ACLODS – A holistic framework for environmentally friendly product lifecycle design

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Abstract
Design for Environment (DfE) is an approach to design where all the environmental impacts of a product are considered over the entire life cycle of a product. Most DfE tools are conceptual in nature, and there is little adoption of these in industry. This paper discusses the development of a holistic framework that should help in both generation and evaluation of environmentally friendly product life cycle proposals. The overall approach is to investigate literature to analyse the existing guidelines, methods, tools and methodologies for environmentally friendly product design, in order to identify the requirements for a holistic framework for design to reduce the environmental impact of a product lifecycle proposal. An ideal framework to satisfy these requirements is proposed.

Keywords:
Life Cycle Design, Product Development, Design for Environment, Life Cycle Thinking

1 INTRODUCTION

Products make a substantial impact on environment. The ratio of product mass to waste mass directly or indirectly produced as a result of the product during its life cycle is about one to twenty [1]. These wastes are thrown into the environment in each stage of the product life cycle from raw material extraction to product retirement. The lifecycle principle, where the whole impact of a product across its life is to be examined (from 'cradle to grave') has been gaining importance in product development [2]. In product development, we need to consider environment as one of the major criteria along with performance, quality and cost. Environment is gaining importance as an evaluation criterion because of government regulations, competition and customers' requirement.

A number of guidelines have been proposed for assisting designers in the choice of materials [3], processes, energy [4], end of life processes [5, 6] etc. These guidelines primarily aid the end of life processes: disassembly, reuse, and recycling. Later, the efforts became directed on product life cycle as the basis for thinking, addressing all stages of a product's life cycle, from material to after-use. There are many collections of general guidelines like [7]. These, however, are unlikely to be directly useful in the day to day product development activities because these are very generic and abstract in nature. All the reported work is on particular lifecycle phases or for a particular design stage or for a particular criterion. But we in reality the decisions taken are considering multiple criteria throughout design for whole lifecycle of the product. There is a need of a holistic framework that can be applied through whole design process for both synthesis and analysis of product lifecycles for multiple criteria to be used by designers.

2 OBJECTIVES AND METHODOLOGY

2.1 Objectives

The objectives of this paper are to:

- Establish the general need and specific requirements for a holistic framework for environmentally friendly product lifecycle design.
- Propose a holistic framework for environmentally friendly product lifecycle design to satisfy these requirements.

2.2 Methodology

In order to establish the general need for a holistic framework for environmentally friendly product lifecycle design, a detailed literature survey has been undertaken. In the survey, existing guidelines, frameworks, tools and methods for supporting environmentally friendly product lifecycle design (EFPLD) have been reviewed by analysing their salient features, advantages and disadvantages, with the aim of identifying specific requirements for a holistic framework for environmentally friendly product lifecycle design (see section 3). In addition, the outcomes from the series of design experiments have been analysed to understand the above requirements in detail (see section 4). Based on the results of these, the dimensions of a holistic framework for product lifecycle design is proposed (see section 5). The current frameworks and approaches are mapped on the proposed framework in order to identify areas where further work is needed before such a framework could be implemented for supporting environmentally benign product life cycle development (see section 6).

3 LITERATURE REVIEW

There are two major types of tools available: analysis tools which are useful in finding the areas where the impact is substantial and where the existing product is weak, and synthesis tools which are useful in supporting development of solutions with reduced environmental impacts by helping a designer to generate appropriate alternatives.

The major barriers against environmentally oriented product development as listed by [8] are: low knowledge of the environmental impacts of specific products, low priority of environmental goals in product design, cost orientation, and lack of methods for early planning.

For assessment of environmental impacts of a product in a specific phase of its life cycle, it is prerequisite that details of all the specific processes that are present in that life cycle phase are available. The use of ecodesign tools may lead not only to environmental improvements but also towards options for cost reduction and new innovative directions [9].

Harsch in [10] proposed a tool called Life Cycle Simulation (LCS) which considers the lifecycle phases of material, production, use, after-use, and considers Performance, Cost and Environment as criteria for evaluation.

Kortman et al. [11] developed Environmental tool box which consists of task clarification, general design and detail design as design stages, analysis and improvement as activities, material, production, use and after-use as lifecycle phases, and performance, cost, manufacturability, safety, styling and environment as product criteria.

Hernández and Hernández [12] presented a tool Total Computer Aided Engineering (TCAE) which supports analysis in detailed design stages for material, production, use and after-use phases, considering performance, cost and environment as criteria for analyses.

Nissen [13] proposed The ideal-eco-product approach which deals with generating, evaluating and selecting objectives and solutions, for material, production, transport, use and after-use phases, in terms of environmental impact, cost and functionality as evaluation criteria.

