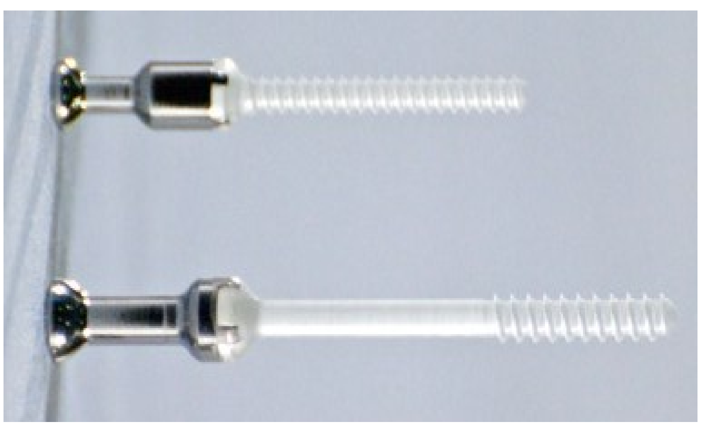
Hydrolysis

Active disassembly concept:

Bio degradable and absorbable screw is used to join fractured bones, after long time of being inside the body it goes in hydrolysis process and then absorbed by the body.

Joint description

The Active screw is bio absorbable screw constructed of bio absorbable lactic/glycolic acid copolymer (PLGA). These polymers have a long history of safe medical use and they degrade in vivo by hydrolysis into alpha-hydroxy acids that are metabolized by the body. Commercial product of (http://www.bioretec.com)



Triggering Field: Nuclear

Joint Title

Physical Effect:

Active disassembly concept:

Joint description

Triggering Field: Combination of fields

Source: Chiodo and Jones (2012)

Joint Title: Hot-wire adhesive release

Physical Effect:

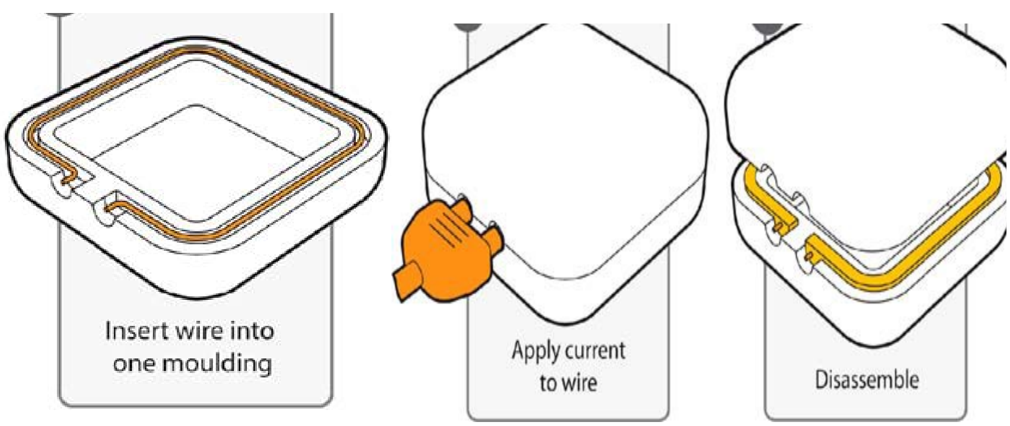
Electrical current produce thermal heat when it passes through electrical resistance

Active disassembly concept:

Fast and flexible localised method of heating using electrical current passes through electrical resistance which passes through adhesive that joins parts. The generated heat is enough to melt the adhesive and disassemble the joint.

Joint description

A thin wire/metallic strip is embedded inside a hot-melt thermoplastic (THMA) adhesive join. This wire loop is connected to a standard electrical jack input. When electrical current is passed through the wire, the resistance of the wire builds up concentrated heat, melting the thermoplastic joint and releasing the components.



Triggering Field: Combination of fields

Combined field: Electrical and thermal Source: Chiodo and Jones (2012)

Joint Title: Hot wire -Glass release

Physical Effect:

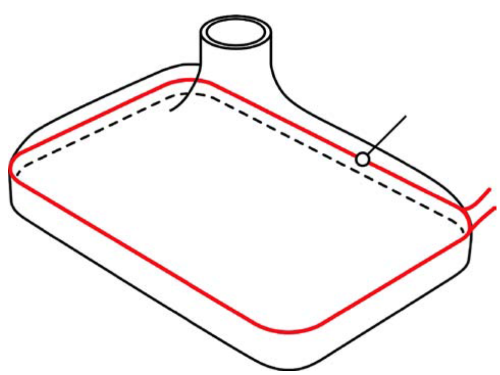
Electrical current produce thermal heat when it passes through electrical resistance

Active disassembly concept:

Fast and flexible localised method of heating using electrical current passes through electrical resistance which passes through two joined glass pieces. The generated heat is enough to initiate crack in the glass making active but destructive disassembly.

Joint description

A thin wire/metallic strip is embedded inside a hot-melt thermoplastic (THMA) adhesive join. This wire loop is connected to a standard electrical jack input. When electrical current is passed through the wire, the resistance of the wire builds up concentrated heat, melting the thermoplastic joint and releasing the components.



