Towards Standards-Based Generation of Reusable Life Cycle Inventory Data Models for Manufacturing Processes

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The production stage of a product's life cycle can significantly contribute to its overall environmental impact. Estimates of environmental impact for a product are typically produced using Life Cycle Assessment (LCA) methods. These methods rely on Life Cycle Inventory (LCI) data containing impact estimates of manufacturing processes and other operations that contribute to a product's creation. The accuracy of LCI data is critical for quality assessments; however, this data is often insufficient in the types and varieties of manufacturing processes covered and is often only a coarse estimate of actual impacts. At the same time, much manufacturing research focuses on how to model, measure, assess, and reduce the environmental impacts of manufacturing processes. Recent standards emerging from ASTM International define a structured format for presenting these studies in a reusable way. In this paper, we investigate the potential for using the ASTM E3012-16 format to generate LCI datasets suitable to perform LCA by mapping from the ASTM standard into the widely-adopted ecoSpold2 format. A process is presented for generating LCI datasets from ASTM models, and overlaps and gaps between the two standards are identified.

1 Introduction

Manufacturing process improvement is critical to reducing the environmental impact of manufacturing as a whole. Manufacturing alone accounts for more than 21 % of greenhouse emissions in the United States [1]. Manufacturers struggle to reduce their impacts partly because of difficulties identifying single improvements that will have broad effects across the facility. The low hanging fruit commonly recommended for many manufacturers addresses facilities heating, ventilation, air conditioning (HVAC), and lighting through better controls; however, these only go so far. Further improvements are unique to each individual manufacturer and require detailed knowledge of each situation to identify inefficiencies and opportunities for reducing impacts [2,3,4,5,6,7,8,9,10]. Several standards are available to guide manufacturers to more responsible environmental stewardship [11, 12, 13, 14, 15, 16, 17, 18, 19]. These standards support expertise at multiple stages in the life cycle. Aligning these standards through data representations has been identified as a possible way to simplify their application [20, 21]. In particular, the International Organization for Standardization (ISO) [1] and ASTM International [2] provide complementary recommendations. ISO standards for environmental management provide guidance to manufacturers for management practices; ASTM International standards for process improvement at the manufacturing operations level address specific manufacturing processes, which depending on the product, can account for the bulk of environmental impact. This paper describes an approach to more closely align the efforts. Any terms described in this paper are taken directly from the ISO Life Cycle Assessment (LCA) suite of standards [12, 13, 14, 18, 19], ASTM standards [11, 15, 17], or ecoSpold2 [22, 23] and are summarized in Appendix A.

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[1]The ISO 14000 series of standards focus on Environment Management and include the standards for Life Cycle Assessments

[2]ASTM Internationals E60.13 Sub-committee focuses on Sustainable Manufacturing standards

1.1 Paper Organization

The rest of the paper is structured as follows. Section 1.2 discusses background standards and methods for reusable LCAs. Section 1.3 presents motivation for the work and section 1.4 gives a background on activity modeling. Section 2 presents the details of ASTM E3012-16 and Section 3 discusses ISO 14040 and the ecoSpold2 representation formats. Section 4 presents a process for creating an LCI dataset from a unit manufacturing process model and the necessary mapping from the ASTM E3012-16 format to the ecoSpold2 format. Section 5 discusses a use case for this activity and Section 6 provides conclusions and areas of future work. Lastly, Appendix A organizes definitions of terms from the standards and data formats, Appendix B contains the ASTM E3012-16 format and Appendix C contains the ecoSpold2 format for the case study.

1.2 Background

The ISO LCA methodology applies to the entire product life cycle including manufacturing and all downstream and upstream activities, as shown in Figure 1 from ISO 14040 [12]. However, often manufacturers are only concerned with the production stage, as this is the only stage that they can directly influence. When an LCA is scoped to only the production stage of the life cycle, it is called a "gate-to-gate" assessment. Gate-to-gate assessments are not LCAs as defined by ISO 14040 [12].

Three set of standards aid manufacturers in analyzing the environmental impact of the production stage of the life cycle: ISO 20140, ISO 14955, and ASTM E60.13 standards. ISO 20140 "Automation systems and integration - evaluating energy efficiency and other factors of manufacturing systems that influence the environment" consists of 5 parts that aid manufacturers in understanding environmental hot spots [16]. It supports manufacturers in analyzing the environmental influence of manufacturing systems and supports the allocation of environmental impacts to individual processes within the interconnected manufacturing system. The ISO 14955 standards provide guidance for manufacturers of NC-controlled metal processing machines to minimize their environmental impacts: ISO 14955-1:2017 "Machine tools - Environmental evaluation of machine tools - Part 1: Design methodology for energy-efficient machine tools" and ISO 14955-2:2018 "Machine tools - Environmental evaluation of machine tools - Part 2: Methods for measuring energy supplied to machine tools and machine tool components" [24, 25]. While these standards provide an in-depth analysis framework very useful for understanding and reducing the impacts of these types of machines through quantification of energy supplied to perform the different functions of the machine, these standards are limited to the particular class of manufacturing processes. Similar study is needed for other manufacturing processes.

The guidance coming from ASTM International's E60.13 subcommittee on Sustainable Manufacturing defines an initial methodology for these types of in-depth studies for the range of manufacturing processes. Three standards support manufacturers in reducing the impacts of manufacturing processes on the environment. The ASTM E2986-15 "Standard Guide for Evaluation of Environmental Aspects of Sustainability of Manufacturing Processes" provides guidance in developing evaluation procedures for environmental performance of manufacturing processes [15]. ASTM E3012-16 "Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes" helps characterize and systematically capture, describe, and clarify techniques for reducing environmental impacts of a manufacturing process [11]. Both standards prescribe the use of a continuous improvement process involving definition of Key Performance Indicators (KPI) to measure environmental performance, but do not provide guidance on how to create these KPIs. The ASTM E3096-17 Standard Guide for Definition, Selection, and Organization of Key Performance Indicators for Environmental Aspects of Manufacturing Processes fills this need and provides guidance on defining, selecting, and organizing sustainable KPIs [17].

While each of these standards helps manufacturers understand and improve the environmental impacts of the production phase, they do not address how a change during production can ripple throughout the rest of the life cycle. For example, a small change to reduce the environmental impact during production might increase the overall impact of the product. An LCA provides the proper analysis to illustrate and calculate the effects of one change on the overall environmental impact of a product, but a full LCA can sometimes be time consuming and difficult for manufacturers (especially small-to-medium manufacturers (SMMs)). On the other hand, product designers often use rough estimates of manufacturing impact based on similar products, which can produce inaccurate results [20]. This paper investigates techniques for using manufacturing process models to generate LCI datasets suitable for use in LCAs. This capability will allow manufacturers to reuse models of the impact of a manufacturing process, originally created to understand impacts only in the production phase, in a full LCA. The models provide an understanding of the effects of production changes on the product's overall environmental impact.

The effort builds on the standard environmental assessment techniques defined in ASTM E3012-16 and ISO 14040:2006. Both standards have data representations [3] for representing impacts of manufacturing processes; however, these representations are currently incompatible, due to differing purposes of each assessment. This paper examines both the ASTM and ISO formats and highlights their intersection. ASTM E3012-16 provides more flexibility to manufacturers as compared to ISO 14040 for different types of analysis on the manufacturing process and system.

The ASTM E3012 standard was initially designed to communicate information about the performance of manufacturing processes including impacts on the environment [6]. It provides a structured way of representing that information so manufacturers can easily understand the ramifica-

[3]The LCA data format is described in ISO 14048 [26] and is the basis of the widely used ecoSpold2 format.

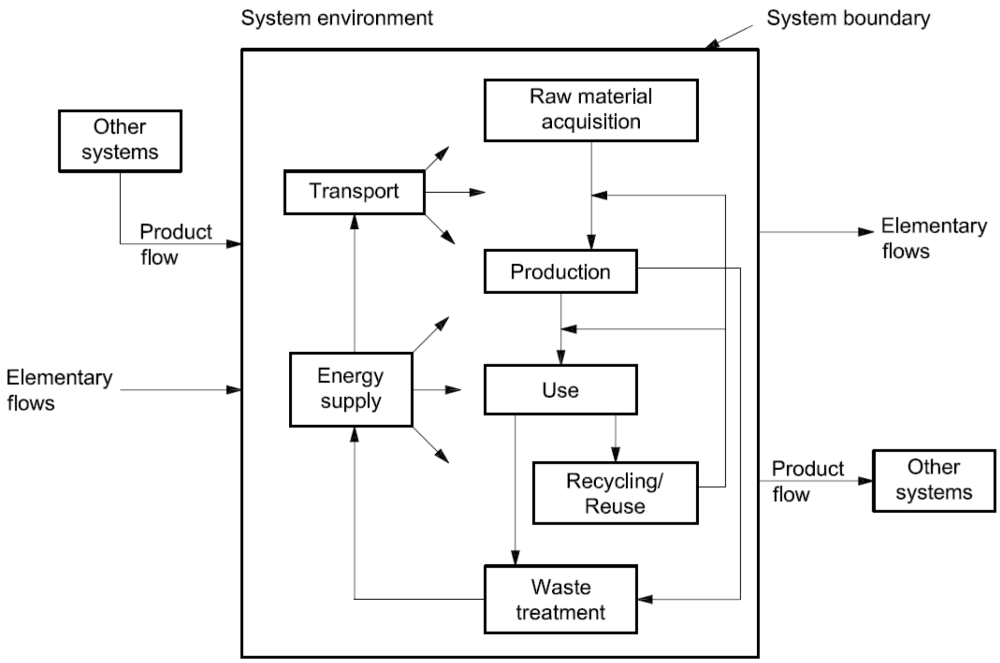

Fig. 1. Example of a system for LCA. Figure taken from [12]. ©ISO. This material is reproduced from ISO 14040:2006 with permission of the American National Standards Institute (ANSI) on behalf of the International Organization for Standardization. The complete standard can be purchased from ANSI at https://webstore.ansi.org. All rights reserved.

tions of changes to the manufacturing process on the environment. Changes can include variations in the input materials, differences in product designs, and changes to operational settings of the process. All of these variables can influence environmental impacts, and manufacturing processes can be optimized based on these variables and/or different performance objectives. By explicitly identifying influences on the environment and providing a means of measuring, benchmarking, and comparing performance of the process over time, more control is gained over environmental impact. ASTM E3012-16 focuses on representing factors that affect performance of manufacturing processes, and producing impact estimates based on those factors. At the core of the standard is a representation for computing impacts through transformation functions, which can be either physics-based or data-driven. Physics-based transformation functions are built when the modeler has a good understanding of the system, and is also able to describe it mathematically while data-driven functions are built when the modeler has lot of data but no direct theoretical knowledge about the represented system. Data-driven models are often outputs from machine learning techniques. Running the physics-based functions or using data with data-driven functions enables the computation or prediction of output values that are similar to output exchange amounts in an ecoSpold2 model. Given the cumulative contribution of manufacturing to the overall environmental impact of society, being able to improve manufacturing process performance will certainly be of great value [1]. Fine tuning the performance of manufacturing processes can also result in economic saving through higher efficiency while reducing environmental impact.

In contrast, ecoSpold2, initially derived from the ISO LCAs data documentation format (ISO/TS 14048:2002 Environmental management Life cycle assessment Data documentation format), was designed as a format for curating data to create LCI datasets for LCA [26, 22]. The format can capture data on environmental impacts across all activities in a product life cycle, from raw material processing through end of life processing and disposal. This data can span the full range of industries, including agriculture, mining, transportation, manufacturing, and others. LCA can make use of databases of previously studied processes. These LCI datasets are collections of scientific studies of many individual product creation activities, called unit processes, that measure impacts of that process on the environment. These datasets can be used in other LCAs to estimate similar undertakings in different contexts. Since an LCA carries significant uncertainty, these studies can serve as proxies in many situations. When no study can be found to adequately represent a given unit process, then a new dataset needs to be produced. Over time LCAs should become more accurate as more LCI datasets become available. The curation of these datasets is very important to reliably reuse LCI datasets in multiple LCAs, and the ecoSpold2 format reflects these curation needs.

