A disassembly process model for end-of-life activities of manufactured products

Mehmet I. Sarigecili*, Mehmet Murat Baysal, Bicheng Zhu and Utpal Roy

Department of Mechanical and Aerospace Engineering,
Syracuse University,
Syracuse, NY 13244, USA
Fax: +1-315-443-9099
E-mail: misarige@syr.edu
E-mail: mmbaysal@syr.edu
E-mail: bizhu@syr.edu
E-mail: uroy@syr.edu
*Corresponding author

Abstract: The companies have to reuse/recover/recycle their products at the end of product life according to new environmental regulations to achieve sustainability. The disassembly process is one of the most important processes to recover/recycle/maintain products safely, economically and efficiently. A process model for disassembly needs to be developed and integrated with the product information model to collect and retrieve the necessary information as per the requirements of different EOL activities. In this paper, different activities related to end-of-life processes (along with the disassembly process) have been studied extensively. The process models related to those activities are created in the IDEF0 diagrams that will help us identify the information flow among the EOL activities. The information flow is then used to develop an information model for the complete, consistent and unambiguous information exchange among different systems.

Keywords: sustainable manufacturing; end-of-life activities; product model; remanufacturing; recycling; disassemble; function representation; behaviour representation; hazardous substances; substance representation; environmental regulations; WEEE; RoHS; disassembly process model.

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Biographical notes: Mehmet I. Sarigecili received his BS and MS in Mechanical Engineering from Cukurova University, Turkey and his PhD in Mechanical and Aerospace Engineering from Syracuse University, NY, USA. His research interests are information modelling and integration, tolerance analysis, sustainable manufacturing and ISO 10303 – STEP. He is a member of ASME, SME and TMMOB – MMO (Union of Chambers of Turkish Engineers and Architects – Chamber of Mechanical Engineers).

Mehmet Murat Baysal received his BS and MS in Mechanical Engineering from Cukurova University, Turkey and his PhD in Mechanical and Aerospace Engineering from Syracuse University, NY, USA. His research interests are product development, CAD/CAM/CAE, sustainable manufacturing, industrial

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automation, information modelling and integration of product life-cycle activities. He is a member of ASME, SME and MMO (Chamber of Mechanical Engineers of Turkey).

Bicheng Zhu received his BS in Mechanical Engineering from Shanghai JiaoTong University, BS in Computer Science from Shanghai JiaoTong University and MS in Mechanical and Aerospace Engineering from Syracuse University, NY, USA. He is currently a PhD candidate in Syracuse University. His research interests are information modelling and integration, sustainable manufacturing, CAD/CAM and disassembly planning analysis. He is a member of ASME.

Utpal Roy is a Professor in the Mechanical and Aerospace Engineering Department at Syracuse University, USA. His current research areas include information modelling of product life-cycle analysis, sustainable manufacturing, product development, knowledge-based engineering, CAD/CAM/CAE, geometric tolerance analysis and synthesis, and automated inspection. He is the author or co-author of numerous publications in journals and conference proceedings. He has also edited two books. He has supervised many research projects funded by industrial sponsors, and by the federal and state governments. He is a member of ASME, IIE, and SME.

1 Introduction

End-of-life (EOL) process information relates to the knowledge regarding the recovery process itself, for example, process plan, operation feasibilities, resource availability, schedules, etc. This information enables matching of resources available with the remanufacturer/recycler to the processing requirements of the product. The new regulations are also pushing companies to take steps to reprocess their products at the end of their life cycle. For example, directive on waste electrical and electronic equipment (WEEE, 2002) requires electrical and electronic equipment manufacturers to reuse/recycle/recover in between 50% and 80% by an average weight per appliance for different categories of products.

The concerns on environmental pollution, depletion of resources and societal well being increase the awareness of sustainability issues. No product development or manufacturing issues are limited to a successful marketing of a financially profitable product only anymore; the total product life-cycle approach (Badurdeen et. al., 2009; Joshi et al., 2006) including the post-use considerations is necessary. It requires the adaptation of the 6R methodology (reduce, reuse, recycle, recover, redesign and remanufacture). The disassembly is the first necessary process for all these activities. A process model for disassembly therefore needs to be developed and integrated with the product information model.

In this study, a functional model for EOL processes showing all related activities and their inter-relationships is developed. The disassembly process is studied in detail because it is the most important process effecting the application of the 6R methodology and the compliance to the legislations (e.g., WEEE). The functions (i.e., decisions, actions and activities) of disassembly are first defined. Inputs and outputs of the functions, mechanisms, and controls to carry out these functions are defined in IDEF0 (2012) (*integration definition for function modelling*) diagrams (i.e., formats). These

diagrams help us in identifying the information flow among the functions. The information flow is then used to develop an information model for complete, consistent and unambiguous information exchange among different systems.

