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A Manufacturing Informatics Framework for Manufacturing Sustainability Assessment

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Abstract

Manufacturing firms that wish to improve their environmental performance of their product, process, and systems are faced with a complex task because manufacturing systems are very complex and they come in many forms and life expectancies. To achieve desired product functionalities, different design and material can be selected; thus the corresponding manufacturing processes are also changed accordingly. There is direct need of assessment tools to monitor and estimate environmental impact generated by different types of manufacturing processes.

This research proposes a manufacturing informatics framework for the assessment of manufacturing sustainability. An EXPRESS information model is developed to represent sustainability information such as sustainability indicators and their associated weighting and uncertainty factors, material declaration information, and hazardous condition information, etc.

This information model is tested with industrial products to validate its completeness and correctness. This information model serves as the first step of establishing close association of sustainability information with product design specification. In the next phase of research, investigation will be conducted to integrate sustainability information model and existing standardized product design model ISO 10303 AP 242.

Keywords: Manufacturing process; Environmental impact; Life Cycle Assessment; Information Model

1 INTRODUCTION

Sustainability is a multi-disciplinary field that involves the areas of ecology, economic development, and social equity [1]. The manufacturing industry is often cited as the cause of many environmental and social problems, yet it is acknowledged as the main mechanism for change through economic growth [2]. It is clear that the world is moving forward aggressively to achieve sustainable design and manufacturing with life cycle considerations. Industry is confronted with the challenge of designing sustainable products and manufacturing processes. The ones who first develop and employ such technologies will gain a competitive advantage in the market place [3]. Many sustainable development strategies [4-8] have been proposed by government agencies and academia since the late 1990s. Research in sustainable manufacturing field can be categorized into the following four main themes [9, 10]: a) Life-Cycle Assessment (LCA) [11-15], b) design-for-X principles and design for sustainability [16-25]; c) end-of-life studies [26-31]; and d) energy efficiency monitoring and studies [32-35].

LCA considers all environmental impacts associated with a product or a service from its inception to the end of its life. It can be broken down in five main stages; namely the material extraction, manufacturing, transportation, use, and disposal. International standards for industrial life cycle assessment, such as ISO 14040-14043, have been published in the past decade. These standards lay out the rules that industry should follow for conducting and reporting life cycle assessment. Considering the diversity and complexity of most manufacturing products, LCA methodologies are hampered by two main challenges: a) the diversity and variations in materials, processing techniques, usage durations, and disposal routes; and b) excessive implementation time. Most LCA research is specifically developed for one particular material or product. In industrial setting, LCA is very data-intensive and requires months to complete. Furthermore, LCA is not connected to business perspectives, and thus it does not measure the value of sustainability practice without additional product cost estimation and optimization factors.

Design for Sustainability (DfS) aims at designing or re-designing a product in order to reduce its environmental impact within one particular stage of the product life cycle. It complements design-for-X principles. Design for manufacturing methodologies have been used with a focus on cutting both the production lead time and cost. That, in turn, may lead to a reduction in energy consumption. Design for disassembly, for remanufacturing, and for recycling fall under the umbrella of "design for end-of-life". Design for durability and for energy efficiency is to minimize material usage such as raw material and fossil fuel. While LCA is intended to determine material and energy flows and to assess the resulting environmental impacts, DfS utilizes information and results from LCA to improve product and process design. One key problem with DfS and LCA is the lack of a close connection and integration with other design, management, and manufacturing tools. Energy efficiency research focuses more specifically on – energy consumption monitoring and estimation. These research fields are segmented and they are specific for certain products, materials or processes. The lack of manufacturing system and sustainability information integration hampers the widespread adaptation of the best sustainability practices in the manufacturing industry.