A number of LCI databases have been developed for a variety of unit processes. These databases have an extensive review process and require additional meta information about the LCI data, such as data source, duration the model is applicable, authors, reviewers, etc. The National

Renewable Energy Laboratory (NREL) created the US LCI database [27]. The goal of NREL is to cover commonly used materials, products, and processes in the United States, while maintaining data quality and transparency. A similar project exists in Europe with the ecoInvent database [28]. The ecoInvent database started in 2003 and has curated over 13000 LCI datasets. A number of other efforts have generated and curated LCI data, through government (GREET [29], USDA [30]), working groups and academics (UPLCI [31], CO2PE! [32]), and commercial efforts (Athena [33], DataSmart [34], GaBi [35]). While these databases can facilitate exchange of models, the LCI datasets still need to be generated and stored in the proper format. Suh et al. studied data mappings between the US LCI database and the ecoInvent database; however, they came to the conclusion that significant effort is required to restructure the databases to fill the information gaps [36]. While these databases enable reuse of LCI datasets for LCA, there is a dearth of reliable manufacturing unit process models that manufacturers can utilize for assessment.

Product designers often use analogy for decision making – a similar manufacturing process yielded X and Y results – however, this often leads to inaccurate, aggregated results [20]. LCA practitioners frequently ignore impacts from manufacturing, as these impacts are less than the cutoff criteria for the analysis, making manufacturing impacts appear less than the actual impact. However, Suh et al. found that varying cutoff criteria can skew hotspot identification and alternative comparisons [37]. A higher cutoff criteria might lead to impacts being under estimated in an LCA as individual activities might fall below the cutoff and are thus excluded from the study, however, the sum of these individual impacts are often significant [38]. Setting a higher cutoff criteria might rise from a lack of time, accurate data, or resources to perform the LCA, but can limit the identification of hotspots from different stages of the life cycle [39, 37]. Enabling standardized and reusable models to accurately analyze various activities within the stages of the life cycle would allow practitioners to lower the cutoff criteria and capture more fine-tuned impacts. Reusable, accurate LCI datasets are critical to reducing time and effort in conducting LCA. To the authors knowledge, there has been no effort in creating a generalized solution to adapt manufacturing process models into LCI data formats. Some solutions were created for parameterization of specific processes, for example wafer fabrication in the semi-conductor industry [40], or for using non-standard solutions [32] for repeatable, reusable, and accurate LCA. Mapping between the ASTM E3012-16 format and ecoSpold2 is the first step towards solving a more generalized solution.

1.3 Motivation

This paper examines the viability of generating new LCI datasets by applying a mapping from the ASTM E3012-16 format into the ecoSpold2 format. This mapping provides potential benefits discussed here in the context of two high level use cases: trade-off analysis and design for manufacturing. A more in-depth use case based on a milling example is presented in Section 5.

The first use case is trade-off analysis for manufacturing a product. By mapping between the ASTM E3012-16 format and ecoSpold2 formats, a sustainability expert can quickly perform trade-off analyses between alternative process plans for manufacturing a part. For example, if multiple machines can perform the same task and are modeled in the ASTM E3012-16 format, an manufacturing process engineer can quickly study the impacts of various machines in the context of a specific part design. Without a mapping between these formats, this would require modeling each process multiple times (once in the ASTM data format and once in the ecoSpold2 format for each process). It can also be hypothesized that performing an LCA with UMP models would be more accurate because UMP models are often more tailorable to the situation than the equivalent unit process in an LCI database. Process models in LCI databases are frequently based on mass of material shaped or surface area of material produced or treated, often leading to the impacts from manufacturing falling within the noise of an LCA. An instantiated UMP has more detail about the process itself and the specific parameters leading to more accurate assessment of the sustainability impact of a process. These types of models allow for a decreased cutoff criteria for LCAs, providing more accurate, refined analysis.

Work at the National Institute of Standards and Technology (NIST) is investigating methods for decreasing the time to model manufacturing processes using a repository of UMPs [41]. This repository will house manufacturing process models that can be instantiated by manufacturers to fit the needs of their system. These models are expected to further reduce time and effort to model manufacturing processes, and to contribute useful, reusable LCI datasets. It will enable manufacturers to investigate alternative processes for producing a part through LCAs.

Another potential use case is in the design of products for a specific manufacturer. Using the mapping, product designers can take a model of a particular manufacturers process configuration and map to the ecoSpold2 format to perform an LCA on the product. This yields more accurate results in less time, because these models are specific to one manufacturer instead of abstracted to generic manufacturers. If this type of mapping was integrated into Computer Aided Design (CAD) programs, designers could link product features to specific environmental impacts, such as energy consumption, further reducing the time to accurately model these impacts. Without a mapping procedure, a product designer would need to remodel the manufacturing process models for the specific manufacturer in the correct format. By using models from multiple facilities, product designers can quickly perform and compare LCAs across multiple facilities using a composed system of UMP models.

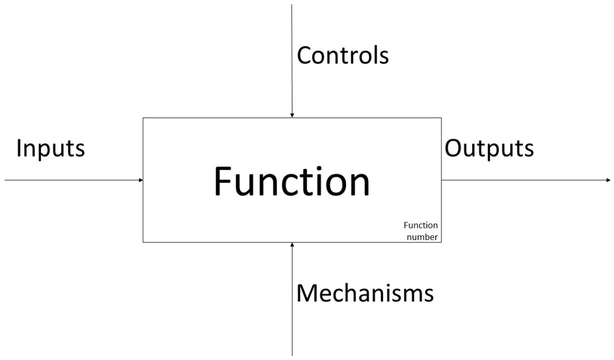

Fig. 2. IDEF0 diagram: boxes represent functions, arrows represent inputs, outputs, controls, and mechanisms as described in [42].

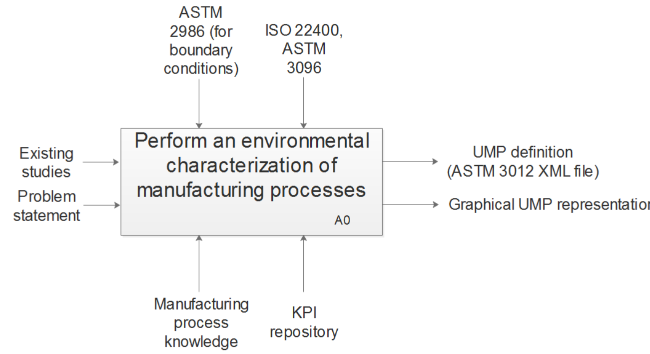

Fig. 3. The IDEF0 diagram for performing activity A0: Environmental characterization of manufacturing processes.

1.4 Activity Modeling

The creation of datasets for each of the two standards is a non-trivial process. In this paper, we use IDEF0 [4] to clarify the functions involved in creating each type of dataset, and follow with a proposed merger of the functions to generate LCI data from the ASTM E3012-16 format. IDEF0 is a diagramming technique for modeling the functions involved in a process [42]. In IDEF0 functions are represented as boxes with arrows flowing into and out as shown in Figure 2.

Arrows coming in from the left represent inputs that are expected to be transformed by the function, arrows coming in from the top represent information guiding the function, arrows going out on the right are outputs of the function (resulting from transformation of the inputs), and the arrows coming in from the bottom are things performing the function. Collectively these arrows are referred to as ICOMs. IDEF0 diagrams are organized hierarchically where each function can be decomposed into a set of sub-functions. This decomposition is indicated by a function number on the diagrams with 0 being the top level activity.

2 ASTM E3012-16

ASTM E3012-16 defines a graphical and formal data representation for manufacturing processes, called unit manufacturing processes or UMPs. UMPs represent a manufacturing process in terms of physical inputs, physical outputs, transformations between them (functions), information requirements such as performance parameters, and the manufacturing resources needed to carry out the process. A UMP is defined in ASTM E3012-16 as the smallest element or subprocess in manufacturing that adds value through the modification or transformation of shape, structure, or property of input material or workpiece [11]]. A UMP as defined by ASTM would be considered a unit process as defined by ISO14040, but not all unit processes are UMPs. Research in the application of UMP models to a wide-range of manufacturing processes and in the need for extending related standards is on-going [43]. The current standard supports the initial use case of facilitating communication between manufacturing stakeholders. Additional work is exploring collection, composition, and the computational reuse of these models system analyses [43].

[4] Integrated Computer Aided Manufacturing (ICAM) DEFinition for Function Modeling (IDEF) modelling language level 0

2.1 Creation of ASTM E3012-16 UMP Models

The IDEF0 diagrams show the methodology proposed in ASTM E3012-16 to environmentally characterize manufacturing processes. Figure 3 represents the top level function A0. The A0 function is broken down into three sub-functions described below.

A0: Perform Environmental characterization of manufacturing processes

This characterization activity makes use of research, existing literature, and ASTM standards to support the construction of UMP models for characterizing the environmental aspects of manufacturing processes. The necessary steps to characterize a UMP are to *Identify the UMP and associated Key Performance Indicators* (KPIs) (A1), *Identify UMP specific information* (A2), and *Identify transformation functions* (A3), and are presented in Figure 4.

A1: Identity UMPs and KPIs Based on the problem statement and existing studies, a UMP scope and KPI definition are defined in the UMP identification activity. This activity consists of sub-activities including:

- Select the manufacturing process to be characterized.
- Specify the boundary encompassing one or multiple UMPs to enable the identification and selection of UMP specific information. This sub-activity is also supported by ASTM E2986-15 [15].
- Select the KPIs appropriate to measure the processs environmental performance, ensuring process control, and ensuring the resulting products conformance to the product specifications. This sub-activity is also supported by

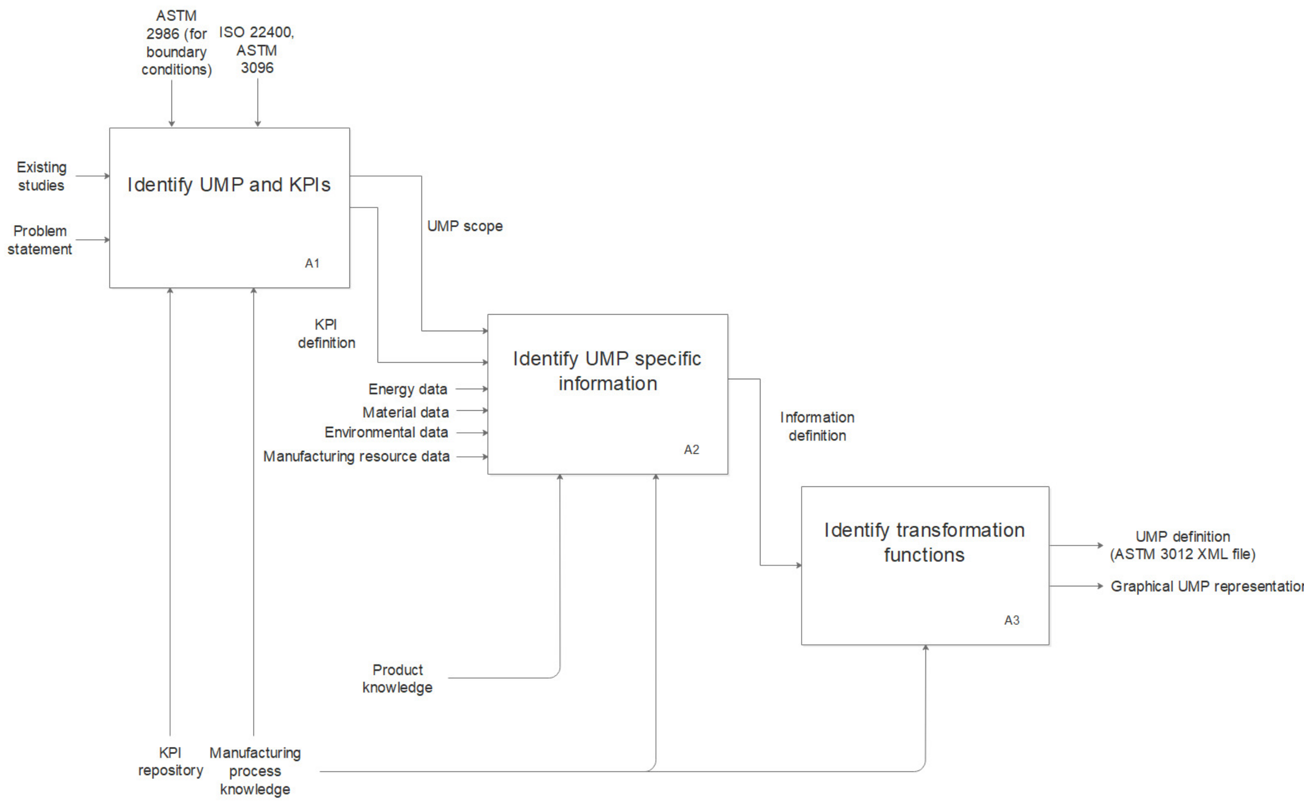

Fig. 4. IDEF0 diagram describing activities for Environmental characterization of manufacturing processes.