The focus of this research is to study the impact of availability (or non-availability) of complete life-cycle information associated with a product on the performance of EOL processes in terms of cost and time for those processes. The availability of new product information models such as the ones developed by NIST (e.g., OAM, CPM models) makes it possible for products to carry complete information associated with it throughout its life-cycle and ascertain to ensure flow of information between the various actors in the supply chain.

In order to build a model for life-cycle information systems, it is essential to first determine the information requirements for decision making at EOL. That will provide a basis for determining the possible characteristics of a life-cycle information management system. Our present work includes the development of a disassembly information model and the representation of this information model with CPM/OAM model.

2 Literature review

In this section, a brief review of presently available product and process models, as reported in the literature, is presented.

The current product information models could be classified into five levels (Zhao et al., 2002): structure-based, geometry-based, feature-based, knowledge-based and integrated product models. The integrated product models are the only ones which could be used throughout the life-cycle of a product. ISO 10303 (ISO 10303-1, 1994a) gives such a product information model and it is an industry standard for the exchange of product model data. It is known as STEP. STEP is developed in parts to have manageable sets of standards. The implementable parts of STEP are application protocols (APs). Each AP is developed for a particular application domain and a product life-cycle stage. For example, AP 214 (ISO 10303-214, 2003) is developed for the representation of core automotive product data for the detail design stage.

The most widely used APs in industry are AP203 2nd edition (ISO 10303-203, 2005) and AP 214 3rd edition (ISO 10303-214, 2010). These APs can represent the product structure, geometry, dimensions and tolerances, configuration control and materials information. AP214 also provides the form feature information representation for process planning. Neither these two APs nor any other STEP product model provide complete information requirements for any disassembly process. However, the information available in STEP product models could be further embellished and utilised to develop an information model for disassembly. For example, Part 44 (ISO 10303-44, 1994), Part 42 (ISO 10303-42, 1994b), Part 43 (ISO 10303-43, 2004) and Part 45 (ISO 10303-45, 1997) are some of the integrated resources of STEP, which are used in the development of AP203 and AP214. Part 44 is developed to represent the product structure and configuration. This part provides the necessary constructs to represent the bill of material (BOM) information and the assembly tree structure information. Part 42 and Part 43 define the information requirements to represent the geometric models of products. Part 42 enables the detailed geometric information representation whereas Part 43 enables the association of any product information representation with the product definition. The

materials information is defined by Part 45. This information could be collected and then properly configured as different classes for the disassembly information model.

Other than STEP, research efforts have also been made to develop integrated product information model that will not only represent product geometry, topology and structure information, but also product's function and behaviour information. The core product model (CPM) (Fenves, 2001) developed in UML by National Institute of Standards and Technology (NIST) can represent a product's function, behaviour and form information. The form information consists of the geometry and material information. As an extension of CPM model, the open assembly model (OAM) and its other modifications (Baysal et al., 2004; Baysal, 2012), are developed to capture all the relationships among the components and the assembly, and their respective assembly associations, kinematic information, assembly feature information, tolerance information, etc.

Other than product models, there are also process models developed by NIST (Feng and Song, 2003; Feng et al., 2009, 2011). First one (Feng and Song, 2003) is a preliminary manufacturing process model. It classifies the available manufacturing processes. In the model, the assembly operations are defined. In the second one (Feng et al., 2009), an information model for disassembly is developed. The model represents the information for the disassembly features, equipment, workflow, separation techniques, cleaning and inspection. The cleaning and inspection information are not defined in detail. This information model is updated in Feng et al. (2011). The updated disassembly model provides, in addition to the previous model, a detailed representation of simple, composite and pattern of features, tolerance information, work piece information, equipment for separation, cleaning and measurement information and workflow information. Their model does not show information on hazardous materials and the plans for the removal of such materials.

In the following sections, a disassembly process model for the EOL activities and integration of this model with the available product models will be discussed.