2 INFORMATION MODELS OF PRODUCT DESIGN AND MANUFACTURING PROCESSES

In recent years, information technology has become increasingly important in the manufacturing enterprise. Effective information sharing and exchange among computer systems throughout a product's life cycle has been a critical issue [36]. Information modeling is a technique for specifying the data requirements that are needed within the application domain [37]. An information model is a representation of concepts, relationships, constrains, rules, and operations to specify data semantics for a chosen domain of discourse [38]. The advantage of using an information model is that it can provide a sharable, stable, and organized structure of information requirements for the domain context. There are different practices in developing an information model. The underlying methodologies for the recent modeling practices are based on three approaches: the Entity-Relationship (ER) approach, the functional modeling approach, and the Object-Oriented (O-O) approach. Based on these approaches, there are many information models existing in manufacturing industry such as UML models, XML models, IDEF1X models, etc. Amongst these information models, the STEP and STEP-NC information models are the most advanced and standardized ones.

STEP and STEP-NC standards have been developed by ISO committee to provide the basis for product design, machining standardization, and integration of part inspections with machining. The information is modeled in EXPRESS language. The purpose of STEP is "to specify a form for the representation and unambiguous exchange of computer-interpretable product information throughout the life of a product" [39]. STEP permits different implementation methods to be used for storing, accessing, transferring, and archiving product data. STEP Application Protocol (AP) 203 edition 1 [40] and edition 2 [41] (Configuration Controlled 3D Designs of Mechanical Parts and Assemblies) provides the data structures for the exchange of configuration-controlled 3D designs of mechanical parts and assemblies. AP 203 is but one part of the entire ISO 10303 product data standard. It does not present itself as the data standard for configuration management of a product throughout its entire life cycle. The AP is centered on the design phase of mechanical parts and the high-level information entities are shown in Figure 1.

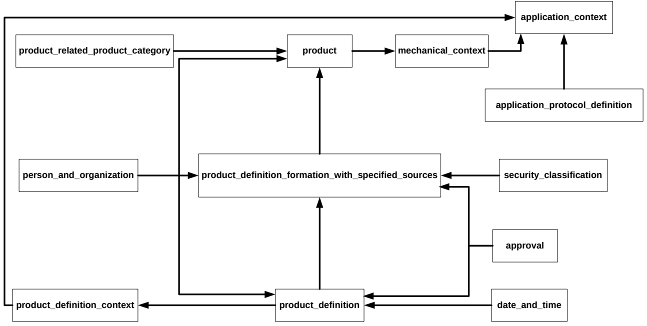


Figure 1: High-level information entities in STEP AP203

Other APs of STEP information models carry the product design data in AP 203 forward through the product life cycle. STEP-NC represents a common standard specifically aimed at NC programming, making the goal of a standardized CNC controller and NC code generation facility a reality [42]. It provides CNC with a detailed and structured data interface that incorporates feature-based programming where a range of information is incorporated such as the features to be machined, tool types used, operations (workingsteps) to perform, and process plan (workplan) to develop [43] as shown in Figure 2. The feature information in STEP-NC can be obtained by processing the product design geometry in STEP AP 203 through a feature recognition process. The material information and Product Lifecycle Management (PLM) information in STEP AP 203 associated to the design geometry can also be passed onto the manufacturing features in STEP-NC, which in turn associates to the manufacturing process parameters such as machine tools, tool-path, cutting strategy, etc. In this way, the design geometry, material, PLM information is connected to the manufacturing process level.

By providing the high level information to machining systems, STEP-NC will not only eliminate the costly and inefficient process of data post-processing, it will also establish a unified environment for the exchange of information between product design, machining process planning and inspection. It enables the realization of a closed, STEP-NC based machining process chain with data feedback and a consolidated data structure at each level [44, 45]. Industrial use of STEP/STEP-NC has shown evidence of significant cost saving, higher quality, and reduced time-to-market. It may become a major building block in e-economy, the effort to unite manufacturing businesses among corporate partners, distant suppliers, and across divers computer environments [24].