Senthil et al. [14] developed Life Cycle Environmental Cost Analysis (LCECA) which supports sensitivity analysis of products or parts for material, production and after-use phases, in terms of environmental impact and cost criteria.

Anderl and Weißmantel [15] proposed a methodology called Design for Environment for the early stages of design, considering environmental impact in material, production, use and after-use phases, for analysis and improvement in terms of geometry, material and weight as criteria.

Roche et al. [16] proposed PAL framework which consists of requirements design, function design, general design and detail design as design stages, and analysis, synthesis and evaluation as activities, for material, production, use and after-use phases, based on environmental impact and structure complexity as criteria.

Spath et al. [17] developed two tools called REKON and LICCOS using which parts, assemblies and products can be developed during idea and conceptual design stage, considering material, production, use and disposal phases for environmental impact and cost criteria.

Wimmer [18] developed Ecodesign Checklist Method (ECM) that supports generation and analysis of both part- and product-level requirements for functionality and environmental impact as criteria, for the whole product lifecycle.

McAloone and Evans [19] presented the need and proposed the DEsign for Environment Decision Support (DEEDS) which is meant to support identification and evaluation of problems and requirements associated with material, production, use and after-use phases for all design stages.

Grüner and Birkhofer [20] presented a methodology called Integrated Product and Process Development (IPPD) for analysis and synthesis of parts and products with respect to material, production, use, recycling and disposal phases, considering functionality and environmental impact as criteria for trade-off during all design stages.

Reinhold et al. [21] developed a tool called Total Product Life-Cycle Cost Optimisation (TOPROCO) for analysis of parts, relationships and products using environmental impact cost and other costs during the after-use phase as criteria, in all stages of design.

Gómez et al. [4] developed a framework called Design for Energy Efficiency (EFEnEf) which deals with analysis, synthesis, evaluation and implementation of energy related environmental impacts, costs, quality and technical issues, in material, manufacturing, distribution, use and disposal phases, for both requirements and solutions.

Suiran et al. [22] proposed a method called Life Cycle Optimisation Design which considers manufacturing, use and end of life phases for generation, evaluation and selection of problems and solutions in all design stages, and insists on considering energy consumption, waste disposal, cost, functionality and quality as criteria.

Otto et al. [23] developed a tool to integrate CAD models with LCA which is used for analysis and improvement of parts, assemblies and products in material, manufacture, use and after-use phases with respect to environmental impact as criterion, and can be used in the detailed design stage.

Lindahl [24] developed a tool called Environmental Effect Analysis (EEA) which is useful in task clarification and conceptual design stages for evaluation, selection and follow up activities on parts and products, from the point of view of functionality and environmental impact criteria applicable during procurement, production, use and after-use phases of the product lifecycle.

Faneye and Anderl [25] proposed a tool called Life Cycle Process Knowledge which considers features, parts, assemblies and products for pre-manufacture, manufacture, use, recycle and disposal phases of their life cycle.

Park and Seo [26] developed a computer aided tool called Knowledge-based approximate life cycle assessment system (KALCS) which is used in embodiment and detailed design stages for evaluation and improvement of design solutions in material, production and use phases from the points of view of performance, cost, recyclability, environmental impact and efficiency.

Kurukawa and Kiriyama [27] proposed a framework called Green Life Cycle Model for generation of solutions for parts and assemblies in conceptual, embodiment and detail design stages with respect to manufacturing, use, disposal and recycle phases considering cost and manufacturability as criteria.

Pascale et al. [28] developed a tool called Ecobilan Group's Environmental Information & Management Explorer (EIME) for parts, assemblies and their relationships in task clarification and detailed design stages for generation and evaluation of requirements and solutions with respect to environmental impacts in manufacturing, distribution, use and end of life phases as criteria.

Takata et al. [29] developed a tool called Facility life cycle management for evaluation of parts, assemblies, relationships and features with respect to cost and strength analyses in embodiment and detailed design stages for the use and after-use phases of the product lifecycle.

Rebitzer and Hunkeler [30] proposed a methodology called Life Cycle Costing (LCC) for evaluation of solutions with respect to cost and environmental impact in material, manufacture, use and end of life phases.

Ernzer and Bey [31] presented a framework called Life Cycle Design (LCD) for analysis and synthesis of parts, assemblies, products and plant systems in various design stages for the whole lifecycle with respect to quality, technology, environmental impact and time as criteria.

Dewulf and Duflou [32] developed a system called EcoDesign Knowledge System which is useful for understanding environmental impact-related requirements for parts, assemblies, materials and functions, associated with material, manufacture, use and end of life phases, and for developing these during various design stages.