ASTM E3096-17 and ISO 22400 [17, 44].

A2: Identity UMP specific information To perform the information identification activity, in addition to the UMP scope and KPI definition, input data including energy, material, resources, and environmental data (waste and/or emissions) are necessary. The result is a list of required information related to the selected UMPs. This activity consists of sub-activities including:

- Describe the physical inputs to the process.
- Describe the physical outputs to the process.
- Describe the product and process information.
- Describe the manufacturing resources used in execution of the process.

A3: Identify transformation functions In this activity, the list of information is taken as input and an ASTM E3012-16 information model is generated including all the information previously defined in the above activities. This activity consists of sub-activities including:

- Specify material transformation functions.
- Specify energy transformation functions.
- Specify information transformation functions.

2.2 ASTM E3012-16 Format

The ASTM E3012-16 information model has a format that is a process-centric representation of manufacturing processes in both a graphical form and an Extensible Markup Language (XML) Schema Definition (XSD) [45]. The XSD for ASTM E3012-16 includes the following information elements:

- *Input*
- *Output*
- *Feedback*
- *ProductProcessInformation*
- *ResourceInformation*
- *Transformation*.

Input describes material, consumables, energy, and external factors entering into the UMP. *Output* includes product, by-product, waste, and emissions from the UMP. *Feedback* is for outputs used as inputs to another UMP, or back to the same UMP. For instance, water may be feedback into a process for reuse. *ProductProcessInformation* includes all parameters and relevant information to compute transformations performed by the UMP. *Resource* describes any equipment, personnel, fixtures, gauges, tooling, external accessories, software and control programs, and required operational settings used in manufacturing a product [15]. *Transformation* includes equations representing the relationship between *Input* and *Output*, but also enables the computation of metrics to characterize the UMP. The schema also enables the representation of a system composed of UMPs, described as a *ComposedSystem*.

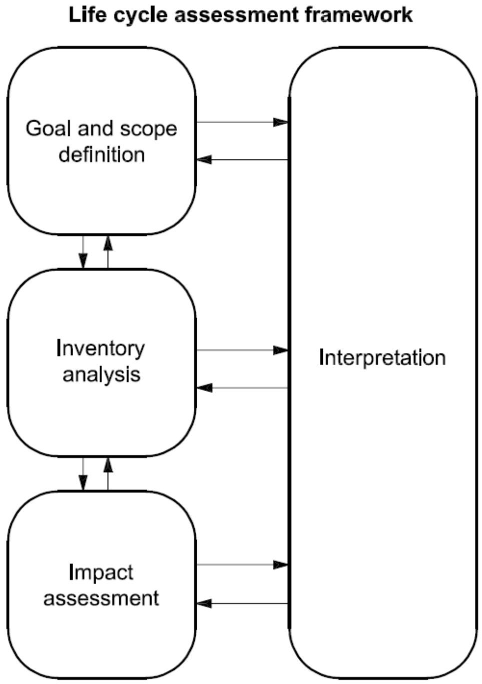

Fig. 5. The various stages of a Life Cycle Assessment. This figure is taken from [12]. ©ISO. This material is reproduced from ISO 14040:2006 with permission of the American National Standards Institute (ANSI) on behalf of the International Organization for Standardization. The complete standard can be purchased from ANSI at https://webstore.ansi.org. All rights reserved.

3 ISO 14040

LCA is a technique to assess sustainability of a product from the cradle, where raw material is extracted, to the grave, where the product is finally disposed [46]. The formal definition from ISO 14040 defines LCA as compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle [12]. LCA has four main phases: 1) goal and scope definition, 2) life cycle inventory (LCI) analysis, 3) life cycle impact assessment (LCIA), and 4) life cycle interpretation [12]. Figure 5 [12] shows the full LCA process from ISO 14040.

The goal and scope definition phase formally defines a system boundary by identifying what is to be studied, the subject, and intended use of the study. The goal includes defining the intended application, audience, and reasons for performing the LCA, while the scope defines:

1. the system to be studied,
2. the functions of the system or systems,
3. the functional unit (A functional unit is the quantified performance of a product system and is used as a reference unit [12].)
4. the system boundary,
5. the allocation procedures,
6. data requirements,
7. assumptions,
8. limitations,
9. data requirements,
10. type and format of the report for the study (can be reported in the form of a “footprint”: the metric(s) used to report LCA results addressing an aspect of the environment (called an area of concern) [19]).

The system boundary of the LCA is defined by the unit processes included in the system. ISO defines unit processes as the smallest element considered in the life cycle inventory analysis for which input and output data are quantified [12]. LCAs can be calculated based on available economic, financial, or material flow data.

The inventory analysis phase identifies, gathers, and aggregates data about the system being assessed. This phase identifies activities impacting the environment within the scope of the assessment, and collects appropriate estimations of their impact [5]. LCI data is collected for each unit process whether from a database or otherwise generated through a separate LCA. This data is often coarse grained since collection is often only reliably done on an aggregate level such as energy use of a manufacturing plant or waste produced by a manufacturing line. The final step of this phase is to aggregate the inventory data contributing to the LCA–a summation of the impacts across the life cycle stages covered by the analysis.

Using the aggregated impact data the impact assessment phase provides information to determine the environmental significance of the inventory analysis. For example, where LCI data might indicate the type and amount of energy used, the impact assessment phase describes the significance of these results over a range of environmental parameters, such as midpoint considerations: and use, human health, toxicity, etc. or endpoint considerations: e.g. fish deaths in Lake Michigan.

Lastly, life cycle interpretation summarizes the results of the previous phases to reach conclusions and develop recommendations in accordance with the goal and scope of the assessment. Life cycle interpretation can be performed at any stage in the LCA process. Full LCAs are not often used by manufacturers due to high cost, time, and data needs, however as stated earlier, LCI data can be reused for multiple LCAs where commonality exists in the production processing steps. Considerable knowledge of downstream unit processes in the life cycle, such as manufacture of the product, is still needed to complete a LCA across the full product life cycle [47]. This paper focuses on utilizing the ASTM methodology for manufacturing process modeling to create LCI datasets for use in LCA.

3.1 Perform LCA

The following IDEF0 diagrams describe the necessary functions to perform an LCA starting from the function B0

[5]Non-environmental impacts might also be collected, such as with life cycle costing, however this is outside the scope of this paper.

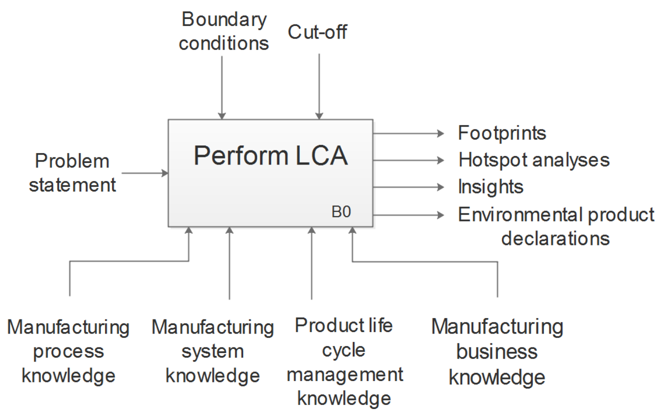

Fig. 6. The IDEF0 diagram for performing activity B0: Perform LCA.

shown in Figure 6.

B0: Perform LCA The necessary steps to perform an LCA are *Define goal and scope* (B1), *Run inventory analysis* (B2) and *Perform Impact Assessment* (B3) [12] as shown in Figure 7. As shown in Figure 5, the interpretation activity is performed during each stage of an LCA. The life cycle interpretation should provide readily understandable, complete and consistent presentation of the results of the LCA [12]. The interpretation step is left out of the IDEF0 diagrams for brevity.

B1: Define goal and scope The goal and scope of the LCA activity are defined during this step. This includes setting system boundaries and defining the unit process for the LCA. System boundaries specifically and clearly identify the system under study. To achieve this clarity, a system is defined in terms of the function it fulfills. This concept is referred to as a functional unit (e.g. extruding 1000 aluminum bars by 2-shot cold extrusion). This LCA activity consists of sub-activities including:

- Define the goal of the LCI
  - Include the application, the reasons for the study, the audience for the study, and the application of the results.
- Define the scope of the LCI
  - Define the functional unit providing references for inputs and outputs and how they are related for comparisons of results.
  - Define reference flows, where a reference flow is the measure of the outputs from processes in a given product system required to fulfill the function expressed by the functional unit [12].
  - Define system boundary
    - Define unit processes included in the system, such as:
      - Acquisition processes of raw materials.
      - Inputs/outputs in manufacturing sequence
      - Distribution/transportation
      - Production of fuels, electricity, heat
      - Use and maintenance of products
      - Waste and products disposal
      - Recovery of used products (recycling)
      - Manufacture of ancillary materials
      - Manufacture, maintenance, and decommissioning of capital equipment
      - Other operations (lighting, heating, etc.)
    - Define the cutoff criteria, which is the amount of material or energy flow or level of environmental significance with unit processes that are to be excluded from the study [12].

B2: Run inventory analysis The run inventory analysis activity organizes all inputs, calculates necessary outputs, and allocates flows to be used in the LCI. This activity has the most overlap with the ASTM standards and is further decomposed into three sub-activities. The resulting output is an ecoSpold2 file with the LCI information. This activity consists of sub-activities, shown in Figure 8 including:

- **B21:** Data collection
  - Inputs
    - Raw material
    - Ancillary material
    - Other physical inputs
  - Products, co-products, waste
  - Emissions to air, discharges to water and soil
- **B22:** Calculation
  - Generalize the results for each process
    - Validate Data
    - Relate data to unit processes
    - Relate data to reference flows
- **B23:** Allocation of Flows
  - Determine what products are yielded, recycled, or discarded.

B3: Perform Impact Assessment The perform impact assessment activity evaluates the significance of potential environmental impacts using the results from the LCI. Data from B2 is associated with specific environmental impact categories and category indicators during this activity [12]. For example, if the the LCI results provide the SO_2 emissions in kg an environmental impact category could be acidification, while the category indicator could be proton release [18]. The output of this activity are footprints, hotspot analyses, insights, and/or environmental product declarations [19].