3 ISSUES OF INTEGRATING LCA IN PRODUCT DESIGN STAGE

Due to the complexity of manufacturing products and their manufacturing processes, conducting LCA for one product alone is a very time-consuming process. Furthermore, because of the various software and hardware tools involved in a product design and manufacturing process, the quality of LCA data is also a pressing issue for industry to accept current LCA results. The various data format in design and process planning software also contributes to the difficulties of integrating LCA information into product design stage. This section discusses these issues in detail.

3.1 Quality and Quality of Data in LCA Process Modeling

Product systems are complex and the manufacturing firms encounter serious problems when using LCA in the design situations for many reasons. Firstly, the large number of parts and the diversity of materials and processes involved inside a product system are true barriers to effective implementation of LCA in the design phase [46, 47]. Collecting and processing all the data needed for modelling the product life cycle does make compiling the inventory a very time consuming task which also requires a lot of efforts [48]. In addition, these elements are not fully available earlier in the design phase [49].

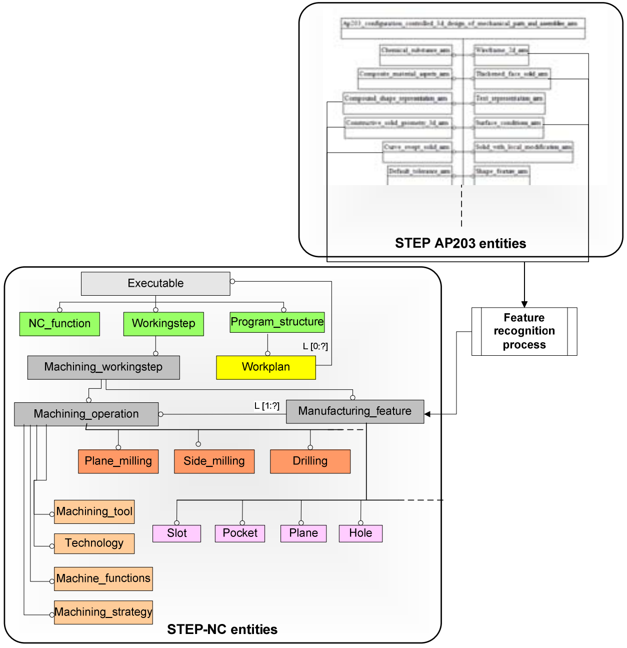


Figure 2: An example of STEP-NC information model in EXPRESS-G diagram

Secondly, it is often difficult to be exhaustive in terms of all the processes, data and parameters of product life cycle modelling as required by LCA procedure [50]. In fact, conducting LCA approach requires that the following four aspects must be taken into account:

1) The level of "depth and detail" of data required in the application(s),
2) The breadth and completeness of the study: life cycle stages, drawn system boundary, inventory and impact category indicators used to meet the intended application(s),
3) The degree of openness and comprehensiveness in the presentation of the results, and
4) The data sources and quality (i.e., are secondary data sources sufficient for the study or primary data required, or a mix of both sources? How much confidence should the users have in the data manipulated and in the study's conclusions?

Also, in LCA, the "functional unit" establishes the process parameters. Unfortunately, in real-life complexity, the utility of a product cannot be reduced to the expression of one or two specifications of use [51]. However, this rationalization of real-life complexity is acknowledged by qualifying the LCA system boundary as "rigid", as either not all the existing parameters can be reduced to a few numbers and inserted into the process model. This LCA data management is therefore often conducted with a certain degree of subjectivity [52] and polluted by a lack of comprehensiveness in terms of data sources [53]. Indeed, data sources can also contribute to inaccuracy, as it is well known and acknowledged that data used in generic processes may be based on averages, unrepresentative sampling, or outdated measures. Additionally, it is also well known that depending on the scope definition, the considered system boundary may be different from one LCA practitioner to another regarding a product life cycle modelling. Thus, it is never possible to obtain an exact life cycle inventory [54].

