Product Lifecycle Analysis and Optimization in an Eco-value Based, Sustainable and Unified Approach

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Abstract— **The current capabilities in most small and medium enterprises in industry are inadequate to meet the sustainable growth challenges from customers, competitors, or from government legislation requirements in the near future. This paper explores new product lifecycle technologies to address the challenges above. An eco-value based and unified product sustainability enhancement approach is proposed that enables comprehensive product lifecycle analysis and optimization. The novelty of the proposed approach is the semantics-based evolvement optimization method which is generic and adaptable to any sustainability issues.**

I. INTRODUCTION

The industry faces the great challenges in improving the innovativeness and competitiveness towards the flexible product configurations, customer satisfaction, market responsiveness, and eventually, the profitability [1]. Increasingly, a new dimension of requirements is emerged to develop methods, frameworks, standards and guidelines to analyze, control and improve sustainability of products over the lifecycle. The optimization of product design to meet the challenges and requirements is most economically and technically effective at early stage. However, with the currently used technologies, lifecycle analysis and optimization at the early design stages are generally very difficult tasks because they involve complex lifecycle inventories, methods, computational algorithms, and interpretation of results. Consequently, lifecycle analysis is primarily used for assessing the lifecycle performance, e.g. environmental impact, for existing products. Incorporating LCA into a new product's technical and economical considerations for new product development at the initial concept design stage is still not easily achievable for broad applications.

Minimizing the environmental impact of a product lifecycle is becoming increasingly demanding because of the stricter legislations and customer/OEM requirements. For example, under the waste electrical and electronic equipment (WEEE) Directive of EU [2], the electrical and electronic equipment (EEE) manufacturers have to be more responsible to take back their used products at end-of-life (EOL) for remanufacturing, recycling (50% to 80% by Dec. 2006), and safe disposal.

Similarly, the German Motor Industry has drawn up plans to enable effective car recycling, reaching 95% by weight by year 2015. In Singapore, the Green Plan 2012 has set target to increase the overall waste recycling rate from 44% to 60%.

It has been recognized that there are many advantages in sustainable development by developing and applying the integrated lifecycle analysis and optimization with product modularization strategies. This will enhance the industry's regulatory conformity, customer satisfaction, economics and market share.

Currently, majority of designers in industry have little or no experience in sustainable product and process development. There is a lack of easy-to-use technological solutions to assess the level of sustainability of a product for meeting the corresponding requirements, and hence to avoid the potential risks of non-compliance with national or international legislations.

This preliminary research is aimed at mapping the necessary ecological value (eco-value) based product lifecycle technologies into the areas of (1) the unified and integrated lifecycle analysis (LCA) with product modularization strategies at the new product development stage and (2) semantics-based evolvement lifecycle optimization. The motivation is to develop an eco-value based, sustainable and unified methodology for product lifecycle analysis and optimization for decision-support at the early stage of new product development.

II. TECHNOLOGY REVIEW

There are classical methodologies, frameworks and toolkits that support the lifecycle analysis and optimization. Included are the ISO 14040 series standards [3], the various simplified LCA studies, and the different static optimization methods for lifecycle issues. They can address the environmental impact of the existing products, and support structured improvement for lifecycle environmental performance.

However, it has been recognized that there should be a shift in research focus from only environmental-sound to sustainability. The latter requires integration of multi-dimensional perspectives of the product into the lifecycle impact models coupling technological and economical aspects for analyzing and optimizing the lifecycle performance.

To overcome certain aspects of the above difficulties, many systems are deployed in manufacturing companies. Included are Product Data Management (PDM), Supply Chain Management (SCM), Enterprise Resource Management (ERP), Manufacturing Execution System (MES), Customer Relationship Management (CRM), Demand Chain Management (DCM), etc. However, they still cannot adequately address the need for collaborative capabilities throughout the entire product lifecycle because they focus on special activities in an enterprise and are not adequately designed to meet new collaborative business requirements [4][5][6].

III. PROPOSED APPROACH

The proposed eco-value based lifecycle modeling and analysis methodology is to apply the multidisciplinary concepts and methods. Concurrently, the following aspects are considered in an integrated and consistent manner: (1) product structure abstraction, specialization and modularization; (2) lifecycle impact evaluation; (3) multi-objectives trade-off analysis; (4) value transfer methods for lifecycle analysis and costing engineering; and (5) product module similarity measurement. Figure 1 gives a schematic view on the suggested approach.