3.2 EcoSpold2 Format

Storing information from an LCA in a standard format simplifies reuse and shareability. In an LCA an activity represents a unit process of a human activity and its exchanges with the environment and other human activities [23]. An example of an activity can be a hard coal mine transforming

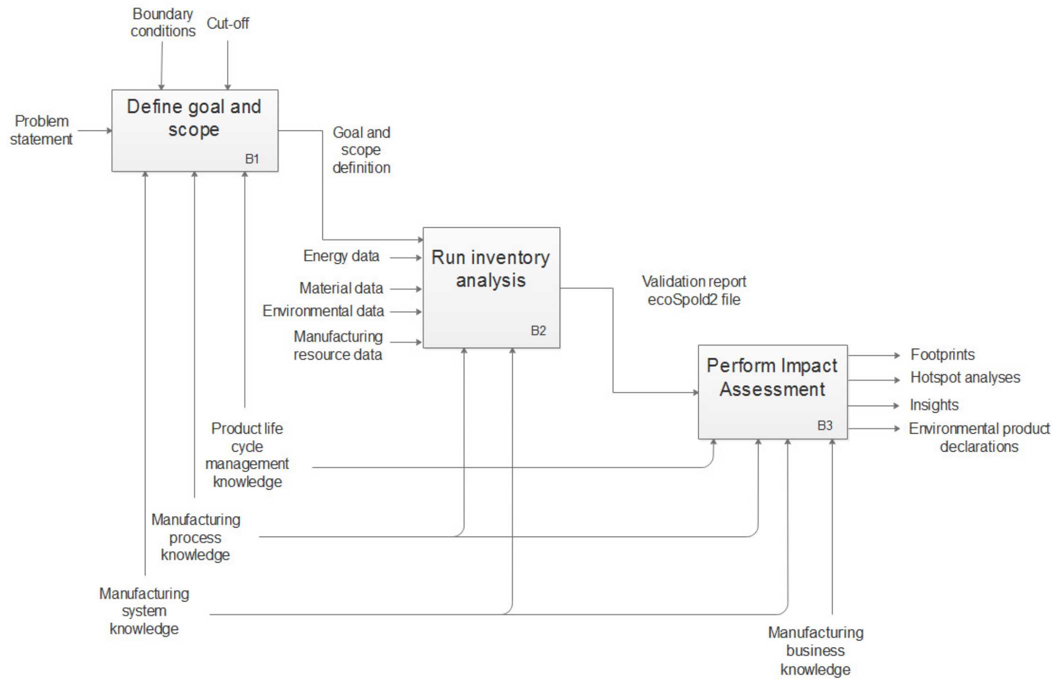

Fig. 7. IDEF0 diagram describing activities for an LCA.

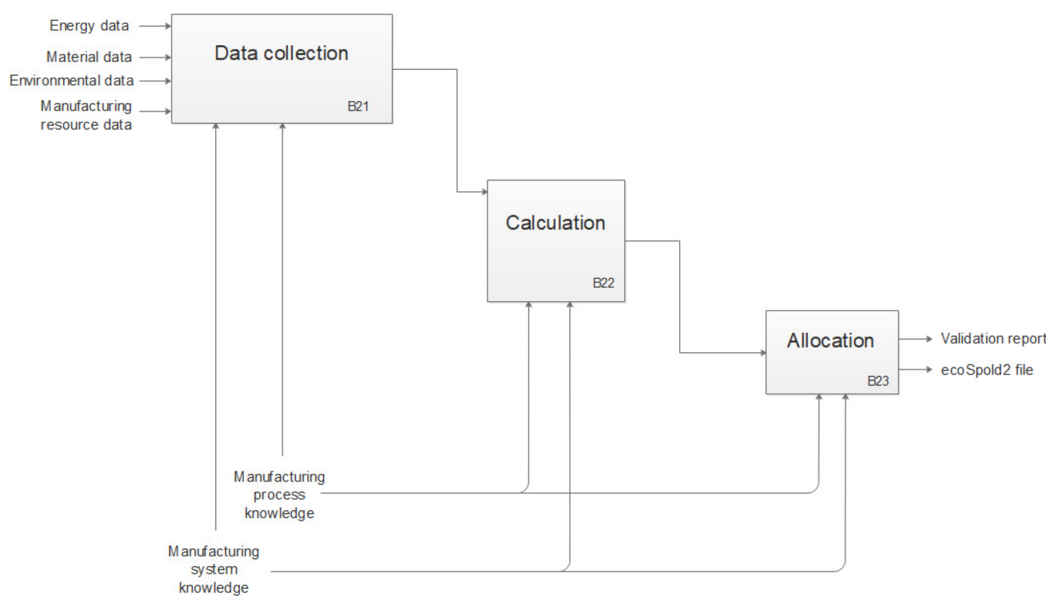

Fig. 8. IDEF0 diagram describing subactivities for running an inventory analysis.

coal from the ground into the product coal or an automobile plant making cars from metal, plastic, and energy. The format studied in this paper, the ecoSpold2 format (specified in an XSD), uses a collection of *activityDataset* elements to represent an activity. Within ecoSpold2, there are four kinds of *activityDataset* elements:

- *activityDescription*
- *flowData*
- *modelingAndValidation*
- *administrationInformation.*

activityDescription provides meta-information describing the activity. In particular, it identifies the dataset with an *id* and *parentID*, classifies the dataset, geographically locates the activity dataset, and defines the period of time the activity dataset is valid. Two types of exchanges are defined in the ecoSpold2 format: *elementaryExchange* and *intermediateExchange*. Elementary exchanges occur between the activity and the environment, and is defined by ecoSpold2 as an exchange with the natural, social or economic environment [23]. Examples include unprocessed inputs from nature, emissions to air, water and soil, physical impacts, such as water from a lake being used to cool a process. An intermediate exchange is an exchange that occurs within an activity or between activities and is defined by ecoSpold2 as an exchange between two activities that stays within the technosphere and is not emitted to or taken from the environment, for example, water from a treatment plant being used to cool a process [23]. The technosphere represents all human activities and is defined as "an exchange of a certain activity can be between the activity and the environment (elementary exchange, for example CO_2 emission to air) or between two activities (intermediate exchange, for example wastewater to be released from one activity to another treatment of wastewater) [23]." *flowData* is used to represent all possible exchanges in the activity and includes formulas to compute values associated to the exchange. Parameters used in the formulas are also defined in a collection of *parameter* that are included in *flowData*. *modelingAndValidation* gives meta-information about how unit processes are modeled, such as how the data has been collected or calculated. This information is included in the *representativeness* element. ecoSpold2 can also represent how the activity has been reviewed, and validated (included in the *review* element). *administationInformation* provides meta-information about the authors and publishers of the activity dataset.

4 Mapping UMP data into ecoSpold2 Format

The two formats and supporting standards complement each other. To illustrate this, the IDEF0 diagram in Figure 9 combines simplified versions of the diagrams presented in Figure 4 and Figure 7. The data contained in an ASTM E3012-16 file generated from A3 can be used as inputs to the activity B2 to perform the inventory analysis. A necessary activity is, however, missing. The ASTM E3012-16 file needs to be transformed into the ecoSpold2 format. We call this activity "Perform data mapping" in the proposed diagram. To define this mapping, it is first necessary to establish a conceptual mapping between the two formats. The ASTM E3012-16 and ecoSpold2 formats have some elements that represent the same information, however, the degree of detail differs and some information is captured formally only in one of them. The proposed mapping focuses on transformations between the two XML formats and defines the generation of ecoSpold2 documents from ASTM E3012-16 files. The parts of the data, including both elements and attributes, that can be directly mapped between the two forms are described in the following subsection. A description of the data that is captured by the ecoSpold2 format but not the ASTM E3012-16 format is also presented. An element in XSD defines the structure of the data and determines the structure of the instance document, while an attribute contains extra information within the element [45]. XSD does not define the distinction of an element, child element, or attribute; therefore, this choice is left to convention.

4.1 Direct Mappings

The Venn diagram in Figure 10 presents the overlap between the two formats. Both data formats aim to represent process inputs and outputs as well as transformations that occur when executing the process. In ecoSpold2, the transformations are represented in the exchanges included in the flowData element. The *mathematicalRelation* attribute in the exchanges defines the equation to compute the value of an exchange if needed. The value can represent a direct measurement. The ASTM E3012-16 format separates this same information into multiple elements. The ASTM E3012-16 equivalent of ecoSpold2 exchanges are *Input*, *Output*, and *ProductAndProcessInformation*. The equations in ASTM E3012-16 are contained in the Equation element. Our mappings focus mainly on these previously mentioned elements since they contain much of the same information in both data formats. In addition, some meta-information about the unit process is also recorded in both formats and is identified in Table 1. Table 1 displays the mappings between the ecoSpold2 XSD (elements, child elements, and attributes) to the ASTM E3012-16 XSD (elements and attributes). This table only displays relationships when the information can be represented in both formats. The majority of mappings are in the ecoSpold2 *flowData* element. The mappings are not always one-to-one, because the elements or attributes contained in *flowData* often apply to *Input*, *Output*, *Feedback*, or *Equation* in the ASTM schema. As stated earlier, this paper looks at mapping from the ASTM E3012-16 format into the ecoSpold2 format.

The first column is a child element of the ecoSpold2 *activityDataset* element. The second column is the child element of the one in the first column. The third column gives the child element or attribute of the element in the second column. The fourth column has the corresponding ASTM E3012-16 element. The fifth column is the corresponding attribute of the element in the fourth column. For example, the *activityName* element of the *activity* contained in the *activityDescription* in ecoSpold2 corresponds to the name attribute of UMP in ASTM E3012-16. Note for understanding: *customExchange* is not defined as an element in ecoSpold2 but as a complexType to serve as parent class of elementary and intermediate exchanges, and contains the elements common to the two types of exchange. These ecoSpold2 exchanges are semantically equivalent to the transformations in ASTM E3012-16.

4.2 EcoSpold2 Coverage Missing from the ASTM E3012-16 Format

In addition to the information that is available in both formats, some information represented in ecoSpold2 is not in the ASTM E3012-16 data format. This information supports good curation practices, which are necessary for the ASTM standard. To enable this curation, the ASTM standard needs the inclusion of the following types of information captured in ecoSpold2:

- ecoSpold2 includes meta-information about the parameters and exchange that occurs in the process with el-

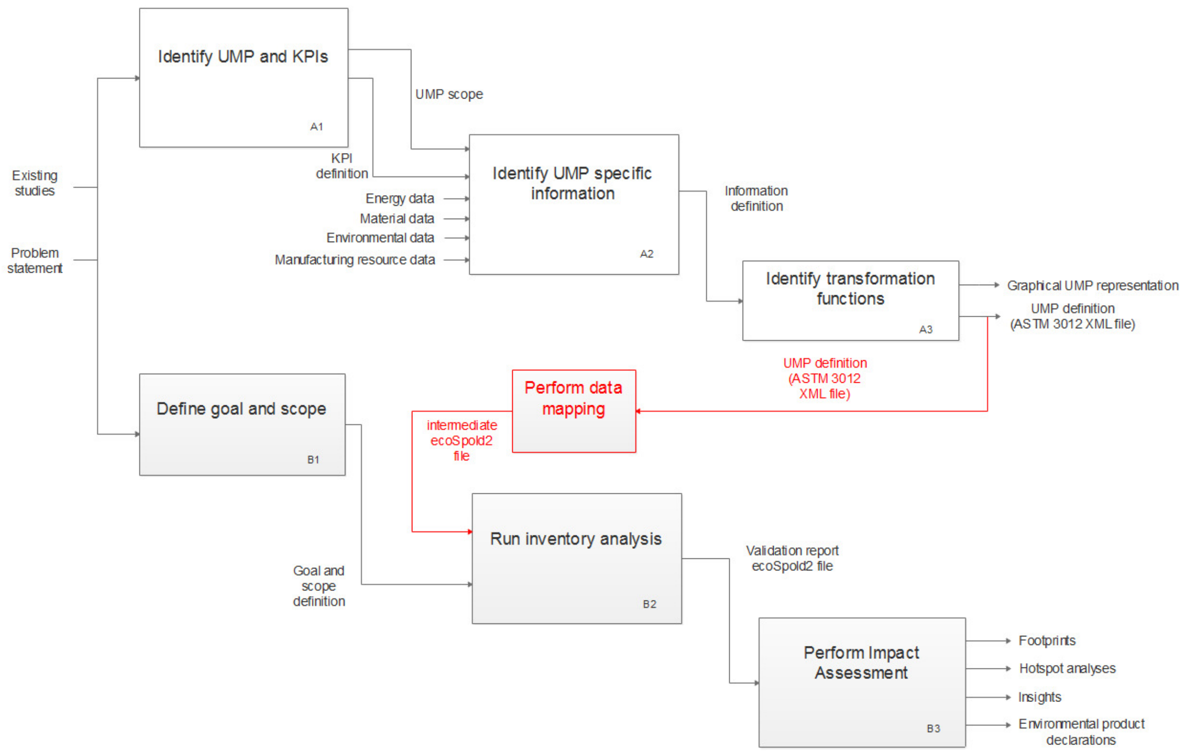

Fig. 9. IDEF0 diagram describing activities for creating LCI data using the UMP format.

ements such as *isCalculatedAmount*, *uncertainty*, and *source*.