Triggering Field: Combination of fields

Combined field: Electrical and magnetic Source: Chiodo and Jones (2012)

Joint Title: Electromagnetic snap fit

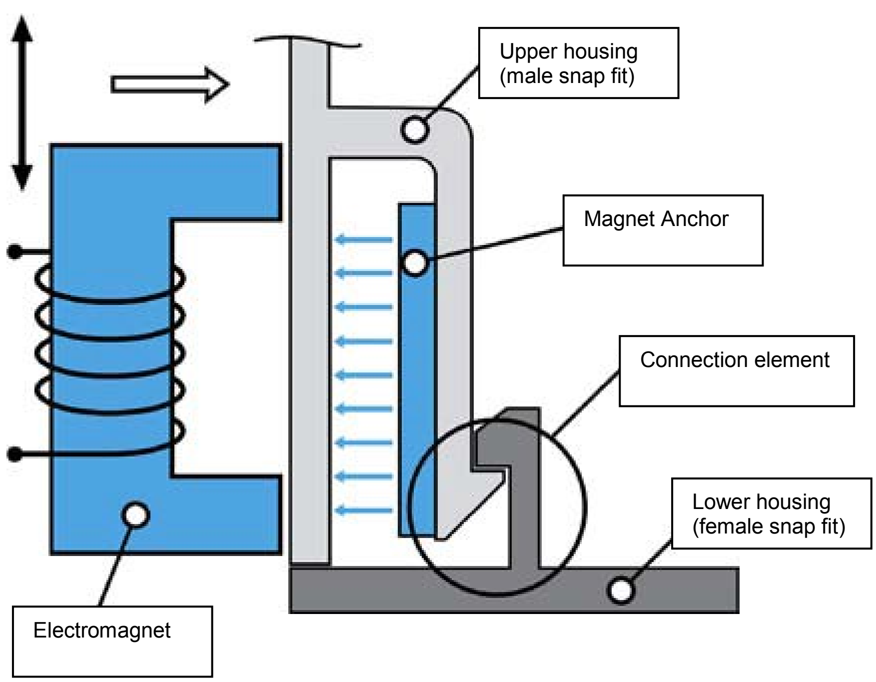
Physical Effect:

Electrical field passes through ferrite material produce magnetic force. **Active disassembly concept**:

Magnetic force produced by electrical field is used to pull snap fit arm which has a magnetic strip

Joint description

Electromagnets can be used as a trigger for disassembly where snap-fits are unreachable, When a magnet anchor has been attached to the flexible part of a snap-fit, the presence of an electromagnet triggers disassembly.



Appendix 4-B: Tool #4: Substance-Field standard solutions

Sources: (Terninko, et al., 2000), (Mao, et al., 2007)

Class 1: Improving the system with no or little change	
1.1. Improving the performance of an inadequate system	
1	**1.1.1. Complete an incomplete model . If there is only an object S1, add a second object S2 and an interaction (field) F.**
2	**1.1.2. The system cannot be changed but a permanent or temporary additive is acceptable. Incorporate an internal additive in either S1or S2.**
3	**1.1.3. As in 1.1.2, but use a permanent or temporary external additive S3 to change either S1or S2.**
4	**1.1.4. As in 1.1.2, but use a resource from the environment as the additive, either internally or externally.**
5	**1.1.5. As in 1.1.2, but modify or change the environment of the system.**
6	**1.1.6. Precise control of small amounts is difficult to achieve. Control small quantities by applying and removing a surplus.**
7	**1.1.7. If a moderate field can be applied which is insufficient for the desired effect, and a greater field will damage the system, the larger magnitude field can be applied to another element which can be linked to the original. Likewise, a substance that cannot take the full action directly but can achieve the desired effect through linkage to another substance can be used.**
8	**1.1.8. A pattern of large/strong and small/weak effects is required. The locations requiring the smaller effects can be protected by a substance S3.**
1.2. Eliminating or neutralizing harmful effects.	
1	**1.2.1. Useful and harmful effects exist in the current design. It is not necessary for S1 and S2 to be in direct contact. Remove the harmful effect by introducing S3.**
2	**Similar to 1.2.1., but new substances cannot be added. Remove the harmful effect by modifying S1 or S2. This solution includes adding "nothing"—voids, hollows, vacuum, air, bubbles, foam, etc., or adding a field that acts like an additional substance.**
3	**1.2.3. The harmful action is caused by a field. Introduce an element S3 to absorb the harmful effects.**
4	**1.2.4. Useful and harmful effects exist in a system in which the elements S1 and S2 must be in contact. Counteract the harmful effect of F1 by having F2 neutralize the harmful effect or gain an additional useful effect**
5	**1.2.5. A harmful effect may exist because of magnetic properties of an element in a system. The effect can be removed by heating the magnetic substance above its Curie point, or by introducing an opposite magnetic field.**
Class 2. Developing the Substance-Field System	
1. Transition to the Complex Su-Field Models	
1	**2.1.1. Chain Su-Field Model: Convert the single model to a chained model by having S2 with F1 applied to S3 which in turn applies F2 to S1. The sequence of two models can be independently controlled.**
2	**2.1.2. Double Su-Field Model: A poorly controlled system needs to be improved but you may not change the elements of the existing system. A second field can be applied to S2.**