Maxwell and vanderVorst [33] proposed a method for Sustainable Product and/or Service Development (SPSD) which is used for analysis and synthesis of functions and solutions in task clarification and conceptual design stages from the points of view of functionality, environment, economy, social aspects, quality, market demand, customer requirements, technical feasibility, and compliance with legislation, during the material, production, distribution, consumption and end of life phases of the life cycle.

Nielsen and Wenzel [34] proposed a Procedure based on quantitative LCA for generation, evaluation, selection and update of requirements and solutions in abstract and detailed design stages, considering environmental effects, functionality and cost related to the various lifecycle phases as criteria.

Curran and Schenck [35] presented a Framework for Responsible Environmental Decision Making (FRED) for evaluation of solutions in the various lifecycle phases with respect to environmental impacts, price and performance as evaluation criteria.

One can summarise the following from analyses of the above guidelines, methods, tools, methodologies and frameworks. It is found that the following six dimensions are variously present in the approaches reviewed above:

- **Activities**: There are various activities envisaged to be carried out during each stage of design. Each approach is meant to support one, some or all of these activities.
- **Criteria**: There are various criteria which a product must satisfy. Each existing approach addressed only one or few of these.
- **Lifecycle Phases**: There are various life cycle phases of a product that need to be considered; each approach is designed to support one, few or all of these.
- **Outcomes**: There are various outcomes during a design process that should be supported. Each existing approach applies to only some of these.
- **Design Stages**: Each approach is applicable to one, some or all of the design stages.
- **Product Structure**: There are various aspects to the structure of a product, only some of which are variously addressed by the existing approaches.

The following preliminary sets of specific elements in each of the above six dimensions of the holistic framework are identified:

Activities: generate, evaluate, modify and select.

Criteria: performance, cost, environment, safety, styling, structure, quality, energy consumption, waste disposal, recyclability, efficiency, manufacturability, strength, time, social aspects, market demand, customer requirements, technical feasibility, compliance with legislation, and price.

Lifecycle Phases: material, production, distribution, usage and after-usage.

Outcomes: requirements and solutions.

Design Stages: task clarification, conceptual design, embodiment design and detail design.

Product Structure: product, assembly, relationship, part and feature.

4 DESIGN EXERCISES

In the last section, the preliminary sets of dimensions for the holistic framework have been identified. In this section, analysis of the design exercises are done from the point of view of these six dimensions in order to modify and add further detail to the dimensions of the framework and its elements.

Following is a summary of the design exercises conducted. Of the twenty four design exercises conducted involving 8 designers and 4 problems, all four problems have been solved by different designers using one of the three interventions – general design literature, Environmentally Friendly Design (EFD) literature, a detailed impact assessment software. Out of the twenty four exercises, the sixteen design exercises that used EFD literature and detailed impact assessment software as intervention have been analysed in order to check and consolidate the requirements identified through literature review for the holistic framework, as discussed below.

The recordings of the design exercises were analysed to identify the following:

- The activities performed by the designers;
- The criteria used in the evaluation of a product's lifecycle;
- The lifecycle phases;
- The outcomes of a design process;
- The design stages through which designers proceed in a design process;
- The structure of a product as it evolves through the design process;

The designers followed the "think aloud protocol" while designing, and the whole process was videotaped and transcribed for analysis. The videos and documentations from the design exercises were analysed using video protocol analysis. The transcribed protocol was analysed by coding each utterance using the categories identified from the literature review detailed in Section 3 as the initial basis, and modifying them according to their efficacy in categorising the events captured in the utterances.

Identify the activities performed by the designers during the design stages

The following activities are identified after analysing the exercises: understand, generate, evaluate, modify and select.

Find the criteria of the product lifecycle that need to be considered

The following criteria have been observed after analysing the exercises: functionality, cost, environmental impact, maintainability, efficiency, performance, safety, ergonomics, aesthetics, manufacturability, quality, portability, usability, weight, compactness.

Find the lifecycle phases

The following lifecycle phases are identified after analysing the exercises: material: *extraction, processing* and *delivery*, Production: *manufacturing, assembly* and *in-plant storage*, Distribution: *packaging, loading, transportation, unloading* and *interim storage*, Usage: *installation, use, maintenance* and *repair*, After-usage: *disassembly, collection, transportation, reuse/remanufacture/recycle* and *disposal*.

Find the outcomes in design

Two types of outcomes are identified: requirements and solutions.

Find the different stages which the designers undergo in the design process

The following stages were verified during the analysis of the exercises: task clarification, conceptual design, embodiment design and detailed design.

