CAX/PLM/ERP-LCA integration to support product life cycle engineering: a conceptual framework

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Abstract. Life cycle engineering (LCE) targets product development and manufacturing activities from a life cycle perspective, with the aim to create more sustainable solutions. Life Cycle Assessment (LCA), which systematically and quantitatively evaluates the environmental impacts associated with the product, is recognized as an essential tool for LCE. However, the complexity of inventory analysis and data structure can discourage the use of LCA by engineers. Most computer-aided engineering and computer integrated manufacturing tools do not effectively support LCA. This paper proposed the conceptual framework of CAX/PLM/ERP-LCA integration for an information environment to address the challenge. The general product life cycle representation is analyzed by tangible product and intangible process perspectives. A multi-view life cycle model is proposed for linking product and process engineering with LCA and life cycle data integration. Following the life cycle model, the integrated CAX/PLM/ERP-LCA system's conceptual architecture is presented, the challenges to the data flows among system components identified and the critical functional requirements of the system to support sustainable product and process engineering proposed. The framework serves as the stepping stone for next-stage work on software engineering.

1. Introduction
With the increasing awareness of environmental crises, manufacturers are concerned about environmental impacts associated with their products and/or services. Life cycle engineering (LCE) targets product development and manufacturing activities in a life cycle perspective to create more sustainable solutions, i.e. to encourage economic progress, keep in mind social concerns, conserve resources, and minimize pollution and waste [1, 2].

Life Cycle Assessment (LCA) [3] is one of the most used methods for systematic and quantitative environmental impact evaluation (i.e. [4-6]). LCA helps determine whether the product and/or process solutions are better for the environment than the currently available ones and enable the trade-offs between environmental impacts and economic cost [7]. Thus, LCA is recognized as an essential tool for product life cycle engineering. Though the approach is widely accepted, LCA implementation is often complex [8, 9]. LCA is very data-dependent. Life cycle data collection can be quite time-consuming. It is a common situation that life cycle-related data scatter in various product/process models and technical documents, i.e. life cycle inventory (LCI) strongly related to product geometry (i.e. CAD model), material choice (i.e. BoM), manufacturing processes (i.e. CAPP process sheets), and service plans. Unfortunately, most computer-aided engineering (CAx) and computer integrated manufacturing
(CIMs) tools currently adopted by the industry do not effectively support LCA-oriented data management [10, 11].

Moreover, due to the discrepancy in the principles of the utilized methodological approaches, these data usually cannot be directly used for LCA modeling and analysis. It requires methods to identify what data in existing product and process models help LCA and what tools to gain access to different data sources and deal with the heterogeneous data for LCA. Thus, aiming to build the method and technical basis, this study proposes a digital information environment for sustainable product life cycle engineering. First, the general product life cycle representation is analyzed from the perspectives of tangible product and intangible process. A multi-view life cycle modeling approach and data model is then proposed to address the integrated data management for sustainable life cycle engineering. Then, CAX/PLM/ERP-LCA integration is presented as the critical enabler of implementing the proposed life cycle modeling to support life cycle engineering.

2. Life cycle modelling approach oriented to LCE

2.1. Life cycle representation from tangible product - and intangible process-based perspectives

Product life cycle engineering generates integrated solutions of tangible product and intangible life cycle processes that fulfill functional and economic requirements and environmental ones. Thus, the product life cycle is characterized by two perspectives- the tangible product entity- and the intangible process-based. From the product entity-based perspective, the life cycle is represented by the physical product's status throughout the life cycle, i.e. from generation to extinction, while form the process-based perspective, the life cycle is characterized by operations and organized activities associated with the product, resulting in product state changes and environmental impacts. Primary "product" and "process" information for life cycle modeling are identified in Table 1.

| Life stage                          | From Product-based perspective                                                                 | From Process-based perspective                                                                 |
|------------------------------------|------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| Manufacturing                      | Geometry (i.e. form, shape)                                                                 | Manufacturing method and technology (i.e. drilling, milling, injection moulding, …)            |
|                                   | Material (i.e. type, density, recyclability, the mixture of recycled materials, …)            | Parameters (i.e. processing time estimated)                                                    |
|                                   |                                                                                               | Equipment & Tooling specifications (i.e. energy efficiency, resource efficiency, …)           |
| Assembly/Disassembly               | Connectivity (i.e. fastening, bolted connections, welded, …)                                 | Method (i.e. manual, automatic by robots)                                                     |
|                                   |                                                                                               | Parameters (i.e. assembly time estimated, labour requirement, …)                             |
|                                   |                                                                                               | Equipment & Tooling specifications (i.e. energy efficiency, resource efficiency, …)           |
| Distribution (part&product transportation) | Mass (estimated.)                                                                 | Method (i.e. type of transportation: by truck, by railway, or mixed with percentage…)         |
|                                   | Volume (estimated)                                                                           | Parameters (i.e. fuel demand/load*distance, distance, …)                                      |
|                                   | Package                                                                                       |                                                                                               |
| Use                                | Functionality & Performance (i.e. useful lifetime, working power, auxiliary use/load, …)     | Customer use pattern (i.e. time & frequency of use, load, …)                                  |
| Maintenance                        | Functionality & Performance (i.e. useful lifetime, reliability)                               | Method (i.e. maintenance strategy: repair, exchange)                                          |
|                                   |                                                                                               | Parameters (i.e. maintenance time, labour requirements, costs, …)                            |
|                                   |                                                                                               | Equipments & Toolings specifications (i.e. energy efficiency, resource efficiency, …)        |
| End-of-life Treatment              | Mass                                                                                          | Method (i.e. collected vs disposed of, reuse, recycling, landfill, incineration, …)          |
|                                   | Material (i.e. type, recyclability)                                                            | Parameters (i.e. retired product collection rate; part reuse rate; material recycling rate, processing time estimated, labour requirements, costs…) |
|                                   | Functionality & Performance (i.e. reparability, reusability, remanufacturability)              | Equipment & Toolings specifications (i.e. energy efficiency, resource efficiency, …)         |
2.2. Multi-view life cycle modelling

Figure 1 presents the multi-view life cycle model oriented to LCE. There are three model views—the product state, the operational, and the environmental view. The model views are related by the information translations between product design, process planning, and environmental evaluation (i.e. LCA). Thus, following the life cycle model, the integrated data model is developed (see Figure 2) for the formation of linkings between LCI and raw data (i.e. product and process models, technical reports, quality management documents).