2.2. Forcing the Su-Field Models	
1	**Replace or add to the poorly controlled field with a more easily controlled field. Going from a gravitational field to a mechanical field provides more control as does going from mechanical means to electrical or mechanical to magnetic. This is one of the patterns of evolution of systems progressing from objects in physical contact to actions done by fields.**
4	**Change S2 from a macro level to a micro level, i.e., instead of a rock consider particles. This standard is actually the pattern of evolution from a macro- to micro-level.**
5	**2.2.3. Change S2 to a porous or capillary material that will allow gas or liquid to pass**
6	**2.2.4. Make the system more flexible or adaptable; becoming more dynamic is another pattern of evolution. The common transition is from a solid to a hinged system to continuous flexible systems.**
7	**2.2.5. Change an uncontrolled field to a field with predetermined patterns that may be permanent or temporary.**
2.3. Controlling the frequency to match or mismatch the natural frequency of one or both	
1	**.3.1. Matching or mismatching the frequency of F and S1 or S2**
2	**2.3.2. Matching the rhythms of F1 and F2.**
4	**2.3.3. Two incompatible or independent actions can be accomplished by running each during the down time of the other.**
2.4. Integrating ferromagnetic material and magnetic fields is an effective way to improve the performance of a system. In Su-field models, the magnetic field due to a ferromagnetic material is given the special designation Fe-field, or FFe.	
1	**2.4.1. Add ferromagnetic material and/or a magnetic field to the system.**
2	**2.4.2. Combine 2.2.1 (going to more controlled fields) and 2.4.1 (using ferromagnetic materials and magnetic fields).**
3	**2.4.3. Use a magnetic liquid. Magnetic liquids are a special case of 2.4.2. Magnetic liquids are colloidal ferromagnetic particles suspended in kerosene, silicone or water.**
4	**Use capillary structures that contain magnetic particles or liquid.**
5	**2.4.5. Use additives (such as a coating) to give a non-magnetic object magnetic properties. May be temporary or permanent.**
6	**2.4.6. Introduce ferromagnetic materials into the environment, if it is not possible to make the object magnetic.**
7	**2.4.7. Use natural phenomena (such as alignment of objects with the field, or loss of ferromagnetism above the Curie point.)**
8	**2.4.8. Use a dynamic, variable, or self-adjusting magnetic field.**
9	**2.4.9. Modify the structure of a material by introducing ferromagnetic particles, then apply a magnetic field to move the particles. More generally, the transition from an unstructured system to a structured one, or vice versa, depending on the situation.**
10	**2.4.10. Matching the rhythms in the Fe-field models. In macro-systems, this is the use of mechanical vibration to enhance the motion of ferromagnetic particles. At the molecular and atomic levels, material composition can be identified by the spectrum of the resonance frequency of electrons in response to changing frequencies of a magnetic field.**
11	**2.4.11. Use electric current to create magnetic fields, instead of using magnetic particles.**
12	**2.4.12. Rheological liquids have viscosity controlled by an electric field. They can be used in combination with any of the methods here. They can mimic liquid/solid phase transitions.**
Class 3. System Transitions	
3.1. Transition to the Bi- and Poly-Systems	
1	**3.1.1. System transition by creating the bi- and poly-systems.**
2	**3.1.2. Improving links in the bi- and poly-systems.**

3	3.1.3. System transition by increasing the differences between elements.
4	3.1.4. Simplification of the bi- and poly-systems.
5	3.1.5. System transition by opposite features of the whole and parts.
3.2. Transition to the Micro-Level	
1	3.2.1. System transition 2: transition to the micro-level
Class 4: Un related	
Class 5. Methods for Simplifying and Improving the Standard Solutions.	
5.1. Introducing Substances	
1	5.1.1.1. Use "nothing" –add air, vacuum, .bubbles, foam, voids, hollows, clearances, capillaries, pores, holes, voids, etc
2	5.1.1.2. Use a field instead of a substance.
3	5.1.1.3. Use an external additive instead of an internal one.
45	5.1.1.4. Use a small amount of a very active additive.
6	5.1.1.5. Concentrate the additive at a specific location.
7	5.1.1.6. Introduce the additive temporarily.
8	5.1.1.7. Use a copy or model of the object in which additives can be used, instead of the original object, if additives are not permitted in the original. In modern use, this would include the use of simulations, and copies of the additives.
9	5.1.1.8. Introduce a chemical compound which reacts, yielding the desired elements or compounds, where introducing the desired material would be harmful.
10	5.1.1.9 Obtain the required additive by decomposition of either the environment or the object itself.
11	5.1.2. Divide the elements into smaller units.
12	5.1.3. The additive eliminates itself after use.
13	5.1.4. Use "nothing" if circumstances do not permit the use of large quantities of material.
5.2. Use fields	
1	5.2.1. Use one field to cause the creation of another field
2	5.2.2. Use fields that are present in the environment.
3	5.2.3. Use substances that are the sources of fields.
5.3 Phase Transitions	
1	5.3.1. Phase transition 1: substituting the phases
2	5.3.2. Phase transition 2: dual phase state.
3	5.3.3. Phase transition 3: utilizing the accompanying phenomena of the phase change.
4	5.3.4. Phase transition 4: transition to the two-phase state.
5	5.3.5. Interaction of the phases. Increase the effectiveness of the system by inducing an interaction between the elements of the system, or the phases of the system.
5.4. Applying the Natural Phenomena (Also called "Using Physical Effects")	
1	5.4.1. Self-controlled Transitions. If an object must be in several different states, it should transition from one state to the other by itself.
2	.4.2. Strengthening the output field when there is a weak input field. Generally this is done by working near a phase transition point.
5.5. Generating Higher or Lower Forms of Substances	
1	5.5.1. Obtaining the substance particles (ions, atoms, molecules, etc.) by decomposition.
2	5.5.2. Obtaining the substance particles by joining.
3	5.5.3. Applying the Standard Solutions 5.5.1 and 5.5.2. If a substance of a high structural level has to be decomposed, and it cannot be decomposed, start with the substance of the next highest level. Likewise, if a substance must be formed from materials of a low structural level, and it cannot be, then start with the next higher level of structure.