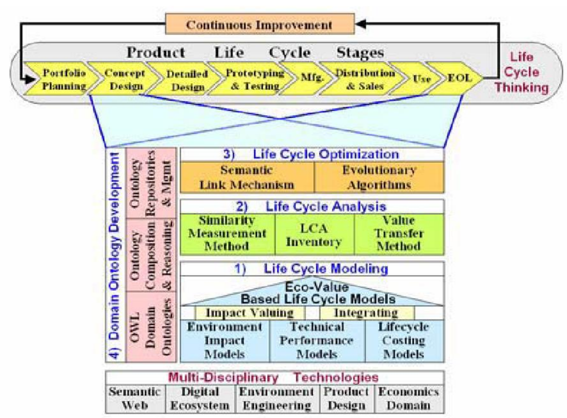

Fig. 1 Development approach to product sustainability enhancement

A. Optimized Product and Process Modularization

Product and process modularization is a powerful technology to enhance manufacturing flexibility, knowledge accumulation, reusability, collaborative coordination and management. Unified feature approach provides the foundation of engineering informatics for lifecycle modeling and analysis [7][8][9]. Products can be customized based on modules to enhance the customer satisfaction and the conformity to the environmental requirements [10]. Processes can be modularized for automation and optimization to reduce waste and cost. We believe that company's sustainability can be significantly enhanced and practically achieved with the modularization approach. Optimization of modularization is to be investigated with the unified feature representation and lifecycle analysis.

In addition, to reduce cost, manufacturers have been seeking to increase the output and versatility of their product lines through product family design. One difficulty for product family positioning is that diverse customer needs can no longer be satisfied by a mass marketing approach. Realizing the importance of customer purchase behaviors for product family positioning, a fuzzy clustering-based market segmentation approach [11] was proposed. With focus on engineering characteristics, the fuzzy clustering-based market segmentation helps plan right products to target segments effectively and efficiently.

B. Product Lifecycle Modeling

Lifecycle modeling is the key to product lifecycle analysis and optimization. Most of the current lifecycle modeling methods is mainly concentrated on formulization of product environmental and economical impacts without fully incorporating explicit relationships between these impacts and product configurations, design features and design for x (DFx) technical considerations [1]. To improve this, we recognize the following issues:

- How to identify and build the relationships and mappings among customer requirements, product technical characteristics, modularity, design features, processes, environmental impact and economical factors.
- How to quantitatively aggregate multiple sustainability indicators into a single lifecycle model and how to value them on a relative monetary base.
- How to resolve the conflicts emerged when trying to achieve the integrated technical, environmental and economical objectives.
- How to extend the existing established and accepted lifecycle performance indicators with inclusions of technical considerations.

We propose a unified feature approach to deal with the abstraction and specialization of product structures (for modular products) to address the associative relationships discussed above [12]. Due to the complexity and numerous associations among PLM system applications and modules, a comprehensive computerized solution is very difficult to design and implement. A UML based graphical software modeling language has been proposed which makes product and process data structures, workflow logics, and system interactions well-defined systematically and consistently [13]. The impact valuation techniques from economic and ecosystem domains will be used to quantify the lifecycle performance in terms of eco-value, a relative cost efficiency measure, for integration of technical, environmental and economical indicators in the lifecycle model. Trade-off analyses and prioritization models will be developed to resolve conflicts caused by multi-objectives. The methods, techniques, and models mentioned here have to be developed together to tackle the model extension and upgrading issues for practical use of lifecycle modeling in real industry.

C. Lifecycle Analysis (LCA)

A full LCA exercise about a product's entire life requires huge amounts of quantitative data, which is not available at early design stages of an intended product. This brings the issue of how to make the previous products' LCA results reusable in new product design. Simplified LCA studies often give only the restricted results with qualitative meanings. How to transfer the LCA results into quantitative measures that are directly related to the technical, environmental and economical parameters will be of interest for product designers. This paper suggests that the LCA data and knowledge reuse issue will be addressed by *Value Transfer* method that involves the adaptation of existing impact estimates from the completed LCA studies to new impact estimations even though little or no LCA inventory data is available.