The structure of a product as it evolves through the design process

Analyses of the outcomes of the exercises resulted in the following product structure and constituents: assemblies: collection of assemblies, sub-assemblies, parts and relationships between them in that particular assembly; subassemblies: collection of parts and relationships between them in that particular subassembly; relations: connection between one or more features of one part and one or more features of another part; parts: smallest (not in size but in that it cannot be divided any further into other parts and relations) physical elements of product; features: different geometrical forms in a part.

5 HOLISTIC FRAMEWORK – A PROPOSAL

It is not the product but its lifecycle which would determine the impact on the environment. There is a need to consider different aspects while developing product lifecycles that are environmentally benign.

5.1 Development of Holistic Framework for EFPLD: ACLODS

From literature we identified activities, criteria, lifecycle phases, outcomes, design stages and product structure dimensions and some of the elements of these. From design exercises these dimensions are consolidated and additional elements like *understand* in the activities dimension, *maintainability, safety, ergonomics, aesthetics, portability, usability, weight, compactness* in the criteria dimension, *manufacturing, assembly, storage, loading, unloading, installation* in the lifecycle dimension, details of the design stages dimension and *subassembly* in the product structure dimension are identified.

Ideally one should consider all the elements of the dimensions identified from literature and design exercises to develop environmentally friendly product lifecycles; a holistic framework should consider all the dimensions and their elements identified above. Figure 1 shows the ACLODS framework which is formed by arranging the first letters of the following dimensions found above: **A**ctivities, **C**riteria, **L**ifecycle phases, **O**utcome, **D**esign stages, **S**tructure.

5.2 Elements in the dimensions of the Framework

- The activities carried out by the designers, i.e. understand, generate, evaluate, modify and select of requirements and solutions should reflect consideration of different issues.
- In a holistic framework, criteria such as functionality, cost, environmental impact, maintainability, efficiency, performance, safety, structure, ergonomics, aesthetics, manufacturability, quality, energy consumption, waste disposal, recyclability, portability, usability, weight, compactness, strength, social aspects, market demand, customer requirements, technical feasibility, legislation compliance and price should be kept in mind through the design process. The list of criteria given here are comprehensive but not necessarily exhaustive; there may be other possible criteria that may have to be considered depending on the specifications and need.
- Designers should design the whole lifecycle of the product consisting of the following phases; material, production, distribution, usage, and after-usage. The material phase consists of extraction, processing, transport in material; the production phase consists of manufacturing and assembly; the distribution phase consists of packaging and transport; the usage phase consists of installation, use and maintenance; and the after-usage phase consists of collection, disassembly, and reuse or remanufacture or recycle or energy recovery or disposal of various portions of the product.
- During any stage of the design process, requirements or solutions should be understood, generated, evaluated, modified or selected (or rejected).
- The designers should take into account the criteria during every stage of the design process i.e., in the task clarification, conceptual design, embodiment design and detail design. When designers are engaged in working on requirements, they try to satisfy the requirements in terms of principles, layouts, sub-functions and final solution.
- Designers would work on product, assembly, sub-assembly, part, relationship and feature during any of the design stages.

6 DISCUSSION

In this section, the approaches reviewed in section 3 are mapped on to the proposed holistic framework, in order to see which areas are already covered by these existing approaches, and which areas are weakly supported and therefore should be improved.

The framework can be viewed in the following ways:

- Activities oriented view
- Criteria oriented view
- Lifecycle oriented view
- Outcome oriented view
- Design stage oriented view
- Structure oriented view

Figure 2 shows the percentage of approaches reviewed that consider the various dimensions of the framework. The approaches are categorised into three different sets a) those in which at-least one element in the dimension under focus is considered, b) those in which some of the elements in the dimension is considered, c) those in which all elements in the dimension is considered.

When at least one element is considered, it can be seen that the lifecycle dimension is considered most, which is not surprising given that literature search is focused primarily on design for environment. The second most considered is the criteria dimension and then the activity dimension. The next most frequently addressed dimension is the design stages, followed by structure; the outcome dimension is considered least frequently.

When some of the elements are considered, it can be seen that the lifecycle dimension is considered most, followed by design stage dimension and then outcome dimension. The next most frequently addressed dimension is criteria, followed by structure and activity dimensions.

When all elements are considered, it can be seen that the outcome dimension is considered most, followed by design stage dimension, and then lifecycle dimension. The next most frequently addressed dimension is the structure. Activity and criteria dimensions are not addressed at all. As per the holistic framework, all elements in all dimensions should be considered; a relatively small proportion of these have been addressed by the reviewed approaches.