Sources:

1. John Terninko, Ellen DombJoe Miller, (The Seventy-six Standard Solutions, with Examples), (2000) http://www.triz-journal.com/archives/2000/03/d/

2. Xiaoming Mao, Xueqing Zhang and Simaan AbouRizk, (2007), Generalized Solutions for Su-Field Analysis. http://www.triz-journal.com/archives/2007/08/03/

Appendix 4-C: Tool #6: Contradiction table and inventive principles

(Source: http://www.triz40.com/aff_Principles.htm)

Improve ↓ / Deteriorate →	Weight of moving object	Weight of stationary object	Length of moving object	Length of stationary object	Area of moving object	Area of stationary object	Volume of moving object	Volume of stationary object	Force (Intensity)	Stress or pressure	Shape	Stability of the object's composition	Strength	Temperature	Use of energy by moving object	Use of energy by stationary object	Power	Loss of Energy	Loss of Substance	Loss of Information	Loss of Time	Quantity of substance	Object-affected harmful factors	Object-generated harmful factors
Weight of moving object		-	15, 8, 29, 34	-	29, 17, 38, 34	-	29, 2, 40, 28	-	8, 10, 18, 37	10, 36, 37, 40	10, 14, 35, 40	1, 35, 19, 39	28, 27, 18, 40	6, 29, 4, 38	35, 12, 34, 31	-	12, 36, 18, 31	6, 2, 34, 19	5, 35, 3, 31	10, 24, 35	10, 35, 20, 28	3, 26, 18, 31	22, 21, 18, 27	22, 35, 31, 39
Weight of stationary object	-		-	10, 1, 29, 35	-	35, 30, 13, 2	-	5, 35, 14, 2	8, 10, 19, 35	13, 29, 10, 18	13, 10, 29, 14	26, 39, 1, 40	28, 2, 10, 27	28, 19, 32, 22	-	18, 19, 28, 1	15, 19, 18, 22	18, 19, 28, 15	5, 8, 13, 30	10, 15, 35	10, 20, 35, 26	19, 6, 18, 26	2, 19, 22, 37	35, 22, 1, 39
Length of moving object	8, 15, 29, 34	-		-	15, 17, 4	-	7, 17, 4, 35	-	17, 10, 4	1, 8, 35	1, 8, 10, 29	1, 8, 15, 34	8, 35, 29, 34	10, 15, 19	8, 35, 24	-	1, 35	7, 2, 35, 39	4, 29, 23, 10	1, 24	15, 2, 29	29, 35	1, 15, 17, 24	17, 15
Length of stationary object		35, 28, 40, 29	-		-	17, 7, 10, 40	-	35, 8, 2,14	28, 10	1, 14, 35	13, 14, 15, 7	39, 37, 35	15, 14, 28, 26	3, 35, 38, 18	-		12, 8	6, 28	10, 28, 24, 35	24, 26,	30, 29, 14		1, 18	