There is a general shortage of LCA and other sustainable growth technologies, skills and tools. There is also a lack of understanding of the regulatory complexity and evolution. How to cast the LCA and other lifecycle technologies into easy-to-use tools for the industry is another challenge. The qualitative LCA results will be quantified as the eco-value based impact measures with the established economic valuation techniques, which would facilitate the easy adoption of the simplified LCA by companies.

To address the difficulty of measuring the similarity between different modular products in order to determine whether reusing LCA results is feasible, a measure of similarity degree in the term of *Module-Distance* is suggested to quantitatively compare the functional, structural and behavioral characteristics of modular products.

D. Lifecycle Optimization

Lifecycle optimization is to improve the performance of all clustering business partners along with the product value chain. The existing methods are generally concerned with a static state space, i.e. given a set of static constraints/conditions to find an optimal solution to a specific lifecycle issue. However, sustainable product development requires simultaneous optimization of an entire product, including its components and modules from different suppliers over an ever-changing supply chain. The research issue is how to support the lifecycle optimization in an evolving state space, where the search for the 'optimum' solution is coupled with the context-sensitive product domain ontology for semantic definitions and relationships. We propose to use a semantics evolvement optimization method.

The semantics-enabled evolvement optimization is new to lifecycle engineering. The issues that need to be addressed include:

- How domain semantics determines the evolvement of optimization constraints, conditions, knowledge sources used, even the results for lifecycle issues.
- There are no patterns to follow for defining how the semantics-based evolvement process should be initiated and iterated in lifecycle optimization.
- How the evolvement algorithms are supported by the domain ontology.
- How to populate the integrated lifecycle models developed with the user active inputs and common semantics described in domain ontology to define the optimization context that can evolve during optimization based on the semantics retrieved.
- How to re-interpret the abstract optimal solutions back to technical, environmental and economical performance measures to help in the decision-making for the selection of the best-balanced product solutions.

Fig. 2 shows a proposed approach at conceptual level to address the challenges above. Among others, the semantic link mechanism and the evolvement algorithms will be the key technologies to be developed.

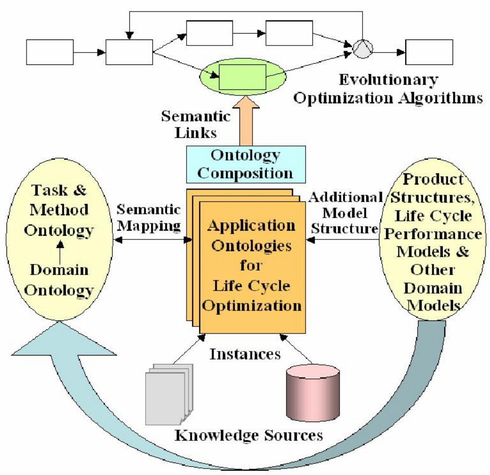

Fig.2: Semantics-enable evolvement optimization for lifecycle issues

E. Domain ontology development

Domain ontology development is to explicitly capture and formalize the specific knowledge about sustainable product development, including the knowledge, concepts, and methods used in product technical, environmental and economical performance modeling, analysis and optimization.

All domain ontology should be developed based on the open standard of Web Ontology Language (OWL) [14] and OWL for Services (OWL-S) [15]. Specifically, the ontology covers product bill of modularity specification, lifecycle performance indicators, and service–oriented specific applications. With our previous ontology development approach, the relationships among domain objects, tasks, methods, and application services are established whenever a semantic link is requested from the optimization. By building this mechanism into the ontological structures, the application-specific semantics can be composed and supplied, on demand, to address the dynamics in evolvement lifecycle optimization.

IV. KEY TECHNOLOGIES

The following key technologies are deemed crucial for product lifecycle analysis and optimization:

1) Quantitative lifecycle analysis. Modeling product lifecycle with the integration of environmental impact analysis, lifecycle cost estimation, and product technical potential assessment through quantitatively eco-valuing by *Multiple Attribute Value* theory [16], and integrating the eco-value based technical, economical and environmental impacts into lifecycle models.

2)Extended analysis for modularity. Product modularity must be evaluated with new features as follows: inclusion of the environmental impact as well as lifecycle costing aspects. Techniques such as *Quantified Similarity Measuring* of the different modular products in terms of module-distance, and the deployment of *Value-Transferring* technique [17] which enables the use of the existing LCA results for new product development according to module similarities, need to be employed.