Figure 3 shows the percentage of consideration of different elements of each dimensions of the ACLODS framework in reviewed approaches. In the lifecycle dimension, after-usage, production and usage are considered by most of the approaches. In the criteria dimension, environmental impact, cost and functionality are the most frequently considered elements. In the activities dimension, evaluation and generation are considered most. In the design stage dimension, conceptual and detail design stages are considered most, followed by task clarification and embodiment design. In the structure dimension, part is the most frequently considered element, followed by product and assembly. In the outcome dimension, requirements and solutions are considered only in 30% of the approaches.

Table 1 first and second columns show the number of approaches among those reviewed where different dimensions have been simultaneously considered, where a dimension is taken to have been considered if at least any one element in that dimension is addressed (for example outcome dimension is taken as considered if requirement or solution or both are addressed). Table 1 first and third columns show the number of existing approaches in which different dimensions are simultaneously considered, where consideration of a dimension is taken to have happened if all the elements in that dimension are addressed (for example outcome dimension is taken as considered if requirement and solution both are addressed. Table 1 first and fourth columns show the number of approaches reviewed in which simultaneous consideration of different dimensions has taken place, where all the elements in all the dimensions are addressed. It can be seen fewer approaches address many elements in many dimensions. Figure 4 shows the percentage of occurrence of the same. From Table 4.7, we can see that only 3 (i.e. 11%, see Figure 4.9) of the 27 approaches considered all the dimensions (but not necessarily all the elements), only 2 (i.e. 7%, see Figure 4.9) of the 27 approaches considered all the dimensions (with all the elements in one or more dimensions), and none (i.e. 0%, see Figure 4) of the 27 approaches considered all the dimensions (with all the elements in all the dimensions). These are the only combinations we could found from the reviewed approaches.

Figure 4 shows the percentage of occurrence of the various combinations of dimensions of the ACLODS framework, as well as the various levels of comprehensiveness of the consideration of the elements in the dimensions within each combination. It can be noted that as the comprehensiveness increases, the coverage of elements in the dimensions become less comprehensive. There is only one approach that addressed all the elements the ACLO combination (Activities, Criteria, Lifecycle and Outcome). The elements of the design stages and product structure dimensions are not addressed in full in any combination with other dimensions. In other words, none of the approaches apply to all design stages, and to all levels of granularity of a product's structure.

7 CONCLUSIONS

A detailed review of the current approaches helped in identifying the dimensions and elements that a holistic framework should constitute, and in establishing the areas in which the existing approaches are deficient.

A holistic framework should constitute the following six dimensions: a) Activities, b) Criteria, c) Lifecycle phases, d) Outcomes, e) Design stages, and f) Structure.

Analyses of design exercises has led to further consolidation of the elements of the dimensions of the holistic framework; from these, a holistic framework for environmentally friendly product lifecycle design, ACLODS has been proposed.

Existing approaches are mapped to the ACLODS framework in order to identify the areas which need improvement; this provided the directions for developing new approaches to fill the gaps and fulfil the overall need. The Design stage and the Product Structure dimensions are found to have been the least addressed in the approaches reviewed, and should be addressed in combination with the other dimensions. Our current research involves developing such a comprehensive design for environment platform.

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Table 1 Mapping of existing approaches on the ACLODS frame work

Combination of Dimensions	No of approaches considering at least one element in at least one dimension	No of approaches considering all elements in at least one dimension	No of approaches considering all elements in all dimensions
ACLODS	3	2	0
ACLOD	3	3	0
ACLOS	7	4	0
ACLO	3	2	1
ACLD	4	1	0
ACLS	1	0	0
CLODS	1	1	0
LODS	1	1	0
CLOS	1	1	0
LS	1	0	0
LA	2	0	0