Area of moving object	2, 17, 29, 4	-	14, 15, 18, 4	-		-	7, 14, 17, 4		19, 30, 35, 2	10, 15, 36, 28	5, 34, 29, 4	11, 2, 13, 39	3, 15, 40, 14	2, 15, 16	19, 32	-	19, 10, 32, 18	15, 17, 30, 26	10, 35, 2, 39	30, 26	26, 4	29, 30, 6, 13	22, 33, 28, 1	17, 2, 18, 39
Area of stationary object	-	30, 2, 14, 18	-	26, 7, 9, 39	-		-		1, 18, 35, 36	10, 15, 36, 37		2, 38	40	35, 39, 38	-		17, 32	17, 7, 30	10, 14, 18, 39	30, 16	10, 35, 4, 18	2, 18, 40, 4	27, 2, 39, 35	22, 1, 40
Volume of moving object	2, 26, 29, 40	-	1, 7, 4, 35	-	1, 7, 4, 17	-		-	15, 35, 36, 37	6, 35, 36, 37	1, 15, 29, 4	28, 10, 1, 39	9, 14, 15, 7	34, 39, 10, 18	35	-	35, 6, 13, 18	7, 15, 13, 16	36, 39, 34, 10	2, 22	2, 6, 34, 10	29, 30, 7	22, 21, 27, 35	17, 2, 40, 1
Volume of stationary object	-	35, 10, 19, 14	19, 14	35, 8, 2, 14	-		-		2, 18, 37	24, 35	7, 2, 35	34, 28, 35, 40	9, 14, 17, 15	35, 6, 4	-		30, 6		10, 39, 35, 34		35, 16, 32 18	35, 3	34, 39, 19, 27	30, 18, 35, 4
Force (Intensity)	8, 1, 37, 18	18, 13, 1, 28	17, 19, 9, 36	28, 10	19, 10, 15	1, 18, 36, 37	15, 9, 12, 37	2, 36, 18, 37		18, 21, 11	10, 35, 40, 34	35, 10, 21	35, 10, 14, 27	35, 10, 21	19, 17, 10	1, 16, 36, 37	19, 35, 18, 37	14, 15	8, 35, 40, 5		10, 37, 36	14, 29, 18, 36	1, 35, 40, 18	13, 3, 36, 24
Stress or pressure	10, 36, 37, 40	13, 29, 10, 18	35, 10, 36	35, 1, 14, 16	10, 15, 36, 28	10, 15, 36, 37	6, 35, 10	35, 24	36, 35, 21		35, 4, 15, 10	35, 33, 2, 40	9, 18, 3, 40	35, 39, 19, 2	14, 24, 10, 37		10, 35, 14	2, 36, 25	10, 36, 3, 37		37, 36, 4	10, 14, 36	22, 2, 37	2, 33, 27, 18
Shape	8, 10, 29, 40	15, 10, 26, 3	29, 34, 5, 4	13, 14, 10, 7	5, 34, 4, 10		14, 4, 15, 22	7, 2, 35	35, 10, 37, 40	34, 15, 10, 14		33, 1, 18, 4	30, 14, 10, 40	22, 14, 19, 32	2, 6, 34, 14		4, 6, 2	14	35, 29, 3, 5		14, 10, 34, 17	36, 22	22, 1, 2, 35	35, 1
Stability of the object's composition	21, 35, 2, 39	26, 39, 1, 40	13, 15, 1, 28	37	2, 11, 13	39	28, 10, 19, 39	34, 28, 35, 40	10, 35, 21, 16	2, 35, 40	22, 1, 18, 4		17, 9, 15	35, 1, 32	13, 19	27, 4, 29, 18	32, 35, 27, 31	14, 2, 39, 6	2, 14, 30, 40		35, 27	15, 32, 35	35, 24, 30, 18	35, 40, 27, 39