- ecoSpold2 includes meta-information about the process with elements such as *synonym*, *classificationID*, *timePeriod*.
- Geographic information may be critical in the ASTM E3012-16 format as the equations or the value of parameters might depend on the location where the process occurs. Thus, multiple ASTM E3012-16 models representing a unique process might be created for various locations.
- Currently, the ASTM E3012-16 format does not include a review process for a model. Including information about the reviewers and their feedback can help users select an appropriate model.
- Similarly, information about the authors of the model (defined as *administrativeInformation* in ecoSpold2) should also be recorded.

These types of information are essential for the organization of models into reusable databases, a feature that the ASTM standards do not currently address but which are envisioned for the future [48]. Table 2 summarizes critical elements or attributes available in the ecoSpold2 schema that cannot be represented in the current ASTM schema.

The first column is a child element of the ecoSpold2 *activityDataset*. The second column gives the child element of the one in the first column. The third column is the child element or the attribute of the element in the second column. The fourth column gives an ASTM E3012-16 element that could be extended to include the corresponding ecoSpold2 element or attribute. When the value of the fourth column is "New element", a new element is required in the standard. For example, the value in the *id* attribute of the *activity* element in the *activityDescription* in ecoSpold2 could be included as an extension of the *UMP* element in ASTM E3012-16. *id* and *parentActivityId* would enable identification of the UMP model as well as traceability when a model is reused. *synonym* and *tag* are meta-information related to a UMP model. Manufacturing process classification such as [49] are available in the literature and could be implemented to enable classification of the UMP model. This data could be represented in a new *classificationId* attribute. *geographyId* and *comment* from the *geography* element, and *startDate* and *endDate* from the *timePeriod* element could be used in the ASTM schema to provide bounds of use for UMP models.

Within the *flowData* element, the *customExchange* and *Parameter* elements could be beneficial to the *ProductProcessInformation* element of the ASTM E3012-16 schema. The *isCalculatedAmount* and *uncertainty* attributes from *customExchange* and *Parameter* should be included in the ASTM E3012-16 format to distinguish an amount as a value calculated from an equation and to provide the uncertainty associated with the value. The *synonym* attribute from *customExchange* can be utilized for searchability in the ASTM E3012-16 format. *isDefiningValue* allows for constants to be defined, used at all abstraction levels of the UMP model. The attributes *sourceID*, *sourceContextID*, *sourceYear*, *sourceFirstAuthor*, and *pageNumbers* can be mapped to *ProductProcessInformation* and *ResourceIn-*

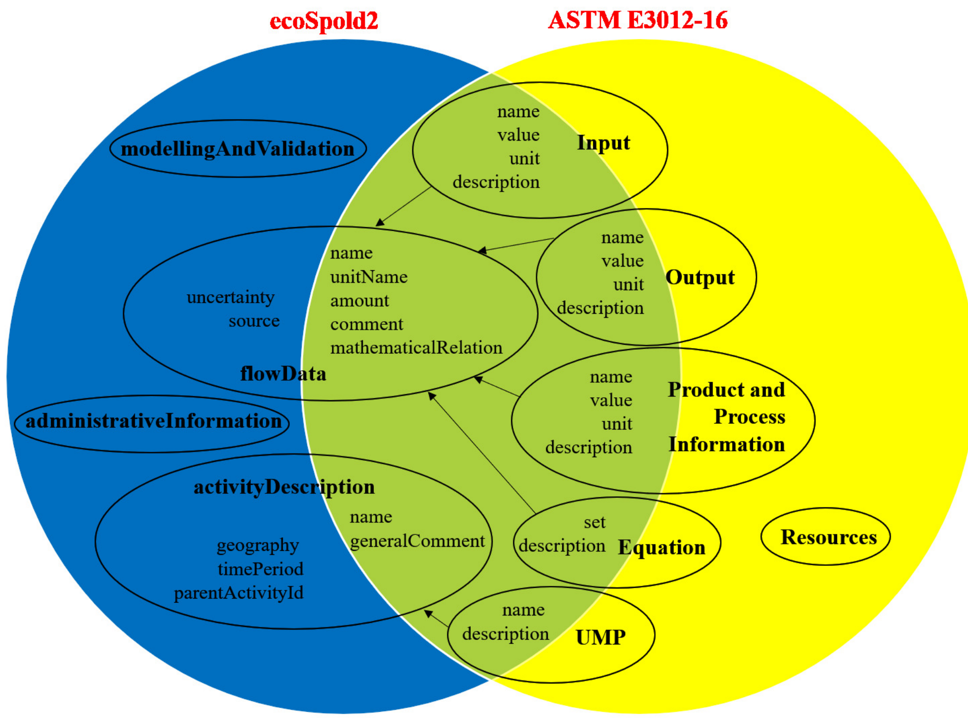

Fig. 10. A Venn Diagram illustrating the mapping between the ASTM E3012-16 UMP format and the ecoSpold2 format.

formation from the ASTM E3012-16 schema. This allows for traceability for the sources of a model.

Finally, model representativeness, and model review are not taken under consideration in the current schema of the ASTM E3012-16 standard. It is, however, critical to ensure the validity of the models built using this schema. The information about these two tasks should be collected. This statement is also valid for the administrative information including meta-information about the authors of the model and the potential data included in the UMP model. Future work, will utilize formal mapping procedures, such as the eXtensible Stylesheet Language Transformations (XSLT), to map between the two data formats [50].

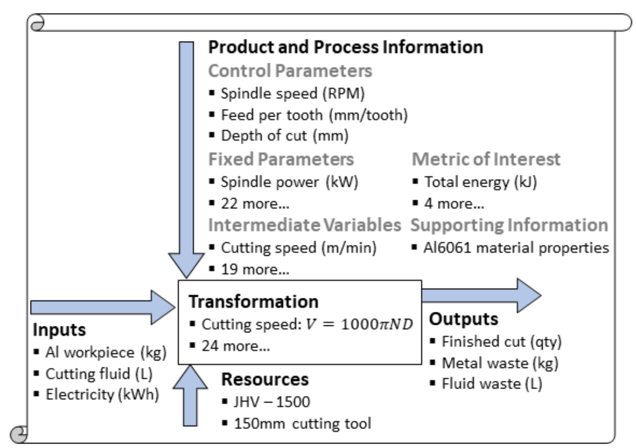

Fig. 11. ASTM E3012 graphical representation of the milling UMP.

5 Use Case

The case study is based on a milling process study reported by the Unit Process Life Cycle Inventory (UPLCI) team (code: MR3) [31]. We reproduced the parametric equations from this example in a UMP model and consulted the MR3 document whenever necessary. The model consists of 3 physical inputs, 3 physical outputs, 52 entities describing product and process information, and 25 equations. Figure 11 shows the corresponding ASTM E3012 graphical representation of the milling UMP.

Starting with the UMP representation we were able to generate an ecoSpold2 file. The theoretical mapping described in this paper was implemented as a Python program. ecoSpold2 elements contain information that are not available in the ASTM E3012-16 model since they are not part of the current standard schema. The Python program creates dummy values for these elements which are: *macroEconomicScenario*, *technology*, timePeriod, geography, fileAttributes, and dataGeneratorAndPublication. In addition to the creation of these elements, the Python program parses the ASTM E3012-15 model to create ecoSpold2 *Exchanges* that represents the ASTM E3012-16 *Inputs* and *Outputs* of the process, and an ecoSpold2 *Parameter* for each ASTM E3012-16 *ProductProcessInformation*. Figure 12 shows the inputs and outputs in the ASTM E3012-16 format (A) and the corresponding ecoSpold2 exchanges (B) generated from the mapping. For clarity, we box the *Input* “Electrical en-

<table>
<tr><th colspan="3">ecoSpold2 format</th><th colspan="2">ASTM E3012-16 format</th></tr>
<tr><th>Activity Dataset Element</th><th>Element</th><th>Attribute</th><th>Attribute</th><th>Element</th></tr>
<tr><td rowspan="3">activityDescription</td><td rowspan="3">activity</td><td>activityName</td><td>name</td><td rowspan="3">UMP</td></tr>
<tr><td>generalComment</td><td>description</td></tr>
<tr><td>specialActivityType</td><td>type</td></tr>
<tr><td rowspan="15">flowData</td><td rowspan="6">customExchange</td><td>name</td><td>name</td><td rowspan="4">Input, Output, Feedback</td></tr>
<tr><td>unitName</td><td>unit</td></tr>
<tr><td>amount</td><td>value</td></tr>
<tr><td>variableName</td><td>name</td></tr>
<tr><td>comment</td><td>description</td><td>Input, Output, Feedback, Equation</td></tr>
<tr><td>mathematicalRelation</td><td>content</td><td>Equation</td></tr>
<tr><td rowspan="2">elementaryExchange</td><td>inputGroup</td><td colspan="2">Input</td></tr>
<tr><td>outputGroup</td><td colspan="2">Output, Feedback</td></tr>
<tr><td rowspan="2">intermediateExchange</td><td>inputGroup</td><td colspan="2">Input</td></tr>
<tr><td>outputGroup</td><td colspan="2">Output, Feedback</td></tr>
<tr><td rowspan="4">parameter</td><td>name</td><td>name</td><td rowspan="4">ProductProcessInformation</td></tr>
<tr><td>amount</td><td>value</td></tr>
<tr><td>unitName</td><td>unit</td></tr>
<tr><td>comment</td><td>description</td></tr>
<tr><td>parameter</td><td>mathematicalRelation</td><td>content</td><td>Equation</td></tr>
</table>

Table 1. Mapping between ecoSpold2 and ASTM E3012-16.

ergy" and the *Output* "Finished part" in the ASTM E3012-16 format, and the corresponding *intermediateExchange* in the ecoSpold2 format. Appendix B includes the entire ASTM E3012-16 model and Appendix C includes the full ecoSpold2 model generated by the Python program.