3.2 LCA Adaptation in the Product Design Stage

Many LCA software tools are commercially available, but SimaPro from Pré Consultants and GaBi from PE International have been around for many years, and are widely used by life cycle assessment professionals. The user interface for both of these products is challenging in terms of intuitiveness.

Concerning the modelling philosophy, GaBi could be qualified as a “process modelling approach”, as it requires users to build a “process-tree” to connect materials, energy and processes to parts. After building the product system in GaBi, users can check if inputs and outputs match up for the assemblies.

SimaPro could be qualified as a “product modelling approach”, as the users are required to enter in data for the product, before switching to a flow chart view to easily see the relative impacts from materials and processes.

Both tools can all the same display inputs/outputs and impacts categories in what appear to be every conceivable format, but the users are responsible for their choices, according to their preferred working philosophy and also related to the nature of the product system needed to be studied. For example, does the product system contain a large amount of parts but involving a few number of processes diversity? Does the product system, whatever the number of components, contain a large diversity of materials and manufacturing processes?

Table 1 shows a summary of the relevant advantages and drawbacks from our usage observation of the two software tools described above. It is noticed that we do not intended to compare these tools about commercial aspects such as their costs or the required hardware materials.

	GaBi	SimaPro
Advantages	Possibility to use parameters for the calculation and modelling; Implemented sensitivity analysis tool (Monte-Carlo Analysis), scenario analysis, parameter analysis; Easy to identify the critical life cycle stage and associated processes, in terms of impacts; Possibility to create different types of diagrams; High quality LCI database, professional database, wide range data sets cover many industrial branches.	More intuitive interface; Quickly learning how to work; Real-time analysis of impact assessment results; Easy to identify the most impact contributor in terms of part/component; Support damage categories in impact assessment methods; Possibility to create easily his assessment methods; Implemented Ecoinvent databases.
Drawbacks	Do not include the reputed Ecoinvent databases in the professional version; Results visualisation and exploitation are complicated; Less intuitive interface.	Sophisticated analysis option for the assessment results (sensitivity analysis, impacts contribution on each life cycle stages…).

Table 1: Advantages and drawbacks of most commonly used LCA software

Behind the choice of LCA tools and softwares, making the LCA method and these sophistically softwares adapted into the design situations is also a veritable challenge. It is due to the problem of time and several efforts needed. Indeed, modelling the product through understanding the implications of system boundaries and the problem of vocabulary gaps between the design and LCA languages make this appropriation impossible for people lacking experience in LCA [55]. Precisely, modelling the product life cycle requires high levels of environmental expertise and specific vocabularies (e.g. unit flow, elementary flow…) to be able to map the product life cycle’s interaction with the environment, in terms of extractions and rejects. These notions are still fuzzy among the actors of the design universe [56]. Moreover, interpreting the complete and detailed results of LCA is often not helpful in a business context [57], since this kind of information can only be understood by an LCA expert, who is not often the decision-maker in the manufacturing firms. It is therefore extremely unrealistic to ask the design actors to model the product directly in LCA software and to interpret the results by themselves.

4 PROPOSED MANUFACTURING INFORMATICS FRAMEWORK FOR THE INTEGRATION OF LCA AT DESIGN STAGE

In order to integrate LCA information into the product design stage, necessary information must be properly represented and associated to the product PLM information. In the proposed research, a case study was first conducted to examine what LCA information should be modelled. Composite parts give interesting examples on a simple piece such as a pedal crank developed with recycled carbon fibres for thermoset organic matrix composite as shown in Figure 3. During the design, product models have to integrate materials information such as matrix composition, reinforcement type (glass, carbon, aramid, and natural), their architecture (unidirectional, woven) and the structure composition (orientations of the different layers in the depth of the product). Other information like inserts or coating completes the bill of material.