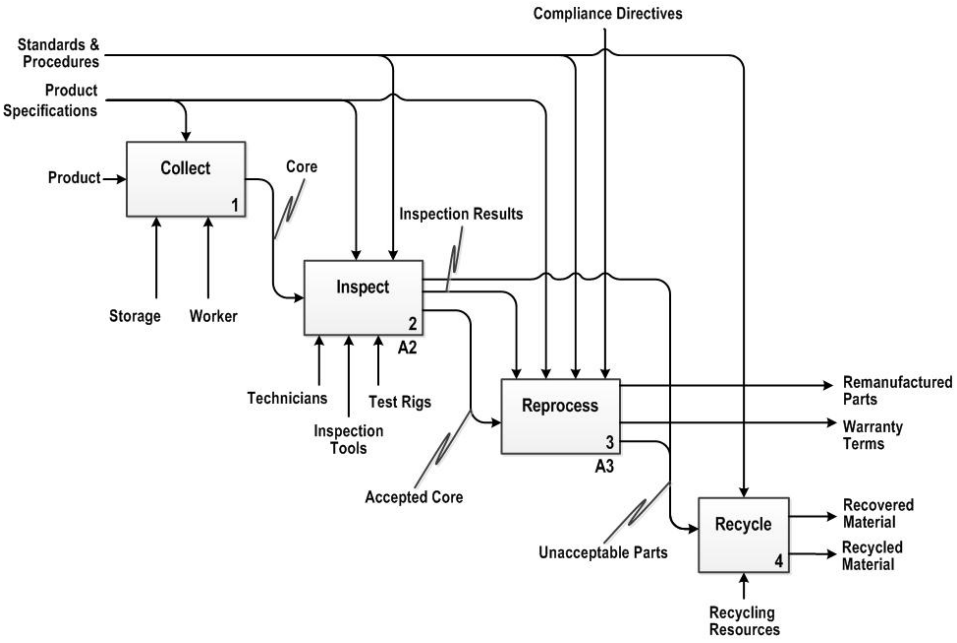
3 Integration of disassembly information model with other EOL process activities

EOL activities (e.g., remanufacturing, recovering, recycling, refurbishing and/or disposal) require planning the collection and the inspection of the used products (i.e., cores) from the market. Based on the inspection results, these products are disassembled for the EOL activity. The conditions of the products after the disassembly dictate which 6R process(es) needs to be followed. The main activities in an EOL of a product are shown in Figure 1.

In Figure 1, the products are collected in storage by the remanufacturer. The product specifications information is required in order to identify and group the products. Outputs from this function determine the 'cores' (i.e., the returned parts), which need to be inspected for the value of the product before remanufacturing. The inspection is carried out by using appropriate inspection tools and test rigs as per standards (and procedures) for the inspection process. The inspection process identifies acceptable cores for reprocessing and unacceptable parts for recycling. The acceptable cores are then reprocessed based on the inspection results from the previous process, and according to compliance directives, product specifications, standards and procedures. Outputs of this

process are remanufactured parts, warranty terms for these parts and unacceptable parts. The unacceptable parts coming from the inspection and the reprocessing are recycled.

Figure 1 Decomposition of the sustainable manufacturing process model



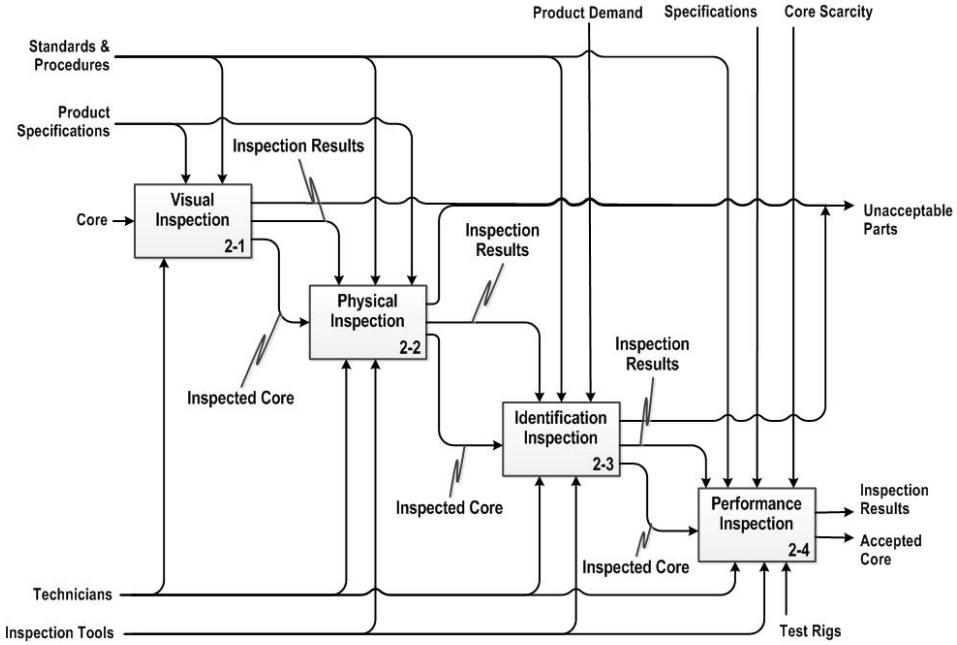
The further decomposition of the inspection process is shown in Figure 2. The first process of the inspection is the visual inspection of the core. At this stage, damaged and unrecoverable parts are separated by technicians. The second step is the physical inspection of the cores to check whether they are working. This process depends on the type of the product. The products that pass the physical inspection are sent to the identification inspection. At this process, the cores which are valuable (in the remanufacturing context) are identified.