Figure 1. Multi-view life cycle model oriented to LCE.

3. CAX\PLM\ERP-LCA integration for the close-loop pathway of LCE

The CAX\PLM\ERP-LCA integration is proposed as the core enabler to realize multi-view life cycle modelling and life cycle data integration to support LCE. Figure 3 presents the conceptual architecture of the integrated system. According to the life cycle modeller’s requirements, the life cycle data integrator collects the product and process-related data. A lifecycle data service module can be a solution to efficient data collection and pre-processing (readers may refer to [12]).

The life cycle modeller then generates the multi-view life cycle model and the calculated life cycle flows (i.e. process input-output) for the LCI and EI analysis. The LCE analyzer derives sustainability suggestions based on the critical influencers to environmental impacts throughout the product life cycle. As the quantitative relationship between product, process data and the EI indicators are explicitly formulated during life cycle modelling, the improvement opportunities are identified by tracing the EI hotspot back to its causing factors, i.e. material choice, product design parameters, process technology. The PLM/ERP system can also achieve the LCA reports via the life cycle data integrator. Thus, the close-loop pathway of LCE is established.
Figure 2. The conceptual life cycle data model.

Figure 3. Conceptual architecture of the integrated CAX\PLM\ERP-LCA system.
The data flow between the system components s is then hypothetically formulated, and the significant challenges to the LCA tool development are proposed (Figure 4). Then, the primary functional requirements of the integrated system to support sustainable product and process engineering are analyzed as followed:

1) Product design
In this stage, the environmental impacts of material choice, functionality, and structure are the focus, as the manufacturing methods are not exact yet. Thus, the integrated system is expected to: a) be able to process the geometry model (i.e. a CAD model) for collection of valuable data such as material type and demand, and provide the suggestion of manufacturing and end-of-life treatment process; b) modelling and evaluation of product use phase based on product CAE results (i.e. expected lifetime, energy efficiency in use). The integrated LCA is used to perform the preliminary assessments of components, assemblies, and products for a more environmentally friendly design.

2) Process planning and design
In this stage, the product design is almost finalized. The integrated LCA tool is expected to model the life cycle with more details of manufacturing. Thus, the data migration between CAPP/CAM and LCA can be beneficial. The integrated LCA tool is therefore used for designing and evaluating the sustainability of manufacturing processes.

3) Product & process finalization
As for finalized products (or existing products), the integrated LCA tool is expected to be able to: a) process the product data (i.e. CAD model, EBOM) and process data (i.e. BOP, MBOM), and manage

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**Figure 4.** Formulated data flow between CAX\PLM\ERP\LCA and identified challenges for LCA tool development.
the interrelations between the two; b) model the whole life cycle based on the MoL (i.e. transportation and distribution, failure and obsolesces, maintenance and updates) and EoL (i.e. disposal and circularity) data and perform the detailed LCA for identification of problems, opportunities of improvements and appropriate corrective actions.

4. Illustrative example

An illustrative case of machined part eco-design based on CAD/PLM-LCA integration is presented in Figure 5. The shaft's UGNX model is built in a bottom-to-top manner with a main revolve feature and several details such as slot feature and groove feature. With the UGNX plug-in integrator (find more details in [13]), the part's manufacturing features are recognized, analyzed (e.g. by rule reasoning [12]), and translated into a "rough turning" operation. With the machine tool, process and material specifications retrieved from the PLM system (e.g. process plan and employed equipment and tooling information of similar parts as references for the LCA study), the material and energy demands as well as emissions and wastes are calculated based on the operation's Input-Output model, and then the environmental impact assessed using the selected method (i.e. Ecoindicator 99). The "LCE analyzer" presents the network of relations between inventory, process input and output, operation and product factors to help identification of engineering considerations related to critical environmental impacts. The module may also provide the report templates for "Conclusions", "Hotspot analysis", and "Improvement measures", in which LCA experts, as well as product and process engineers, can leave conclusive remarks on the LCA study from different perspectives.

Figure 5. Illustrative example of machined part eco-design based on CAX/PLM-LCA integration.
5. Conclusions

LCA is considered valuable and essential for life cycle engineering. It is necessary to provide engineers with tools for efficient collections of life cycle data. In this study, the product- and process-oriented life cycle representation are presented. The multi-view life cycle modelling approach and the conceptual model of life cycle data are proposed to address the life cycle-oriented data integration. Then, the framework of CAX/PLM/ERP-LCA integration was presented to realize the proposed lifecycle model, data integration, and thus to support life cycle engineering. The data flow between the subsystems (i.e. CAX, PLM, ERP, and LCA) was hypothetically formulated. The significant challenges to realizing the data migration and the development of LCA-based sustainability assessment tool are identified. The integrated system's functional requirements in different stages of product development are analyzed. This study provides the stepping stone for our next-stage work on software engineering.

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