Figure 3: Natec pedal crank made with recycled Carbon Firers Reinforcements (developed with recycled fibres at I2M) [30]

Currently in STEP AP 203, only very limited material information is modelled as shown in the following entities:

```
ENTITY Material_identification;
   material_name : STRING;
   items : SET[1:?] OF material_item_select;
END_ENTITY;

TYPE material_item_select = SELECT
   (Anisotropic_material,
    Braided_assembly,
    Coating_layer,
    Isotropic_material,
    Laminate_table,
    Part_view_definition,
    Substance_view_definition,
    Woven_assembly);
END_TYPE;

ENTITY Composite_material_identification
   SUBTYPE OF (Material_identification);
DERIVE
   composite_material_name : STRING :=
      SELF\Material_identification.material_name;
END_ENTITY;
```

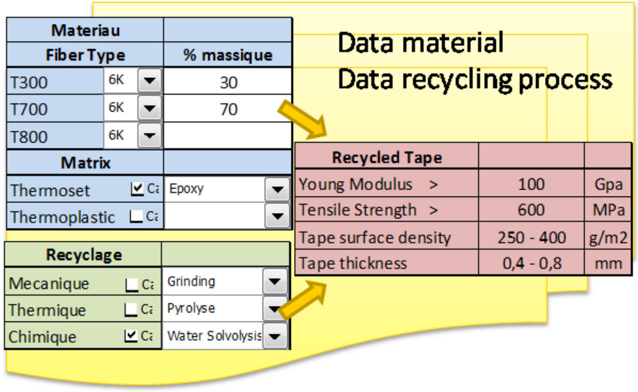
To associate composite material information to a product design, the following entities were developed in this research. The new entities are written in bold.

```
TYPE material_item_select = SELECT
   (Anisotropic_material,
    Braided_assembly,
    Coating_layer,
    Isotropic_material,
    Laminate_table,
    Part_view_definition,
    Substance_view_definition,
    Woven_assembly
    Composite_material);
END_TYPE;
```

```
ENTITY Composite_material
ABSTRACT SUPERTYPE OF (ONEOF
(carbon_fibre_reinforced_composite,
glass_reinforced_composite,
thermoplastic_composites));
   name:               STRING;
   matrics:            composite_matrix;
   resins:             composite_resin;
   reinforcement:      composite_reinforcement;
END_ENTITY;

ENTITY composite_matrix
ABSTRACT SUPERTYPE OF (ONEOF (mud, cement,
polymers, metals, ceramics));
   name:               STRING;
END_ENTITY;

ENTITY composite_resin
ABSTRACT SUPERTYPE OF (ONEOF (polyester_resin,
vinylester_resin, epoxy_resin,
shape_memory_polymer_resin));
   name:               STRING;
   material_property:  STRING;
END_ENTITY;

ENTITY composite_reinforcement
ABSTRACT SUPERTYOP OF (ONEOF (glass_fibre,
carbon_fibres, aramid_fibres, boron_fibres));
   name:               STRING;
   architecture:       fibre_architecture;
END_ENTITY;

ENTITY fibre_architecture;
ABSTRACT SUPERTYPE OF (ONEOF
(short_fibre_reinforced,
continuous_fibre_reinforced));
   name:               STRING;
   direction:          fibre_directions;
END_ENTITY;

ENTITY fibre_directions;
SUPERTYPE OF (ONEOF (continuous_aligned,
discontinuous_aligned, discontinuous_random,
unidirectional, woven));
END_ENTITY;
```

Manufacturing data must also been included in order to ensure the product / material / process combined design in the case of composite parts. Promoting recycled carbon fibres eco-design [58] imposes to access to material data (from end of life scenario and properties) at the early stage of the design. It means developing a specific data storage for material properties (depending to the recycling process) and properties models prediction (based on the different type of fibres) as illustrated on Figure 4.