Improve \ Deteriorate	Weight of moving object	Weight of stationary object	Length of moving object	Length of stationary object	Area of moving object	Area of stationary object	Volume of moving object	Volume of stationary object	Force (Intensity)	Stress or pressure	Shape	Stability of the object's composition	Strength	Temperature	Use of energy by moving object	Use of energy by stationary object	Power	Loss of Energy	Loss of Substance	Loss of Information	Loss of Time	Quantity of substance	Harmful factors affected object	Object-generated harmful factors
Strength	1, 8, 40, 15	40, 26, 27, 1	1, 15, 8, 35	15, 14, 28, 26	3, 34, 40, 29	9, 40, 28	10, 15, 14, 7	9, 14, 17, 15	10, 18, 3, 14	10, 3, 18, 40	10, 30, 35, 40	13, 17, 35		30, 10, 40	19, 35, 10	35	10, 26, 35, 28	35	35, 28, 31, 40		29, 3, 28, 10	29, 10, 27	18, 35, 37, 1	15, 35, 22, 2
Temperature	36, 22, 6, 38	22, 35, 32	15, 19, 9	15, 19, 9	3, 35, 39, 18	35, 38	34, 39, 40, 18	35, 6, 4	35, 10, 3, 21	35, 39, 19, 2	14, 22, 19, 32	1, 35, 32	10, 30, 22, 40		19, 15, 3, 17		2, 14, 17, 25	21, 17, 35, 38	21, 36, 29, 31		35, 28, 21, 18	3, 17, 30, 39	22, 33, 35, 2	22, 35, 2, 24
Use of energy by moving object	12, 18, 28, 31	-	12, 28	-	15, 19, 25	-	35, 13, 18	-	16, 26, 21, 2	23, 14, 25	12, 2, 29	19, 13, 17, 24	5, 19, 9, 35	19, 24, 3, 14		-	6, 19, 37, 18	12, 22, 15, 24	35, 24, 18, 5		35, 38, 19, 18	34, 23, 16, 18	1, 35, 6, 27	2, 35, 6
Use of energy by stationary object	-	19, 9, 6, 27	-		-		-		36, 37			27, 4, 29, 18	35		-				28, 27, 18, 31			3, 35, 31	10, 2, 22, 37	19, 22, 18
Power	8, 36, 38, 31	19, 26, 17, 27	1, 10, 35, 37		19, 38	17, 32, 13, 38	35, 6, 38	30, 6, 25	26, 2, 36, 35	22, 10, 35	29, 14, 2, 40	35, 32, 15, 31	26, 10, 28	2, 14, 17, 25	16, 6, 19, 37			10, 35, 38	28, 27, 18, 38	10, 19	35, 20, 10, 6	4, 34, 19	19, 22, 31, 2	2, 35, 18
Loss of Energy	15, 6, 19, 28	19, 6, 18, 9	7, 2, 6, 13	6, 38, 7	15, 26, 17, 30	17, 7, 30, 18	7, 18, 23	7	36, 38			14, 2, 39, 6	26	19, 38, 7			3, 38		35, 27, 2, 37	19, 10	10, 18, 32, 7	7, 18, 25	21, 22, 35, 2	21, 35, 2, 22
Loss of substance	35, 6, 23, 40	35, 6, 22, 32	14, 29, 10, 39	10, 28, 24	35, 2, 10, 31	10, 18, 39, 31	1, 29, 30, 36	3, 39, 18, 31	14, 15, 18, 40	3, 36, 37, 10	29, 35, 3, 5	2, 14, 30, 40	35, 28, 31, 40	21, 36, 39, 31	35, 18, 24, 5	28, 27, 12, 31	28, 27, 18, 38	35, 27, 2, 31			15, 18, 35, 10	6, 3, 10, 24	33, 22, 30, 40	10, 1, 34, 29
Loss of Information	10, 24, 35	10, 35, 5	1, 26	26	30, 26	30, 16		2, 22									10, 19	19, 10			24, 26, 28, 32	24, 28, 35	22, 10, 1	10, 21, 22
Loss of Time	10, 20, 37, 35	10, 20, 26, 5	15, 2, 29	30, 24, 14, 5	26, 4, 5, 16	10, 35, 17, 4	2, 5, 34, 10	35, 16, 32, 18	10, 37, 36, 5	37, 36, 4	4, 10, 34, 17	35, 3, 22, 5	29, 3, 28, 18	35, 29, 21, 18	35, 38, 19, 18	1	35, 20, 10, 6	10, 5, 18, 32	35, 18, 10, 39	24, 26, 28, 32		35, 38, 18, 16	35, 18, 34	35, 22, 18, 39
Quantity of substance/the matter	35, 6, 18, 31	27, 26, 18, 35	29, 14, 35, 18		15, 14, 29	2, 18, 40, 4	15, 20, 29		35, 14, 3	10, 36, 14, 3	35, 14	15, 2, 17, 40	14, 35, 34, 10	3, 17, 39	34, 29, 16, 18	3, 35, 31	35	7, 18, 25	6, 3, 10, 24	24, 28, 35	35, 38, 18, 16		35, 33, 29, 31	3, 35, 40, 39
Harmful factors affected object	22, 21, 27, 39	2, 22, 13, 24	17, 1, 39, 4	1, 18	22, 1, 33, 28	27, 2, 39, 35	22, 23, 37, 35	34, 39, 19, 27	13, 35, 39, 18	22, 2, 37	22, 1, 3, 35	35, 24, 30, 18	18, 35, 37, 1	22, 33, 35, 2	1, 24, 6, 27	10, 2, 22, 37	19, 22, 31, 2	21, 22, 35, 2	33, 22, 19, 40	22, 10, 2	35, 18, 34	35, 33, 29, 31		
Object-generated harmful factors	19, 22, 15, 39	35, 22, 1, 39	17, 15, 16, 22		17, 2, 18, 39	22, 1, 40	17, 2, 40	30, 18, 35, 4	35, 28, 1, 40	2, 33, 27, 18	35, 1	35, 40, 27, 39	15, 35, 22, 2	22, 35, 2, 24	2, 35, 6	19, 22, 18	2, 35, 18	21, 35, 2, 22	10, 1, 34	10, 21, 29	1, 22	3, 24, 39, 1		