The theoretical mapping required several steps. For instance, Table 1 shows a direct mapping between the ecoSpold2 *specialActivityType* and the ASTM E3012-16 *type*. However, the values of these two types are not similarly categorized. *specialActivityType* can take 11 different values to represent different types of activity such as ordinary transforming activity (default), market activity, residual activity, import activity, etc. The ASTM E3012-16 *type* is defined as "a specific UMP type, for example, machining, casting, molding" which means that *type* is freely defined by the modeler or an available classification chosen by the modeler. In our scenario, the Python program transformed the *type* "Milling" as the *specialActivityType* ordinary transforming activity, which is the appropriate classification in ecoSpold2 for manufacturing processes, but loses the detail desired for curation of the manufacturing models.

The *content* of the ASTM E3012-16 *Equation* can also possibly be mapped into the ecoSpold2 *mathematicalRelation* attribute of a *Parameter* or an *Exchange*. However, the translation may be complex as more than one *Equation* might be required to calculate the amount of one *Parameter* or *Exchange*. In the current mapping, because of the complexity *Equation* is omitted as it it not required to produce a valid ecoSpold2 model.

The attribute *amount* of a *Parameter* or an *Exchange* is required in ecoSpold2, and might not be included in the ASTM E3012-16 format as *value* is optional. The current Python program sets the *amount* of a *Parameter* or an *Exchange* to 0 if *value* is not defined in the ASTM E3012-16 model.

These different issues need to be resolved in the theoretical mapping for a more complete system. While some resolutions may be found in more complex algorithms, others may require changes to the ASTM E3012-16 format to facilitate generation of data sets suitable for LCA. For instance, a complex mapping could include the execution of ASTM E3012-16 *Equations* and include the results of these computations as *amount* of a *Parameter* or an *Exchange*. This will be researched in future work.

ecoSpold2 format			ASTM E3012-16 format
Activity Dataset Element	**Element**	**Attribute**	**Element**
activityDescription	activity	id	UMP
		parentActivityId	
		synonym	
		tag	
	classification	classificationID	
	geography	geographyId	
		comment	
	timePeriod	startDate	
		endDate	
flowData	customExchange	isCalculatedAmount	ProductProcessInformation
		uncerttainty	
		synonym	
		SourceID sourceContextID sourceYear sourceFirstAuthor pageNumbers	ProductProcessInformation ResourceInformation
		isDefiningValue	ProductProcessInformation
	parameter	isCalculatedAmount	ProductProcessInformation
		uncertainty	
modellingAndValidation	representativeness	samplingProcedure	New element(s)
		extrapolations	
	review	reviewerName reviewerEmail reviewDate	
		details	
administrativeInformation	dataEntryBy	personID personName personEmail	
	dataGeneratorAndPublication	personID personName personEmail	

Table 2. Extending the ASTM format using elements from ecoSpold2

6 Conclusions and Future Work

This paper provides mappings between two data formats that represent environmental impacts of manufacturing processes: ASTM E3012-16 and ecoSpold2. Differences between the formats are identified, indicating potential extensions for the ASTM E3012-16 format. A use case is pre-

```xml
<Input name="Workpiece" unit="KGM" description="assuming to be steel"/>
<Input name="Electrical energy" unit="KWH" description="necessary to process the workpiece"/>
<Input name="Lubricating oil" unit="KGM" description="necessary for the machine"/>
<Output name="Finished part" unit="unit" description="assumed to create a single part per cycle"/>
<Output name="Scrap" unit="KGM" description="aluminium scrap generated"/>
<Output name="Waste" unit="KGM" description="Waste mineral oil"/>
```

A

```xml
<intermediateExchange amount="0" id="4f3f81da-8fe9-29da-25b0-40fe162239b8" intermediateExchangeId="6b1256f6-a494-aa82-615d-f90323b84fca" unitId=
"05d1a32f-283c-cfaa-a345-91cd6e3d33c5">
  <name xml:lang="en">Workpiece</name>
  <unitName xml:lang="en">KGM</unitName>
  <comment xml:lang="en">assuming to be steel</comment>
  <inputGroup>5</inputGroup>
</intermediateExchange>
<intermediateExchange amount="0" id="060e3c79-cf26-a466-5ff8-f570470d8e79" intermediateExchangeId="9b193c6e-bbc5-9afa-81c6-bc99bf3e7525" unitId=
"7d25fb62-c5f0-5142-bc48-725c09e059f6">
  <name xml:lang="en">Electrical energy</name>
  <unitName xml:lang="en">KWH</unitName>
  <comment xml:lang="en">necessary to process the workpiece</comment>
  <inputGroup>5</inputGroup>
</intermediateExchange>
<intermediateExchange amount="0" id="234c5560-147f-d514-0839-0858d9f87bd1" intermediateExchangeId="037dbcaf-b8d8-5a89-9a98-2598cc19682d" unitId=
"0542badf-998e-0bc1-38b3-ae36ebf4c1ca">
  <name xml:lang="en">Lubricating oil</name>
  <unitName xml:lang="en">KGM</unitName>
  <comment xml:lang="en">necessary for the machine</comment>
  <inputGroup>5</inputGroup>
</intermediateExchange>
<intermediateExchange amount="0" id="bee173aa-e9e6-7b92-e785-5e2231093772" intermediateExchangeId="b0a2a269-9add-508a-fd76-d06c1dd104ed" unitId=
"58f5748b-880c-1ad2-8ad5-b431cd1ac273">
  <name xml:lang="en">Finished part</name>
  <unitName xml:lang="en">unit</unitName>
  <comment xml:lang="en">assumed to create a single part per cycle</comment>
  <outputGroup>0</outputGroup>
</intermediateExchange>
<intermediateExchange amount="0" id="70486568-adc9-9a6c-71c1-48fa0735bacb" intermediateExchangeId="059a26f1-fa9a-b6ee-0910-a4cf53f331cb" unitId=
"74dac717-5c29-8b96-0947-95b38b8dfdd5">
  <name xml:lang="en">Scrap</name>
  <unitName xml:lang="en">KGM</unitName>
  <comment xml:lang="en">aluminium scrap generated</comment>
  <outputGroup>3</outputGroup>
</intermediateExchange>
<intermediateExchange amount="0" id="adb1b2a9-d095-8ee6-4b8d-b09615512049" intermediateExchangeId="d07b50e4-0dad-256c-c426-7cb398ea9956" unitId=
"a4500ca0-c53e-84b2-d3bc-d9980aa54d7f">
  <name xml:lang="en">Waste</name>
  <unitName xml:lang="en">KGM</unitName>
  <comment xml:lang="en">Waste mineral oil</comment>
  <outputGroup>3</outputGroup>
</intermediateExchange>
```

B

Fig. 12. Representation of inputs and outputs of a milling process in the ASTM E3012-16 format and the corresponding ecospold2 format.

sented illustrating the mapping between these formats. Areas for future work include:

- A formalization of the mapping that supports automation, such as XSLT. As a complement to this, the Brightway framework [51] could execute the LCA calculations and support the transformation of ASTM E3012-16 documents into ecospold2 documents. Formalized mappings can be used to automatically translate one format to the other for quicker sustainability assessment. A tool for capturing a UMP model, called UMP builder [43], was developed to reduce the time and effort necessary to create the models and might be a suitable platform on which to build a formal mapping tool.
- More detailed case studies based on multiple manufacturing processes. Such studies would illustrate the time and cost savings of translating these models compared to creating separate models in different formats.
- An analysis of LCI data studies to determine the utility of building UMP models to represent some common manufacturing processes. Existing LCI data sets are empirical and hence constrained to specific situations. Should the formulation of more theoretical UMP models prove useful for creating LCI data, then efforts to harvest the research from the data studies to make it more broadly usable in the form of ASTM E3012-16 UMP models should be undertaken.

Disclaimer

The use of any products described in this paper does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that products are necessarily the best available for the purpose.

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Appendix A: Definitions of Terms

This appendix (Table 3) contains definitions of terms and the references in which they were defined.

Appendix B: The Milling ASTM E3012-16 Model

This appendix (Fig. 13) includes the milling ASTM E3012-16 model used as input in our use case.

Appendix C: The ecoSpold2 Model Automatically Generated from the ASTM E3012-16 Model

This appendix (Fig. 14) includes the ecoSpold2 model automatically generated from the ASTM E3012-16 model.

Term	Definition	Reference
Unit Process	smallest element considered in the life cycle inventory analysis for which input and output data are quantified	[12]
Unit Manufacturing Process (UMP)	the smallest element or sub-process in manufacturing that adds value through the modification or transformation of shape, structure, or property of input material or workpiece	[11]
Reference Flow	measure of the outputs from processes in a given product system required to fulfill the function expressed by the functional unit	[12]
Activity	a unit process of a human activity and its exchanges with the environment and other human activities	[22]
Elementary Exchange	exchange with the natural, social or economic environment	[22]
Intermediate Exchange	an exchange between two activities that stays within the technosphere and is not emitted to or taken from the environment	[22]
Functional Unit	measure of the outputs from processes in a given product system required to fulfill the function expressed by the functional unit	[12]
Cutoff Criteria	specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from a study	[12]
Technosphere	exchange of a certain activity can be between the activity and the environment (elementary exchange, for example CO2 emission to air) or between two activities (intermediate exchange, for example wastewater to be released from one activity to another treatment of wastewater)	[22]
Footprint	metric(s) used to report life cycle assessessment results addressing an area of concern	[19]
Area of concern	aspect of the natural environment, human health or resources of interest to society	[19]