Currently in STEP AP 203, the limited material information, shown above in unbold entities, is not associated to design geometry. The material information is defined only for annotation display. In order to fully integrate material information with design process, the association between product geometry and its material must be semantic. Today no integrated environment allows taking all these facets into consideration. And the next step is to compare, for an expected set of functions, the n-plet [59] in order to optimise both technically, but also environmentally with specific focus such as material resources minimization (mix of less material and improved end of life possibilities), energy optimisation and/or pollution reduction. These multi objective optimisation needs to handle all these data, models, life stages, functional unit definition in a coherent environment and at the early stage of product development.



Materiau	
Fiber Type	**% massique**
T300 6K	30
T700 6K	70
T800 6K	
Matrix	
Thermoset ☑	Epoxy
Thermoplastic ☐	
Recyclage	
Mecanique ☐	Grinding
Thermique ☐	Pyrolyse
Chimique ☑	Water Solvolysis

Recycled Tape		
Young Modulus >	100	Gpa
Tensile Strength >	600	MPa
Tape surface density	250 - 400	g/m2
Tape thickness	0,4 - 0,8	mm

Figure 4: Recycling End of Life scenario and product/material properties evaluation tool.

STEP and STEP-NC is the most suitable information structure framework that needs to be enriched by the environmental aspects of the product/process data as shown in Figure 5. Eventually, with the proposed information framework, LCA related information is integrated to the design and process planning aspects of product development. The LCA knowledge and data accumulated throughout a product life cycle can be fed back to the product design stage to improve new product development and to reduce environmental impact.

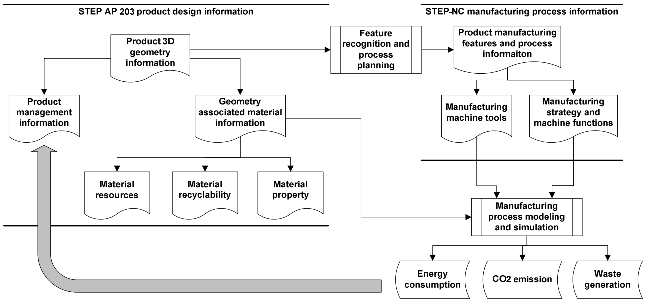


Figure 5:Proposed information framework for integrating LCA in product design stage

5 FUTURE WORK AND CONCUSIONS

The research reported in this paper is the very beginning stage of developing an information framework to support the integration of LCA at the product design stage. A simple case study was conducted to examine what composite material information should be defined in association with product design information. The next steps of the proposed research are:

1) data structure:
   - Identify all the Product Life Phases (from Fife Cycle Analysis) needs in terms of environmental data versus the existing data into STEP,
   - Identify a dynamic ontology of environmental data for product development. This will give, for every stage of the product development, the expected environmental data that must be integrated in the product data,
   - Structure the data and evaluation models to propose, usable simulation results (technical and environmental) for decision making, depending of product/process definition enrichment, and
   - Propose a STEP extension for End of Life support.
2) Data acquisition
   - Start low level implementation (at the process level for the manufacturing phase) in order to start enriching STEP with environmental concepts and to start creating data base for process evaluation and optimization,
   - Develop design approach and integrated tools specification based on STEP for Environmental Friendly

Development for some simple case study. Some interoperability problems must be identified between product development models and tools and, Life Cycle Assessment Software and Database.

Sustainable product design and manufacturing is the future of today's manufacturing industry. Sustainability research in manufacturing industry has been conducted in several different approaches from life cycle assessment, to design for sustainability, and to energy efficiency analysis. These research fields are segmented and they are specific for certain products, materials or processes. The lack of manufacturing system and sustainability information integration hampers the widespread adaptation of the best sustainability practices in the manufacturing industry. In order to provide product designer with comprehensive material and environmental related information at the design stage, a complete information structure must be developed to associate sustainability information with product design information and product manufacturing process. This research proposes to develop such an information framework based upon STEP and STEP-NC information models. An initial case study was conducted to identify composite material information that should be defined for product design.

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