Appendix 4-C: Tool #6: Contradiction table and inventive principles (Continue)

Inventive principles

1. Segmentation
Divide an object into independent parts.
Make an object easy to disassemble.
Increase the degree of fragmentation or segmentation.
2. Taking out
Separate an interfering part or property from an object, or single out the only necessary part (or property) of an object.
3. Local quality
Change an object's structure from uniform to non-uniform, change an external environment (or external influence) from uniform to non-uniform.
Make each part of an object function in conditions most suitable for its operation.
Make each part of an object fulfill a different and useful function.
4. Asymmetry
Change the shape of an object from symmetrical to asymmetrical.
If an object is asymmetrical, increase its degree of asymmetry.
5. Merging
Bring closer together (or merge) identical or similar objects, assemble identical or similar parts to perform parallel operations.
Make operations contiguous or parallel; bring them together in time.
6. Universality
Make a part or object perform multiple functions; eliminate the need for other parts.
7. Nested doll
Place one object inside another; place each object, in turn, inside the other.
Make one part pass through a cavity in the other.
8. Anti-weight
To compensate for the weight of an object, merge it with other objects that provide lift.
To compensate for the weight of an object, make it interact with the environment (e.g. use aerodynamic, hydrodynamic, buoyancy and other forces).
9. Preliminary anti-action
If it will be necessary to do an action with both harmful and useful effects, this action should be replaced with anti-actions to control harmful effects.
Create beforehand stresses in an object that will oppose known undesirable working stresses later on.
10. Preliminary action
Perform, before it is needed, the required change of an object (either fully or partially).
Pre-arrange objects such that they can come into action from the most convenient

place and without losing time for their delivery.
11. Beforehand cushioning
Prepare emergency means beforehand to compensate for the relatively low reliability of an object.
12. Equipotentiality
In a potential field, limit position changes (e.g. change operating conditions to eliminate the need to raise or lower objects in a gravity field).
13. The other way round
Invert the action(s) used to solve the problem (e.g. instead of cooling an object, heat it).
Make movable parts (or the external environment) fixed, and fixed parts movable.
Turn the object (or process) 'upside down'.
14. Spheroidality - Curvature
Instead of using rectilinear parts, surfaces, or forms, use curvilinear ones; move from flat surfaces to spherical ones; from parts shaped as a cube (parallelepiped) to ball-shaped structures.
Use rollers, balls, spirals, domes.
Go from linear to rotary motion, use centrifugal forces.
15. Dynamics
Allow (or design) the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition.
Divide an object into parts capable of movement relative to each other.
If an object (or process) is rigid or inflexible, make it movable or adaptive.
16. Partial or excessive actions
If 100 percent of an object is hard to achieve using a given solution method then, by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve.
17. Another dimension
To move an object in two- or three-dimensional space.
Use a multi-story arrangement of objects instead of a single-story arrangement.
Tilt or re-orient the object, lay it on its side.
Use 'another side' of a given area.
18. Mechanical vibration
Cause an object to oscillate or vibrate.
Increase its frequency (even up to the ultrasonic).
Use an object's resonant frequency.
Use piezoelectric vibrators instead of mechanical ones.
Use combined ultrasonic and electromagnetic field oscillations.
19. Periodic action
Instead of continuous action, use periodic or pulsating actions.
If an action is already periodic, change the periodic magnitude or frequency.
Use pauses between impulses to perform a different action.
20. Continuity of useful action
Carry on work continuously; make all parts of an object work at full load, all the time.
Eliminate all idle or intermittent actions or work.
21. Skipping

Conduct a process , or certain stages (e.g. destructible, harmful or hazardous operations) at high speed.
22. *Blessing in disguise* or *Turn Lemons into Lemonade*
Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect.
Eliminate the primary harmful action by adding it to another harmful action to resolve the problem.
Amplify a harmful factor to such a degree that it is no longer harmful.
23. Feedback
Introduce feedback (referring back, cross-checking) to improve a process or action.
If feedback is already used, change its magnitude or influence.
24. 'Intermediary'
Use an intermediary carrier article or intermediary process.
Merge one object temporarily with another (which can be easily removed).
25. Self-service
Make an object serve itself by performing auxiliary helpful functions
Use waste resources, energy, or substances.
26. Copying
Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies.
Replace an object, or process with optical copies.
If visible optical copies are already used, move to infrared or ultraviolet copies.
27. Cheap short-living objects
Replace an inexpensive object with a multiple of inexpensive objects, comprising certain qualities (such as service life, for instance).
28. Mechanics substitution
Replace a mechanical means with a sensory (optical, acoustic, taste or smell) means.
Use electric, magnetic and electromagnetic fields to interact with the object.
Change from static to movable fields, from unstructured fields to those having structure.
Use fields in conjunction with field-activated (e.g. ferromagnetic) particles.
29. Pneumatics and hydraulics
Use gas and liquid parts of an object instead of solid parts (e.g. inflatable, filled with liquids, air cushion, hydrostatic, hydro-reactive).
30. Flexible shells and thin films
Use flexible shells and thin films instead of three dimensional structures
Isolate the object from the external environment using flexible shells and thin films.
31. Porous materials
Make an object porous or add porous elements (inserts, coatings, etc.).
If an object is already porous, use the pores to introduce a useful substance or function.
32. Color changes
Change the color of an object or its external environment.
Change the transparency of an object or its external environment.
33. Homogeneity
Make objects interacting with a given object of the same material (or material with

identical properties).
34. Discarding and recovering
Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation.
Conversely, restore consumable parts of an object directly in operation.
35. Parameter changes
Change an object's physical state (e.g. to a gas, liquid, or solid.)
Change the concentration or consistency.
Change the degree of flexibility.
Change the temperature.
36. Phase transitions
Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.).
37. Thermal expansion
Use thermal expansion (or contraction) of materials.
If thermal expansion is being used, use multiple materials with different coefficients of thermal expansion.
38. Strong oxidants
Replace common air with oxygen-enriched air.
Replace enriched air with pure oxygen.
Expose air or oxygen to ionizing radiation.
Use ionized oxygen.
Replace ozonized (or ionized) oxygen with ozone.
39. Inert atmosphere
Replace a normal environment with an inert one.
Add neutral parts, or inert additives to an object.
40. Composite materials
Change from uniform to composite (multiple) materials.