The performance inspection is then required to evaluate the performance of the core. This step is required to show that the core can be remanufactured economically as per specifications. The core scarcity is also a controlling parameter for the accepted core. The outputs of the inspection process are the acceptable cores, unacceptable parts and the inspection results.

After the inspection process, the cores are reprocessed. The reprocessing process model is further elaborated in Figure 3. The reprocessing starts with disassembling the core with respect to the inspection results, standards & procedures. The compliance directives also affect the disassembly process because of the requirements for reusing/recycling/recovering. A detailed discussion on the disassembly process is given in Section 4. The disassembled products are either classified as unacceptable parts or accepted for the cleaning process. The cleaned products are classified as either reusable or remanufacturable products. The reusable products do not require any remanufacturing process whereas the remanufacturable products may have to go through a number of manufacturing processes. The unusable products are classified as unacceptable products.

The remanufacturing process is controlled by the cost constraints, product specifications, compliance directives, standards and procedures. Outputs are the remanufactured products and they have to be tested before they leave the remanufacturing facility.

Figure 2 Decomposition of inspection process model



The remanufacture activity, shown in Figure 3, is decomposed further into sub-activities and given in Figure 4. The parts which are cleaned are classified into reusable and remanufacturable parts as mentioned before. The remanufacturable products are reconditioned with respect to the product specifications and cost constraints. This process requires the resources, process models, process knowledge, material stock description and time/cost reference data. At the end of the reconditioning, the parts are classified either as remanufactured or unacceptable parts. The unacceptable parts have to be replaced in the reassembly process.

4 Disassembly process model: identification and representation of information

In this section, the disassembly activity defined as a sub-activity of the reprocess in Figure 3, is further decomposed. The information requirements for building a product's disassembly process model have been shown in Figure 5. After describing the broad activities in the IDEF0 diagrams, detailed information models have been discussed for important disassembly activities in the following sections using either IDEF0 or UML diagrams.