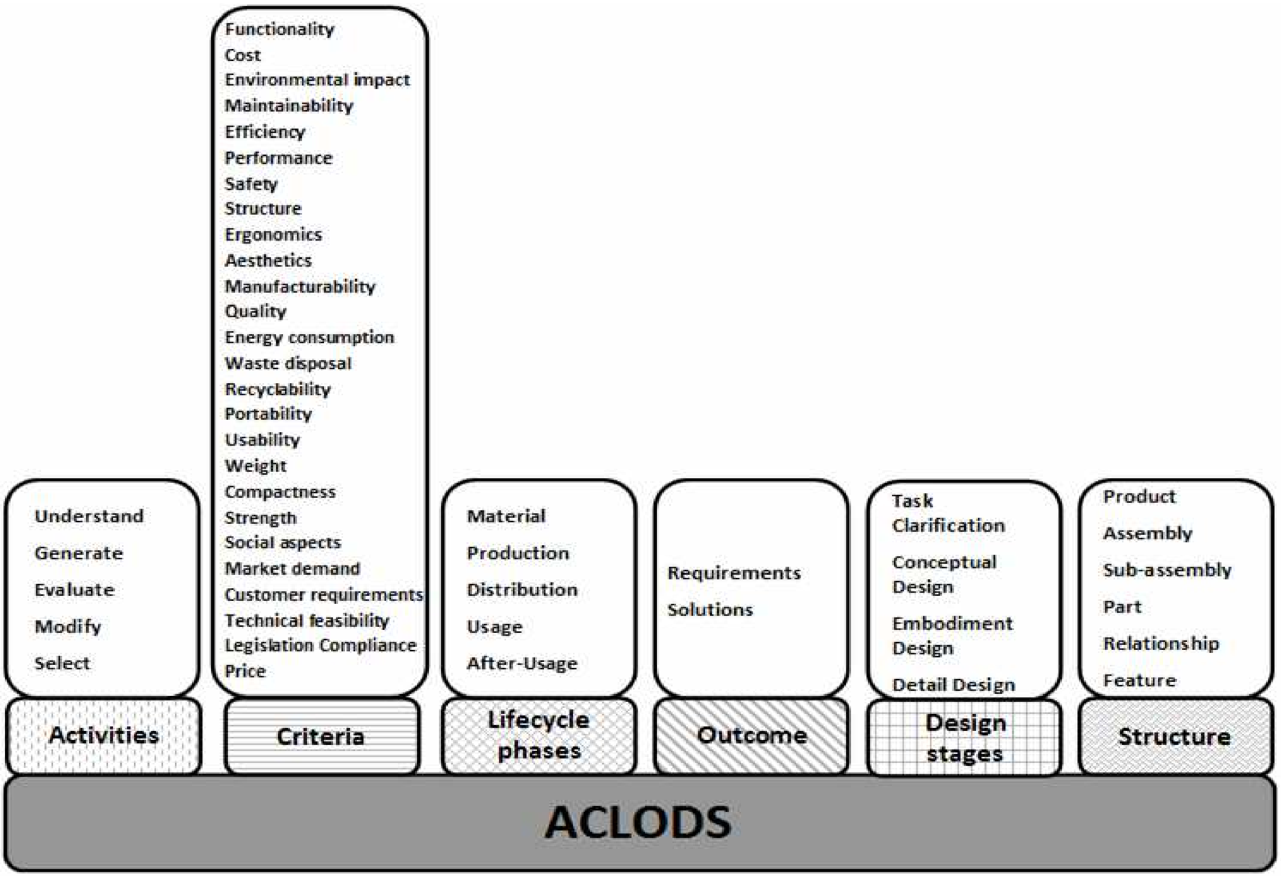

Figure 1 ACLODS Framework

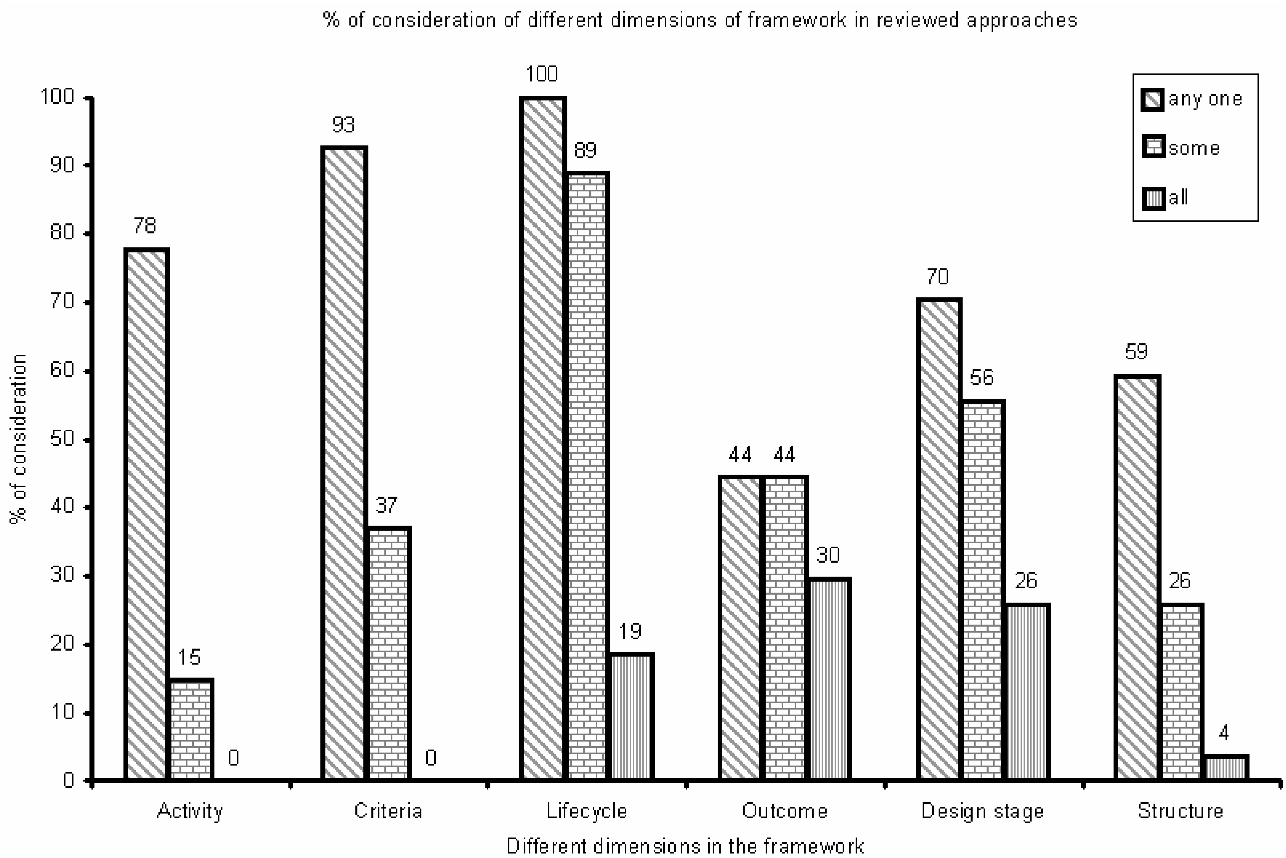

Figure 2 Mapping of existing approaches with the