Source: http://www.triz40.com/aff_Principles.htm

Appendix 4-D: Tool #10: Triggering fields and possible physical effects

Triggering field	Physical effect	AD design concept
Mechanical	Gravitation (Pahl&Beitz,1996) (Duflou et al.,2006)	1. Acceleration: No concept has been suggested.
	Inertia (Pahl&Beitz,1996) (Duflou et al.,2006)	1. Mechanical vibration: Fasteners Collapse at certain vibration frequency. (Willems B., et al,2007) 2. Sound waves: No concept has been suggested.
	Centrifugal force (Pahl&Beitz,1996) (Duflou et al.,2006)	1.Centrifugal force cause snap fits to unlock/unsnap (Willems B., et al,2007) 2.Centrifugal force cause ball-socket joint to open (Ziout A., et al, 2009)
Hydraulic	Hydrostatic (Pahl&Beitz,1996)	Appendix D Tool # 10: Triggering Fields and possible physical effect
	Hydro dynamic (Pahl&Beitz,1996) (Duflou et al.,2006)	1.Water jet: No concept has been suggested.
Pneumatic	Aerostatic (Pahl&Beitz,1996)	
	Aerodynamic (Pahl&Beitz,1996)	1.Compressed air: High ambient pressure is used to unfasten specially designed snap fit, the snap fit is made of a closed air-filled cavity and locking feature. (Willems B., et al,2007)
Electrical	Electrostatic (Pahl&Beitz,1996)	
	Electrodynamics (Pahl&Beitz,1996) (Duflou et al.,2006)	Electric current
	Inductive (Pahl&Beitz,1996)	
	Capacitative (Pahl&Beitz,1996)	
	Piezoelectric (Pahl&Beitz,1996)	

Triggering field	**Physical effect**	**AD design concept**
Magnetic	Ferromagnetic (Pahl&Beitz,1996)	
	Electromagnetic (Pahl&Beitz,1996) (Duflou et al.,2006)	1.Magnetising vs. demagnetizing. 2.Magnetic ray interference (MRI) 3.Magneto-rheological materials. (Willems B., et al,2007)
Optical	Polarization (Pahl&Beitz,1996)	
	Infra-red UV-radiation (Pahl&Beitz,1996)(Duflou et al.,2006)	1. Photo-induced phase-transition material
	Interference (Pahl&Beitz,1996)	
Thermal	Expansion (Pahl&Beitz,1996)	1.Shape memory material: Heat cause shape change to fasteners made of Shape memory materials. (Chiodo et al., 1998). 2.Water evaporation: evaporation of trapped water in a joint causes destructive disassembly of the joint. (Kasa and Suga, 1999). 3.Freezing element: Water expansion due to freezing cause unlocking of water filled cavity in snap fit joint. (Willems B., et al,2007)
	Bimetal effect (Pahl&Beitz,1996)	1.Bi-material snap fit: the difference in thermal expansion open bi-material snap fit. (Willems B., et al,2007) and (Li et al., 2001)
	Heat transfer (Pahl&Beitz,1996) (Duflou et al.,2006)	1.Joule effect 2.Radiation 3.Microwaves 4.Submerging in hot water
Chemical	Combustion (Pahl&Beitz,1996)	

Triggering field	Physical effect	AD design concept
	Absorption	1.Hydrogen embitterment: Hydrogen absorption of metallic alloy cause destructive disassembly of the joint. (Suga and Hosoda, 2000).
	Oxidation (Pahl&Beitz,1996)	
	Reduction (Pahl&Beitz,1996) (Duflou et al.,2006)	1. Reagent in surrounding atmosphere. 2.Water soluble Fastener: soluble fasteners where the locking mechanism vanishes (Willems B., et al,2007)
	Combination (Pahl&Beitz,1996)	
	Endothermic (Pahl&Beitz,1996)	
	Exothermic (Pahl&Beitz,1996)	
Nuclear	Radiation (Pahl&Beitz,1996)	
	Isotopes (Pahl&Beitz,1996)	
Biological	Decomposition (Pahl&Beitz,1996)	
	Fermentation (Pahl&Beitz,1996) (Duflou et al.,2006)	1.Presence of bacteria
	Putrefaction (Pahl&Beitz,1996) (Duflou et al.,2006)	1. Enzymes including chemical reactions.

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Academic and research experience:

Research engineer at University of Windsor, Windsor, Canada

I do the following research activities:

•Conducting research on product active disassembly.

•Conducting research on sustainability assessment in active disassembly.

•Conducting collaborative research on manufacturing systems as a team member in Product lifecycle management (PLM) lab

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Industrial experience:

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Publications:

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