Figure 3 Decomposition of the reprocessing process model

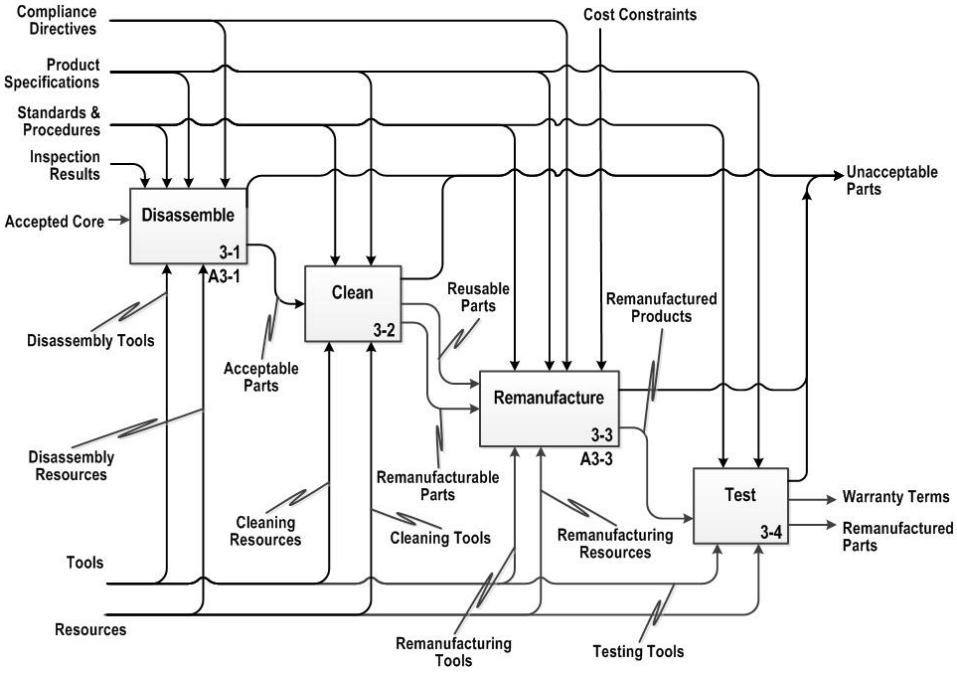
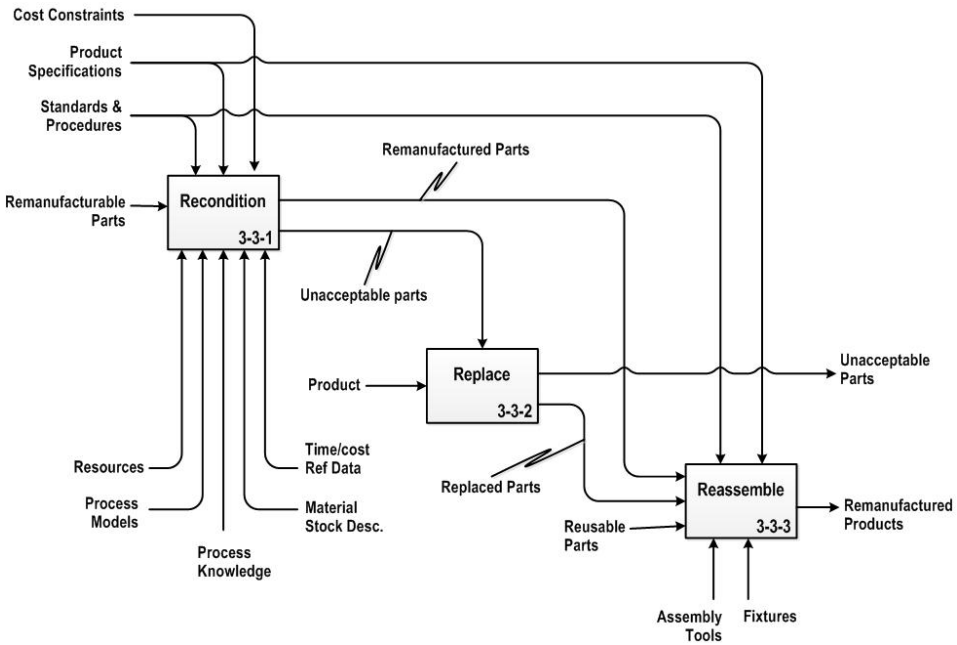
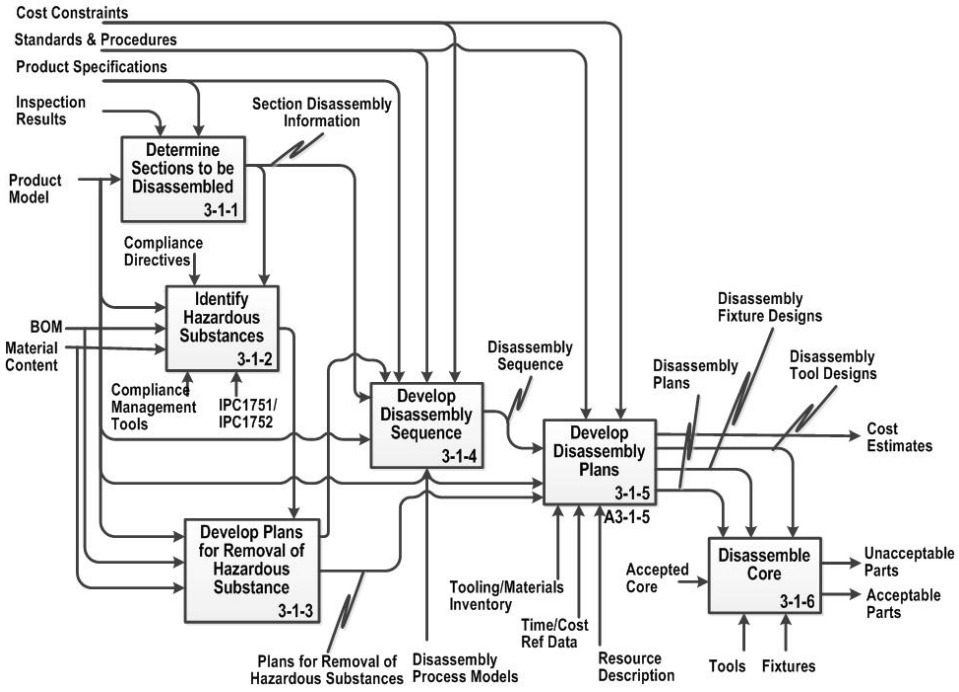


Figure 4 Decomposition of 'remanufacture activity'



The first activity in the disassembly process decomposition (Figure 5) is to determine the subassemblies/parts that are to be disassembled depending on whether it is a selective or total disassembly. The most important component of this activity is the availability of a complete assembly model (i.e., detailed product specification in terms of geometry, topology, feature, function and behaviour). The inspection results and product specifications dictate the decision on which parts need to be disassembled. Once it is decided, the hazardous substances have to be identified for the acceptable cores (which are the returned parts). This requires information regarding the product model, BOM and material contents. The compliance management tools, IPC-1751A (2012a) Generic Requirements for Declaration Process Management and IPC-1752A (2012b) Materials Declaration Management can be used to provide that information. A comprehensive information model for hazardous materials must be developed for this purpose. Outputs of this activity are used to develop plans for removal of hazardous substances.