ACLODS framework dimensions

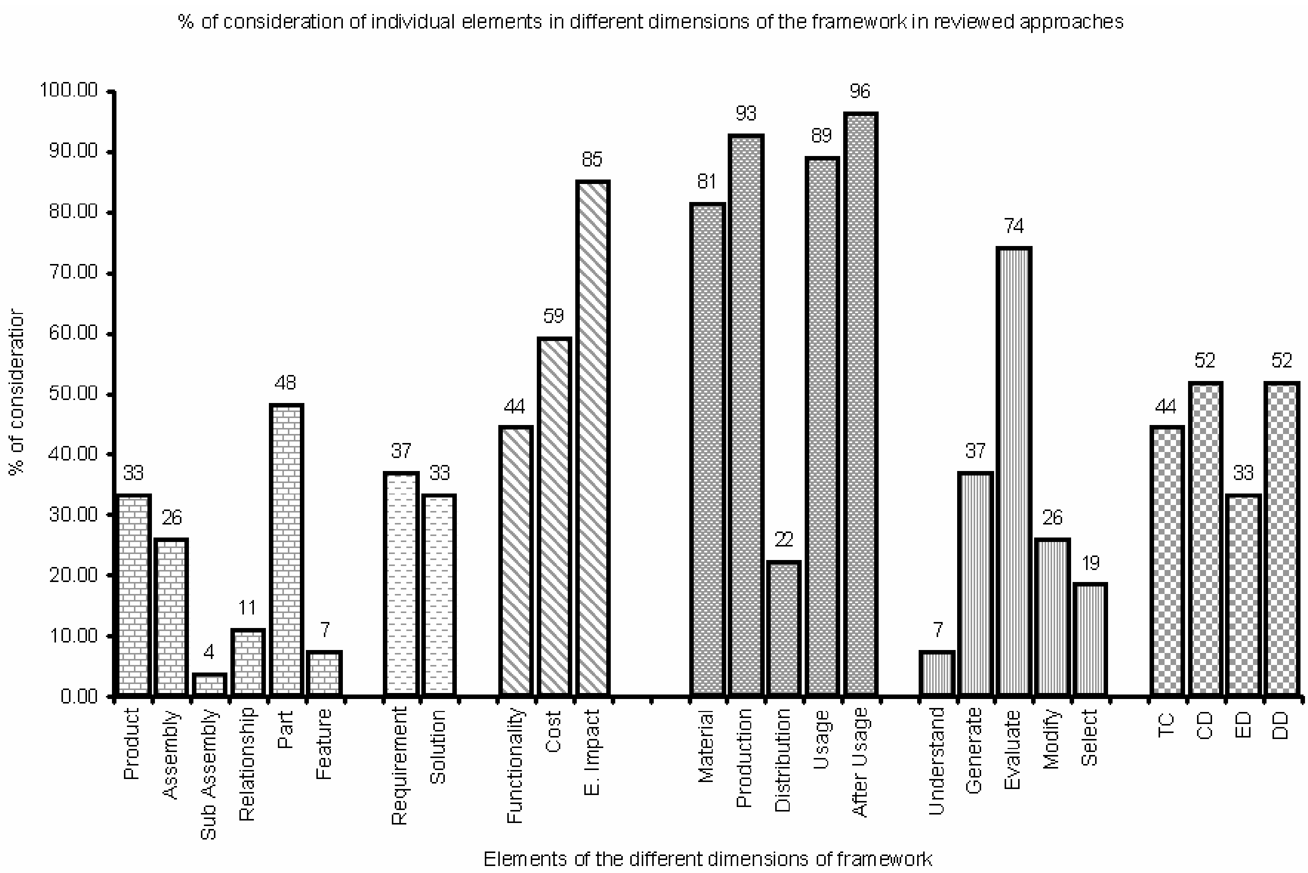

Figure 3 % of Consideration of elements in the dimensions of the ACLODS framework in the approaches reviewed