Table 3. Definitions of terms from the various standards and data formats.

```xml
<?xml version="1.0" encoding="UTF-8"?>
<UMP xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
    xsi:noNamespaceSchemaLocation="UMP-standard%20format.xsd" name="Milling
Example"
    description="This model predicts the energy consumed of a milling process by"
type="Milling">
    <Input name="Workpiece" unit="KGM" description="assuming to be steel"/>
    <Input name="Electrical energy" unit="KWH" description="necessary to process the
workpiece"/>
    <Input name="Lubricating oil" unit="KGM" description="necessary for the
machine"/>
    <Output name="Finished part" unit="unit" description="assumed to create a single
part per cycle"/>
    <Output name="Scrap" unit="KGM" description="aluminium scrap generated"/>
    <Output name="Waste" unit="KGM" description="Waste mineral oil"/>
    <ProductProcessInformation name="Spindle speed" category="ControlParameter"
unit="RPM"/>
    <ProductProcessInformation name="Feed per tooth" category="ControlParameter"
unit="MMT/tooth"/>
    <ProductProcessInformation name="Depth of cut" category="ControlParameter"
unit="MMT"/>
    <ProductProcessInformation name="Work piece length" category="FixedParameter"
unit="MMT" value="500"/>
    <ProductProcessInformation name="Approach distance" category="FixedParameter"
unit="MMT" value="25"/>
    <ProductProcessInformation name="Specific cutting energy"
category="FixedParameter" unit="WTT/MMQ" value="0.98"/>
    <ProductProcessInformation name="Number of items per cycle"
category="FixedParameter" unit="C62" value="1"/>
    <ProductProcessInformation name="Density of aluminum" category="FixedParameter"
unit="KMQ" value="2712"/>
    <ProductProcessInformation name="Work piece width" category="FixedParameter"
unit="MMT" value="60"/>
    <ProductProcessInformation name="Work piece height" category="FixedParameter"
unit="MMT" value="100"/>
    <ProductProcessInformation name="Diameter of the cutter"
category="FixedParameter" unit="MMT" value="150"/>
    <ProductProcessInformation name="Number of teeth" category="FixedParameter"
unit="C62" value="10"/>
    <ProductProcessInformation name="Offset distance of tool"
category="FixedParameter" unit="MMT" value="25"/>
    <ProductProcessInformation name="Approach distance of tool"
category="FixedParameter" unit="MMT" value="8"/>
    <ProductProcessInformation name="Rapid traverse speed (horizontal)"
category="FixedParameter" unit="2X*1000" value="30"/>
    <ProductProcessInformation name="Rapid traverse speed (vertical)"
category="FixedParameter" unit="2X*1000" value="24"/>
    <ProductProcessInformation name="Spindle power" category="FixedParameter"
unit="KWT" value="4"/>
    <ProductProcessInformation name="Coolant power" category="FixedParameter"
unit="KWT" value="1"/>
    <ProductProcessInformation name="Axis power" category="FixedParameter"
unit="KWT" value="5"/>
    <ProductProcessInformation name="Loading time" category="FixedParameter"
unit="SEC" value="12"/>
    <ProductProcessInformation name="Cleaning time" category="FixedParameter"
unit="SEC" value="25"/>
    <ProductProcessInformation name="Unloading time" category="FixedParameter"
unit="SEC" value="12"/>
    <ProductProcessInformation name="Basic power" category="FixedParameter"
```

```
unit="KWT" value="7.5"/>
    <ProductProcessInformation name="Cost per kWh of energy"
category="FixedParameter" unit="DOL/KWH" value="0.12"/>
    <ProductProcessInformation name="Co2 per kWh of energy" category="FixedParameter"
unit="KGM/KWH" value="0.5864"/>
    <ProductProcessInformation name="Number of cycles" category="FixedParameter"
unit="C62" value="1"/>
    <ProductProcessInformation name="Cutting speed" category="IntermediateVariable"
unit="2X"/>
    <ProductProcessInformation name="Basic process time"
category="IntermediateVariable" unit="SEC"/>
    <ProductProcessInformation name="Retract time" category="IntermediateVariable"
unit="SEC"/>
    <ProductProcessInformation name="Volume of material removed"
category="IntermediateVariable" unit="1S"/>
    <ProductProcessInformation name="Feed rate" category="IntermediateVariable"
unit="MMT/MIN"/>
    <ProductProcessInformation name="Volume mat removal rate"
category="IntermediateVariable" unit="MMQ/MIN"/>
    <ProductProcessInformation name="Extent of first contact"
category="IntermediateVariable" unit="MMT"/>
    <ProductProcessInformation name="Basic energy" category="IntermediateVariable"
unit="KJO"/>
    <ProductProcessInformation name="Milling time" category="IntermediateVariable"
unit="SEC"/>
    <ProductProcessInformation name="Milling power" category="IntermediateVariable"
unit="KWT"/>
    <ProductProcessInformation name="Milling energy"
category="IntermediateVariable" unit="KJO"/>
    <ProductProcessInformation name="Approach and overtravel time"
category="IntermediateVariable" unit="SEC"/>
    <ProductProcessInformation name="Handling time" category="IntermediateVariable"
unit="SEC"/>
    <ProductProcessInformation name="Milling idle time"
category="IntermediateVariable" unit="SEC"/>
    <ProductProcessInformation name="Milling idle power"
category="IntermediateVariable" unit="KWH"/>
    <ProductProcessInformation name="Milling idle energy"
category="IntermediateVariable" unit="KJO"/>
    <ProductProcessInformation name="Milling energy per cycle"
category="IntermediateVariable" unit="KJO/unit"/>
    <ProductProcessInformation name="Total time per cycle"
category="IntermediateVariable" unit="SEC"/>
    <ProductProcessInformation name="Yield" category="IntermediateVariable"
unit="C62"/>
    <ProductProcessInformation name="Input volume" category="IntermediateVariable"
unit="MMQ"/>
    <ProductProcessInformation name="Total time" category="MetricOfInterest"
unit="SEC"/>
    <ProductProcessInformation name="Total waste" category="MetricOfInterest"
unit="KGM"/>
    <ProductProcessInformation name="Total energy" category="MetricOfInterest"
unit="KWH"/>
    <ProductProcessInformation name="Total cost" category="MetricOfInterest"
unit="DOL"/>
    <ProductProcessInformation name="Waste of mineral oil"
category="MetricOfInterest" unit="KGM"/>
    <ProductProcessInformation name="Total CO2" category="MetricOfInterest"
unit="KGM"/>
    <Transformation>
```

```
        <Equation description="Cutting speed"
set="cutting_speed"><Content>V=N×(D×π)×1000</Content></Equation>
        <Equation description="Feed rate"
set="feed_per_tooth"><Content>fr=ft×N×nt</Content></Equation>
        <Equation description="Volume mat removal rate"
set="material_removal"><Content>VRR=ww×dc×fr</Content></Equation>
        <Equation description="Extent of first contact"
set="first_contact_extent"><Content>Lc=sqrt(ww×(D-ww))</Content></Equation>
        <Equation description="Milling time"
set="milling_time"><Content>tm=60(lw+2Lc)/fr</Content></Equation>
        <Equation description="Milling power"
set="milling_power"><Content>pm=VRR×Up/1000</Content></Equation>
        <Equation description="Milling energy"
set="milling_energy"><Content>em=pm×tm</Content></Equation>
        <Equation description="Approach time"
set="approach_time"><Content>tao=60×2da/fr</Content></Equation>
        <Equation description="Handling time"
set="handling_time"><Content>th=tao+tm</Content></Equation>
        <Equation description="Retract time"
set="retract_time"><Content>60*(10+lw+10)/(vv*1000) </Content></Equation>
        <Equation description="Idle time"
set="idle_time"><Content>ti=th+tm</Content></Equation>
        <Equation description="Idle power"
set="idle_power"><Content>pi=ps+pc+pa</Content></Equation>
        <Equation description="Idle energy"
set="idle_energy"><Content>ei=pi×ti</Content></Equation>
        <Equation description="Basic energy"
set="basic_energy"><Content>eb=pb×tc</Content></Equation>
        <Equation description="Cycle energy"
set="cycle_energy"><Content>ec=em+ei+eb</Content></Equation>
        <Equation description="Waste mineral oil"
set="waste_oil"><Content>wcf=0.68×tm/60</Content></Equation>
        <Equation description="Cycle time"
set="cycle_time"><Content>tc=tl+tc+tu+ti</Content></Equation>
        <Equation description="Basic time"
set="basic_time"><Content>tb=tl+tcl+tu</Content></Equation>
        <Equation description="Input volume"
set="input_volume"><Content>Vi=lw×ww×hw×nc</Content></Equation>
        <Equation description="Volume removed per cut"
set="volume_removed_per_cut"><Content>Vr=lw×ww×dc </Content></Equation>
        <Equation description="Amount produced"
set="amount_produced"><Content>nT=nc×ni</Content></Equation>
        <Equation description="Total time"
set="total_time"><Content>tT=tc×nc</Content></Equation>
        <Equation description="Total predicted energy"
set="total_energy"><Content>ET= ec×nc×0.000277777777777777</Content></Equation>
        <Equation description="Total predicted cost"
set="total_cost"><Content>CT=ET×Cenergy</Content></Equation>
        <Equation description="Total waste"
set="total_waste"><Content>mw=Vr×rho×0.000000001</Content></Equation>
        <Equation description="Total CO2"
set="total_co2"><Content>CO2T=ET×CO2energy</Content></Equation>
    </Transformation>
</UMP>
```