Figure 5 A typical disassembly process model of an artifact



Next activity is to develop disassembly sequence for the acceptable cores. Disassembly process models are used for the sequence generation. After the disassembly sequence information and plans for the removal of hazardous substances from the acceptable cores are determined, disassembly plans are developed.

For this process, tools/materials inventory, time/cost reference data and resource description are used. Cost constraints, standards and procedures control the disassembly plans. Cost estimates of the disassembly process are generated as an output of the process. The design, tools and fixtures also control the disassembly of the acceptable cores. The output of disassembly process helps in determining the acceptable and unacceptable parts at the end.

Regarding the above activities, four (4) areas have been specially identified for further development of their information models and have been discussed in detail with pertinent examples. These are:

1 product information model

2 hazardous substance information model

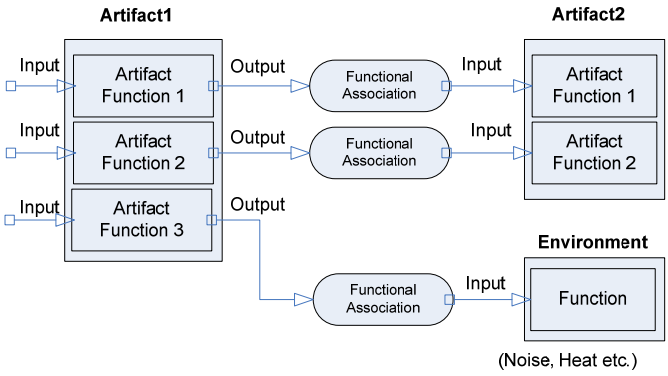
3 disassembly sequence information model

4 disassembly plan information model.

4.1 The product information model

To carry out the first activity of disassembly (i.e., for determining the parts to be disassembled) we need to have an integrated product information model that will provide complete information about the assembly features and their associations, functions and behaviours. It should be noted that the disassembly process model is intricately connected with the product's assembly information model. The OAM model is thus modified and embellished by incorporating the function and behaviour information for the product (Figure 6). The knowledge of product functions and behaviours is crucial in making intelligent decisions about product's disassembly. In the following sections, the effect of the function and behaviour information on the disassembly process will be discussed. In the OAM model, a mechanical product, together with its assembly, every subassembly and part, is termed as an 'artifact'. In the following paragraphs, we will use the terms 'product' and 'artifact' interchangeably.

Figure 6 Functional associations among artifacts (see online version for colours)



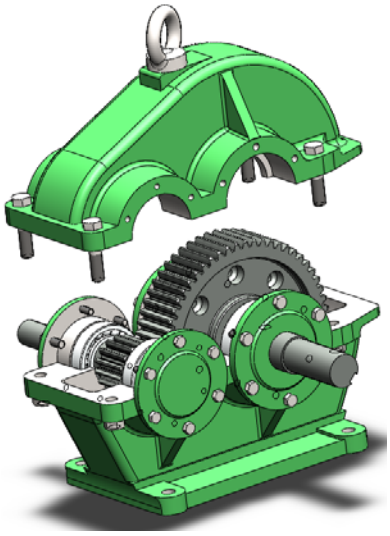
4.1.1 Function

The functional information includes functional requirements (or purpose – i.e., transfer power, connect, contain etc.), the functional input and output of the artifact (e.g., rotational or translational mechanical energy, with parameters such as torque, force, angular and linear velocity, etc.), and functional associations among artifacts. Functional associations are generally defined based on the associations in the assembly. Functional associations (Figure 6) are also defined based on design requirements designated by the

designer. For example, when a certain tension or compression force is needed between connected two artifacts, a functional association is defined as 'Maintaining friction'. Functional associations, as a part of the function definition, are used to trace the required functional and behavioural information in the assembly.

In this study, a typical speed reducer system (i.e., gearbox) has been used as an example. The assembly structure for the gearbox is represented in Figure 7. The individual part functions of a part of the gearbox have been shown in Figure 8. Corresponding Figure 9 shows the functional structure, including all lower-level sub-functions, and the input-output flows between different parts to fulfil the overall 'reduce speed' function of the system. As mentioned earlier, functional associations are defined among artifacts' spatial and design relations (e.g., maintaining friction between two surfaces). For the gear system, the main functions are: 'Transmit energy' and 'reduce speed'. For the 'transmit energy' function, the relationship among associated artifacts/features can be defined by the mechanical energy couples (i.e., f-v: force-velocity and M – ω: moment-angular velocity, Figure 9).