3)Lifecycle evolving optimization. A product lifecycle can be modeled in an evolving state space with semantic links to domain ontologies which are commonly used to retrieve the structured knowledge and task-solving methods. To obtain the best-balanced solutions, the evolvement of constraints, conditions, and knowledge has to be incorporated in the searching algorithms. Duality theory will be used to re-interpret the optimal solutions in lifecycle performance improvement.

The integrated lifecycle modeling approach, the LCA analysis method, and the semantics-based evolvement optimization method should be generic and adaptable to any sustainability issues, though the modular product recyclability assessment and EOL cost optimization will be used as the test cases in this project.

V. CHALLENGES

There are many foreseeable challenges ahead to be addressed in future research. The most important ones, which should be watched out and further studied, are:

1) How to describe context sensitive domain knowledge in the form of ontology, which could include domain objects, tasks, and application services based on the open standards;

2) How to provide semantic support in modeling, analyzing, especially in optimizing, the lifecycle performance indicators;

3) How to design the ontological structures and entities to support ontology composition and reasoning; and

4) Ontology repository development and management.

VI. APPLICATION OPPORTUNITIES

This proposed approach can be implemented for the following potential applications.

A. New Product Development

Fung et *al.* [18] recognised that if a company can duly transform the genuine and major customer attributes into product attributes, such as quality characteristics and the related features, it would have distinct advantage in competition. To do so, firstly, customer requirements should be translated and mapped into product quality characteristics. Secondly, product quality characteristics must be decomposed, transformed and implemented into product design processes. Finally, they are represented with part features, dimensions, geometric relations, tolerances and material requirements [10].

A fundamental research on the modeling and propagation of customer requirements throughout the whole product development lifecycle has been reported [10]. It covers three processes, i.e. the qualification and classification of customer requirements, the generation and transformation of product quality characteristics, and product quality characteristics optimization. Analytic network process (ANP) approach has been adopted to establish the weights of different customer requirements and product quality characteristics. The intra- and inter-relations for customer requirements and quality characteristics are modeled. The matching and conflict resolving algorithms are proposed. Key influential factors, such as the cost, time to market, the existing resources usage and the feasibility, are coherently considered.

B. Product Recycle-ability Assessment

The proposed integrated lifecycle modeling, the relationships between product configurations and product modularity are considered. Through the implementation of the modeling method in a company, the resulted system will provide the impact indications of the product structural and technical parameters for the modular design optimization as well as recycle-ability assessment. Based on the multidisciplinary concepts and methods, the propose research is promising to eliminate the traditional LCA's complexity and the lack of data inventory at early lifecycle stages; hence optimization can be carried out before intensive resource-consuming stages are involved. This will allow the local manufacturing Small and Medium Enterprises (SMEs) to work out competitive lifecycle strategies and to plan for modular product recycle-ability easily without the overwhelming cost incurred.

C. End-Of-Life (EOL) Cost Optimization

As an example, the European Union's environmental legislation on electrical and electronic products has required manufacturers to take more responsibility for their products' EOL. This trend causes significant concerns in the whole manufacturing industry, as few know how to fulfill the responsibility. Is it possible to minimize the EOL cost, even to generate the EOL value?

In this case, the optimization of the EOL cost for the entire product must be considered at the early stage of the product development. However, at this stage, the product definition, its mechanisms, components and modules, are not finalized. Further more, the EOL options, the component/module supply chains, and the product lifecycle costing elements are still evolving. It is beyond the capabilities of the traditional, static optimization methods to answer these questions. It becomes even more challenging with the increasing collaborative manufacturing activities.

The proposed evolvement optimization enables the search of the optimal EOL cost solutions in an evolving state space where the optimization context may change. The semantic link mechanism will dynamically compose and allocate the required application ontology to define the optimization context in the evolvement process. With this novel lifecycle optimization method implemented a prototype solver, the EOL cost will be simultaneously optimized over the evolving EOL strategies and supply chains.

VII. CONCLUSION

The semantics-enabled evolvement lifecycle optimization, especially coupled with the domain semantics in OWL standard-based ontologies, is the original idea, and novel to address the dynamic nature of the product lifecycle over the evolving state space. It is expected to solve the problem of insufficient data and knowledge for dynamic lifecycle optimization in the early product development stages. The incorporation of collaboration relationships, and ever-changing customer demands, is also new in the field. We have not found any similar research work reported in literature.

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