Fig. 13. The Milling ASTM E3012-16 Model.

```xml
<?xml version="1.0" ?>
<ecoSpold xmlns="http://www.EcoInvent.org/EcoSpold02">
  <activityDataset>
    <activityDescription>
      <activity activityNameId="832b7bc3-db51-4f5c-d125-d3ab8884abf7"
id="b562e7e8-8288-902b-cd24-da9e4bfda394" specialActivityType="0" type="1">
        <activityName>Milling Example</activityName>
        <generalComment>
          <text index="1">This model predicts the energy consumed of a milling process by</text>
        </generalComment>
      </activity>
      <geography geographyId="0e1fd65e-7932-e915-ffcc-cca41641097f">
        <shortname xml:lang="en">Milling Example</shortname>
      </geography>
      <technology/>
      <timePeriod endDate="2019-01-01" isDataValidForEntirePeriod="true" startDate="2018-01-01"/>
      <macroEconomicScenario macroEconomicScenarioId="779a1fad-36de-6b06-246c-209e35eb107f">
        <name>scenario 1</name>
      </macroEconomicScenario>
    </activityDescription>
    <flowData>
      <intermediateExchange amount="0" id="4f3f81da-8fe9-29da-25b0-40fe162239b8"
intermediateExchangeId="6b1256f6-a494-aa82-615d-f90323b84fca"
unitId="05d1a32f-283c-cfaa-a345-91cd6e3d33c5">
        <name xml:lang="en">Workpiece</name>
        <unitName xml:lang="en">KGM</unitName>
        <comment xml:lang="en">assuming to be steel</comment>
        <inputGroup>5</inputGroup>
      </intermediateExchange>
      <intermediateExchange amount="0" id="060e3c79-cf26-a466-5ff8-f570470d8e79"
intermediateExchangeId="9b193c6e-bbc5-9afa-81c6-bc99bf3e7525"
unitId="7d25fb62-c5f0-5142-bc48-725c09e059f6">
        <name xml:lang="en">Electrical energy</name>
        <unitName xml:lang="en">KWH</unitName>
        <comment xml:lang="en">necessary to process the workpiece</comment>
        <inputGroup>5</inputGroup>
      </intermediateExchange>
      <intermediateExchange amount="0" id="234c5560-147f-d514-0839-0858d9f87bd1"
intermediateExchangeId="037dbcaf-b8d8-5a89-9a98-2598cc19682d"
unitId="0542badf-998e-0bc1-38b3-ae36ebf4c1ca">
        <name xml:lang="en">Lubricating oil</name>
        <unitName xml:lang="en">KGM</unitName>
        <comment xml:lang="en">necessary for the machine</comment>
        <inputGroup>5</inputGroup>
      </intermediateExchange>
      <intermediateExchange amount="0" id="bee173aa-e9e6-7b92-e785-5e2231093772"
intermediateExchangeId="b0a2a269-9add-508a-fd76-d06c1dd104ed"
unitId="58f5748b-880c-1ad2-8ad5-b431cd1ac273">
        <name xml:lang="en">Finished part</name>
        <unitName xml:lang="en">unit</unitName>
        <comment xml:lang="en">assumed to create a single part per cycle</comment>
        <outputGroup>0</outputGroup>
      </intermediateExchange>
      <intermediateExchange amount="0" id="70486568-adc9-9a6c-71c1-48fa0735bacb"
intermediateExchangeId="059a26f1-fa9a-b6ee-0910-a4cf53f331cb"
unitId="74dac717-5c29-8b96-0947-95b38b8dfdd5">
        <name xml:lang="en">Scrap</name>
        <unitName xml:lang="en">KGM</unitName>
        <comment xml:lang="en">aluminium scrap generated</comment>
        <outputGroup>3</outputGroup>
      </intermediateExchange>
      <intermediateExchange amount="0" id="adb1b2a9-d095-8ee6-4b8d-b09615512049"
intermediateExchangeId="d07b50e4-0dad-256c-c426-7cb398ea9956"
unitId="a4500ca0-c53e-84b2-d3bc-d9980aa54d7f">
        <name xml:lang="en">Waste</name>
        <unitName xml:lang="en">KGM</unitName>
        <comment xml:lang="en">Waste mineral oil</comment>
        <outputGroup>3</outputGroup>
      </intermediateExchange>
      <parameter amount="0" parameterId="0ca889cd-0951-7eeb-1209-764e74f33da8">
        <name xml:lang="en">Spindle speed</name>
```

```xml
  <unitName xml:lang="en">RPM</unitName>
</parameter>
<parameter amount="0" parameterId="8b4c72ae-2999-4075-7859-564e01244907">
  <name xml:lang="en">Feed per tooth</name>
  <unitName xml:lang="en">MMT/tooth</unitName>
</parameter>
<parameter amount="0" parameterId="109ffe1d-a609-1e2f-6f94-94c490eaf8be">
  <name xml:lang="en">Depth of cut</name>
  <unitName xml:lang="en">MMT</unitName>
</parameter>
<parameter amount="500" parameterId="cf97f0dc-e295-5a98-585f-5039d8665119">
  <name xml:lang="en">Work piece length</name>
  <unitName xml:lang="en">MMT</unitName>
</parameter>
<parameter amount="25" parameterId="d9aece31-cef8-8c3a-a54d-5a8335a90e47">
  <name xml:lang="en">Approach distance</name>
  <unitName xml:lang="en">MMT</unitName>
</parameter>
<parameter amount="0.98" parameterId="1b4bff0b-da52-50fb-7e24-91cb50e7aa9c">
  <name xml:lang="en">Specific cutting energy</name>
  <unitName xml:lang="en">WTT/MMQ</unitName>
</parameter>
<parameter amount="1" parameterId="ae3287ec-d30b-53f3-9db1-96bdfc7637db">
  <name xml:lang="en">Number of items per cycle</name>
  <unitName xml:lang="en">C62</unitName>
</parameter>
<parameter amount="2712" parameterId="2a33c6d6-11f8-5cc7-ab7c-f6cbb14ada48">
  <name xml:lang="en">Density of aluminum</name>
  <unitName xml:lang="en">KMQ</unitName>
</parameter>
<parameter amount="60" parameterId="920d8f2e-f878-bb45-dd3a-1e33d1f0807c">
  <name xml:lang="en">Work piece width</name>
  <unitName xml:lang="en">MMT</unitName>
</parameter>
<parameter amount="100" parameterId="6fe78709-f761-b3a4-e369-ca970f1c5e82">
  <name xml:lang="en">Work piece height</name>
  <unitName xml:lang="en">MMT</unitName>
</parameter>
<parameter amount="150" parameterId="f191d380-634e-147e-247f-d2787a7432d3">
  <name xml:lang="en">Diameter of the cutter</name>
  <unitName xml:lang="en">MMT</unitName>
</parameter>
<parameter amount="10" parameterId="ff62f2fe-56b5-2e2f-b762-e7366a96ba67">
  <name xml:lang="en">Number of teeth</name>
  <unitName xml:lang="en">C62</unitName>
</parameter>
<parameter amount="25" parameterId="b90ba312-0255-2740-4c9b-69100f378275">
  <name xml:lang="en">Offset distance of tool</name>
  <unitName xml:lang="en">MMT</unitName>
</parameter>
<parameter amount="8" parameterId="e8110e5a-e111-d208-2d77-b8928b45aacc">
  <name xml:lang="en">Approach distance of tool</name>
  <unitName xml:lang="en">MMT</unitName>
</parameter>
<parameter amount="30" parameterId="155d11ca-ece4-afee-fbfe-8c88feea624e">
  <name xml:lang="en">Rapid traverse speed (horizontal)</name>
  <unitName xml:lang="en">2X*1000</unitName>
</parameter>
<parameter amount="24" parameterId="969802aa-901d-bb24-fd1a-060c03aa8592">
  <name xml:lang="en">Rapid traverse speed (vertical)</name>
  <unitName xml:lang="en">2X*1000</unitName>
</parameter>
<parameter amount="4" parameterId="0464e0ac-0b66-4a1a-b450-98fb46216529">
  <name xml:lang="en">Spindle power</name>
  <unitName xml:lang="en">KWT</unitName>
</parameter>
<parameter amount="1" parameterId="dfa39114-e47a-c92c-36e9-606aabc6ad71">
  <name xml:lang="en">Coolant power</name>
  <unitName xml:lang="en">KWT</unitName>
</parameter>
<parameter amount="5" parameterId="52c47fe2-a7f6-b8f9-81cd-39df11e1d854">
```

```xml
          <name xml:lang="en">Axis power</name>
          <unitName xml:lang="en">KWT</unitName>
        </parameter>
        <parameter amount="12" parameterId="c9e108bd-db8a-3891-e8ae-eaaa41fd0374">
          <name xml:lang="en">Loading time</name>
          <unitName xml:lang="en">SEC</unitName>
        </parameter>
        <parameter amount="25" parameterId="09bc473a-29e1-75da-f30a-3da2cd9ec03c">
          <name xml:lang="en">Cleaning time</name>
          <unitName xml:lang="en">SEC</unitName>
        </parameter>
        <parameter amount="12" parameterId="86f59c8d-7577-39fb-d258-5e9b80c3a896">
          <name xml:lang="en">Unloading time</name>
          <unitName xml:lang="en">SEC</unitName>
        </parameter>
        <parameter amount="7.5" parameterId="6c939cfb-d02b-e508-bf06-4d91d267b9c0">
          <name xml:lang="en">Basic power</name>
          <unitName xml:lang="en">KWT</unitName>
        </parameter>
        <parameter amount="0.12" parameterId="701a3b88-91d2-0a89-96a3-b72c6200fe68">
          <name xml:lang="en">Cost per kWh of energy</name>
          <unitName xml:lang="en">DOL/KWH</unitName>
        </parameter>
        <parameter amount="0.5864" parameterId="cd68562e-2a16-32ae-97ae-aef0ceb38ff8">
          <name xml:lang="en">Co2 per kWh of energy</name>
          <unitName xml:lang="en">KGM/KWH</unitName>
        </parameter>
        <parameter amount="1" parameterId="1c725c28-47fa-406b-233b-21d4005974eb">
          <name xml:lang="en">Number of cycles</name>
          <unitName xml:lang="en">C62</unitName>
        </parameter>
        <parameter amount="0" isCalculatedAmount="true" mathematicalRelation="V=N×(D×π)×1000"
parameterId="15781aa2-2dbc-aefb-d542-e2775e999c95">
          <name xml:lang="en">Cutting speed</name>
          <unitName xml:lang="en">2X</unitName>
        </parameter>
        <parameter amount="0" parameterId="08686711-38f1-f8b0-6239-a66c294bf532">
          <name xml:lang="en">Basic process time</name>
          <unitName xml:lang="en">SEC</unitName>
        </parameter>
        <parameter amount="0" isCalculatedAmount="true"
mathematicalRelation="60*(10+lw+10)/(vv*1000) "
parameterId="647c91fb-7aed-bf00-8dd5-951515c409d1">
          <name xml:lang="en">Retract time</name>
          <unitName xml:lang="en">SEC</unitName>
        </parameter>
        <parameter amount="0" parameterId="47901e39-cd5a-ee71-222e-399f0af84e32">
          <name xml:lang="en">Volume of material removed</name>
          <unitName xml:lang="en">1S</unitName>
        </parameter>
        <parameter amount="0" isCalculatedAmount="true" mathematicalRelation="fr=ft×N×nt"
parameterId="f9ea3683-e999-1c84-f76f-b64e243810c4">
          <name xml:lang="en">Feed rate</name>
          <unitName xml:lang="en">MMT/MIN</unitName>
        </parameter>
        <parameter amount="0" isCalculatedAmount="true" mathematicalRelation="VRR=ww×dc×fr"
parameterId="37e971b6-0c0b-4d28-2f2f-f87d45be8dd9">
          <name xml:lang="en">Volume mat removal rate</name>
          <unitName xml:lang="en">MMQ/MIN</unitName>
        </parameter>
        <parameter amount="0" isCalculatedAmount="true" mathematicalRelation="Lc=sqrt(ww×(D-ww))"
parameterId="5be2987c-af07-68d8-80c7-8873df4c68a1">
          <name xml:lang="en">Extent of first contact</name>
          <unitName xml:lang="en">MMT</unitName>
        </parameter>
        <parameter amount="0" isCalculatedAmount="true" mathematicalRelation="eb=pb×tc"
parameterId="b7f9378f-06e0-f5af-850a-2665a6b6b26e">
          <name xml:lang="en">Basic energy</name>
          <unitName xml:lang="en">KJO</unitName>
        </parameter>
        <parameter amount="0" isCalculatedAmount="true" mathematicalRelation="tm=60(lw+2Lc)/fr"
```

```
parameterId="99aa26e5-ce34-1adc-5c02-3be3d90827e8">
        <name xml:lang="en">Milling time</name>
        <unitName xml:lang="en">SEC</unitName>
      </parameter>
      <parameter amount="0" isCalculatedAmount="true" mathematicalRelation="pm=VRR×Up/1000"
parameterId="4d9ec875-22f5-1f68-728a-9a135b8a7277">
        <name xml:lang="en">Milling power</name>
        <unitName xml:lang="en">KWT</unitName>
      </parameter>
      <parameter amount="0" isCalculatedAmount="true" mathematicalRelation="em=pm×tm"
parameterId="b8fcc942-0e63-5cb1-d1cf-640f1c138ac9">
        <name xml:lang="en">Milling energy</name>
        <unitName xml:lang="en">KJO</unitName>
      </parameter>
      <parameter amount="0" parameterId="1018af57-cd82-468f-5e41-0f6a64360fa9">
        <name xml:lang="en">Approach and overtravel time</name>
        <unitName xml:lang="en">SEC</unitName>
      </parameter>
      <parameter amount="0" isCalculatedAmount="true" mathematicalRelation="th=tao+tm"
parameterId="4c85a557-5ecf-36ed-37f3-6bad25b0be3b">
        <name xml:lang="en">Handling time</name>
        <unitName xml:lang="en">SEC</unitName>
      </parameter>
      <parameter amount="0" parameterId="fdb6983b-616c-0e9b-8c79-d82b5c697305">
        <name xml:lang="en">Milling idle time</name>
        <unitName xml:lang="en">SEC</unitName>
      </parameter>
      <parameter amount="0" parameterId="a79e80aa-c1f8-8179-7775-bfbc3487156a">
        <name xml:lang="en">Milling idle power</name>
        <unitName xml:lang="en">KWH</unitName>
      </parameter>
      <parameter amount="0" parameterId="7afe109a-c05f-7306-1609-77d92ad6e417">
        <name xml:lang="en">Milling idle energy</name>
        <unitName xml:lang="en">KJO</unitName>
      </parameter>
      <parameter amount="0" parameterId="ed0c4461-87cd-8596-62f0-13a14ac226b7">
        <name xml:lang="en">Milling energy per cycle</name>
        <unitName xml:lang="en">KJO/unit</unitName>
      </parameter>
      <parameter amount="0" parameterId="cf93f722-0715-75e4-d457-e56bc0223b97">
        <name xml:lang="en">Total time per cycle</name>
        <unitName xml:lang="en">SEC</unitName>
      </parameter>
      <parameter amount="0" parameterId="6bdd0926-46f5-7e9d-aad4-378e00617815">
        <name xml:lang="en">Yield</name>
        <unitName xml:lang="en">C62</unitName>
      </parameter>
      <parameter amount="0" isCalculatedAmount="true" mathematicalRelation="Vi=lw×ww×hw×nc"
parameterId="471530d5-af85-1081-1c4e-43a3ea1867be">
        <name xml:lang="en">Input volume</name>
        <unitName xml:lang="en">MMQ</unitName>
      </parameter>
    </flowData>
    <modellingAndValidation/>
    <administrativeInformation>
      <dataEntryBy personEmail="bill@nist.gov" personId="759f1c10-9f66-b615-72b5-b9ba54b1ab97"
personName="Bill Bernstein"/>
      <dataGeneratorAndPublication isCopyrightProtected="true" personEmail="bill@nist.gov"
personId="3be45ff7-eca9-5bc5-78cd-884ce51acd8f" personName="Bill Bernstein"/>
      <fileAttributes majorRelease="1" majorRevision="1" minorRelease="1" minorRevision="1"/>
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  </activityDataset>
</ecoSpold>
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Fig. 14. The ecoSpold2 milling model automatically generated from the ASTM E3012-16 model.