Figure 7 A typical gearbox (see online version for colours)



Source: CAD model (2012)

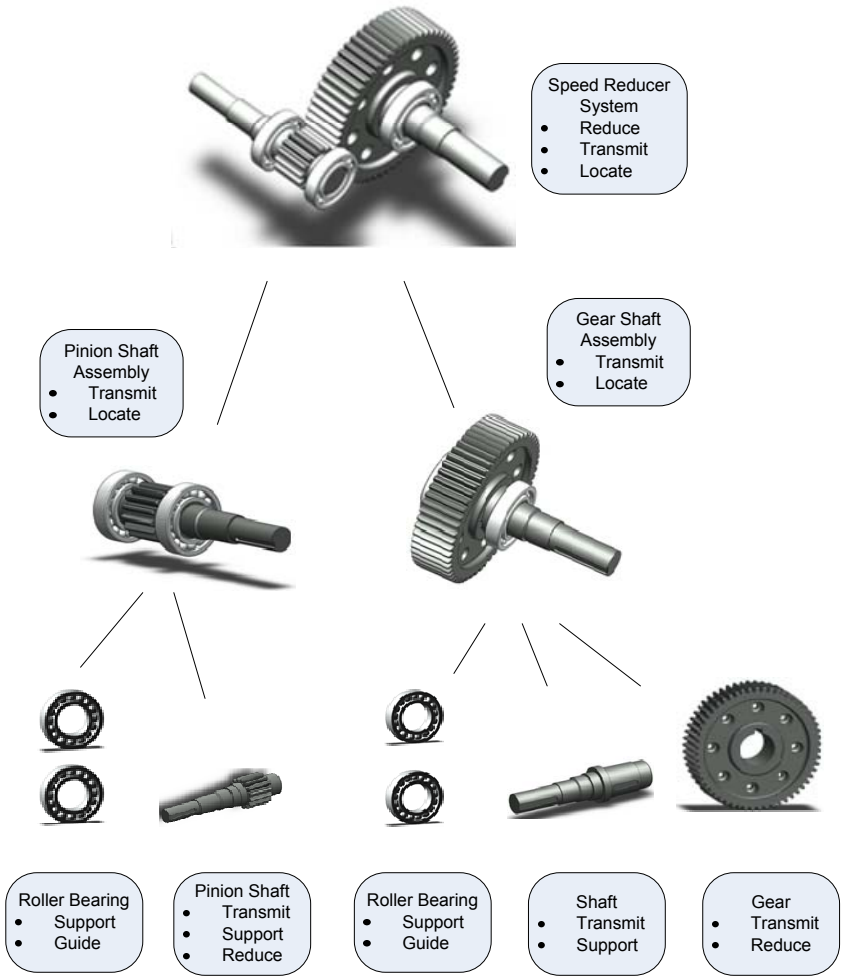
The functional representation information can also be used for planning the removal of the hazardous substances before starting the disassembly process. For example, the oil contained in the gear box should be drained out before starting the disassembly process. This type of information can be fetched from the function 'contain' defined for the housing (Figure 7).

4.1.2 Behaviour

Behaviour is defined as the response of something (an artifact) to its environment. In our model, we define *artifact_behaviour* as a result of the interactions of the artifact with other artifacts in the assembly and with the environment, through a set of relevant functional associations. Here, the defined behaviour is the 'estimated behaviour', which

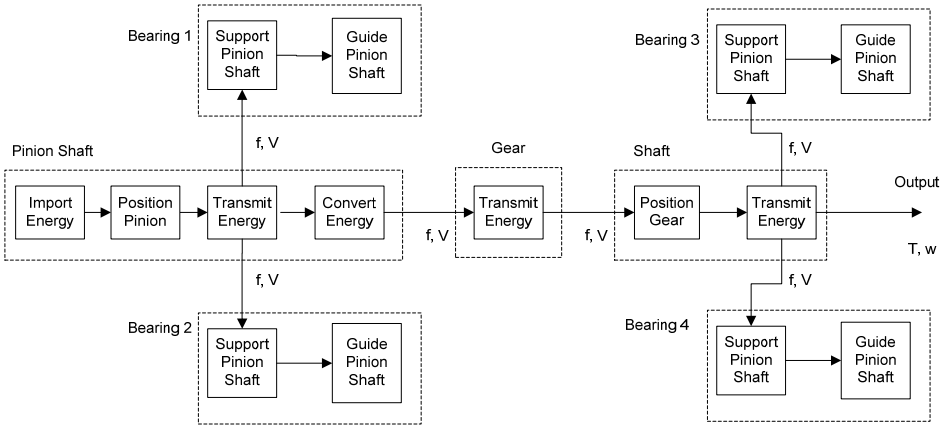
only considers identified functional inputs and known (considered) environmental effects. The connection between function and behaviour consists of the functional associations between features/artifacts. Considering these functional inputs and functional associations, the behaviour model is developed based on relevant physical laws and engineering formulas.