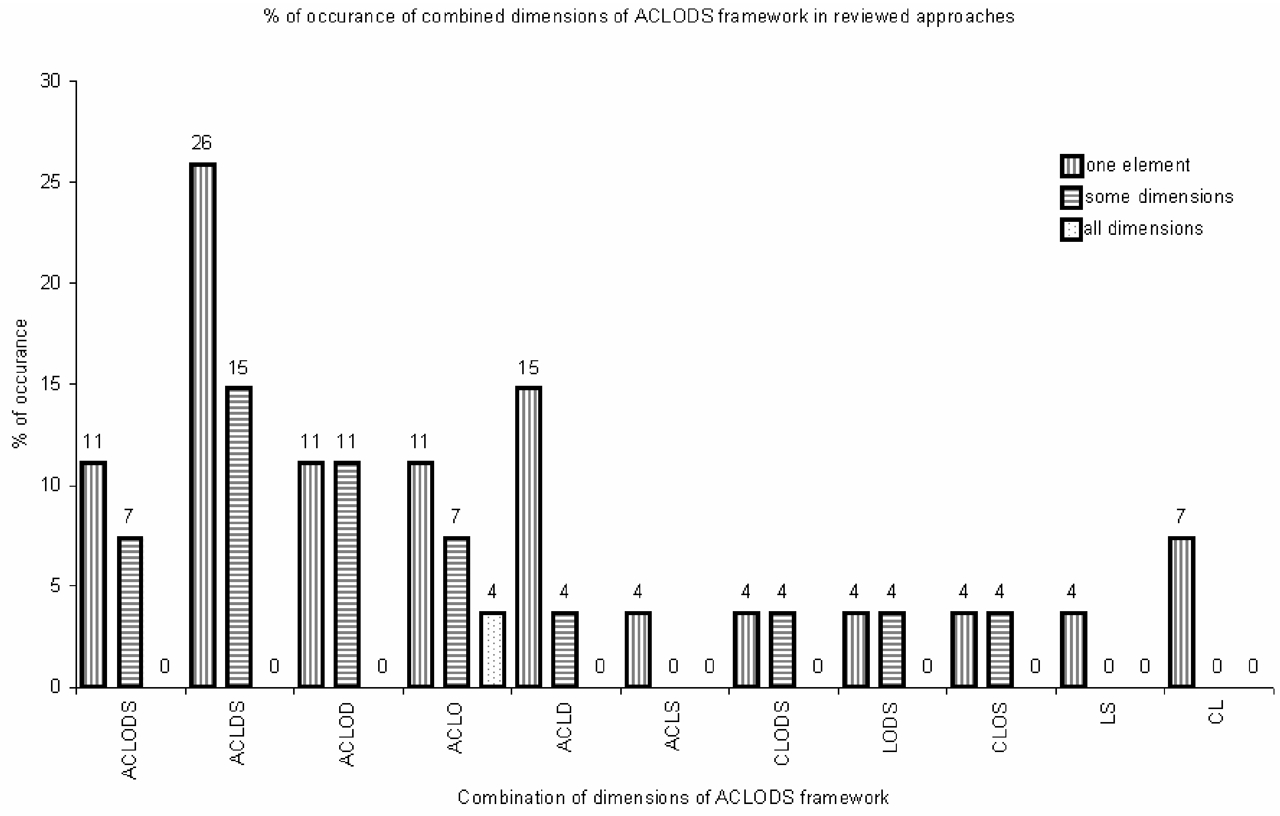

Figure 4 Percentage of occurrence of combined dimensions of ACLODS Framework in the existing approaches