Figure 8 Assembly of parts and their individual functions in the speed reducer systems as shown in Figure 7



As an example, the gear (Figure 8) has three functional associations among the pinion shaft, the shaft and the key, according to artifact associations. The parameters of force, moment, velocity, etc., come through these functional associations that affect the behaviour of the gear. The gear can then be designed with engineering formulas and 'form' (material and geometry) information, and the behavioural model will simulate the estimated behaviour of the gear assembly. This behavioural model can then be utilised to define the disassembly process based on whether a key has been used to locate the gear or a shrink fit has been applied to locate it.

Figure 9 The planetary gear system and the functions that fulfil the overall function



In a similar way, each set of nuts and bolts required for the gearbox housings shown in Figure 7 has the function of 'fasten'. The functional associations between the housings and the sets of a nut and a bolt are defined. Sometimes, in the design process, the designer may consider the unintended behaviour of corrosion into effect and may consider introducing a new function (e.g., prevent corrosion) to counter the unintended behaviour. Therefore, the functional-behavioural model will be dynamic, and this allows new functions to be added, based on the behaviour of the artifact. Another consideration in the evaluation process is functional modifiers (e.g., which might be 'apply anti-corrosive materials') to measure the performance of the artifact function. The corrosion as an observed behaviour can also be used as additional information for the disassembly process. For example, the rust might be severe and there might be the risk of breaking the bolts. Additional precautions can be taken from this information automatically.

Figure 10 shows the interrelationships among the function, behaviour and form of an artifact. An artifact has a function or functions, and these functions have input and output in terms of energy, material and signal, with parameter, position/orientation and associated artifact information. In addition, the function also has order information and functional association(s). Behaviour is defined based on the interaction between parts/features of the associated artifact, and the environment.

4.1.3 Artifact assembly details

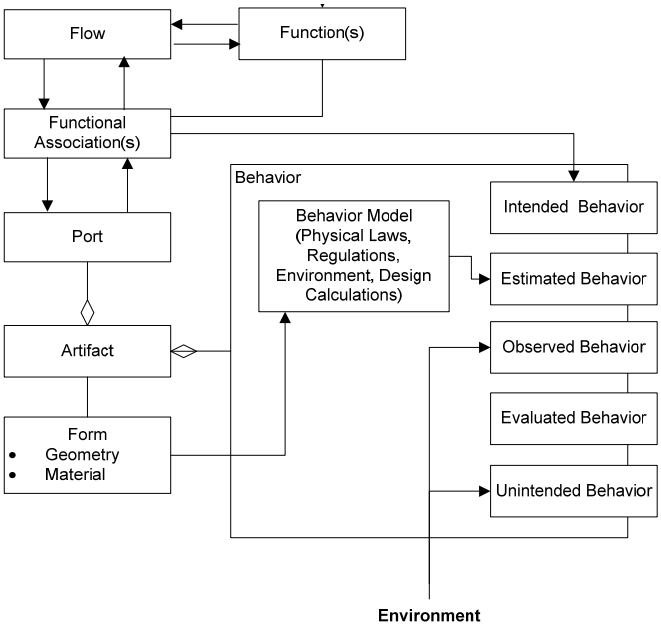
In addition to the function and behaviour information, a detailed assembly information model including individual assembly associations between assembly features, joint information and kinematic information, has been developed and reported; a detailed review of this work is available in Baysal et al. (2004) and Baysal (2012).

4.2 The hazardous substance information model

From the sustainability point of view, the amount of hazardous substances and their removal processes are restricted by legislations (e.g., RoHS, 2002; WEEE, 2002; REACH, 2006; JIG-101, 2012, etc.). The industrial standards IPC 1751A and 1752A are developed to report the information regarding the product structure (i.e., BOM), the

amount of materials in each product, whether the hazardous substances are above the limits restricted by the legislations in any product and where these substances are used in the product. The representation of the materials information and the integration of the IPC 1751/1752 standard material declaration forms with the integrated product information model would help create disassembly plans in compliance with the legislations. The materials information model is developed based on STEP standard's Part 41 and Part 45. In the following discussion, the UML object (class) names will be given in **bold** whereas the attributes will be given in *italic* font.

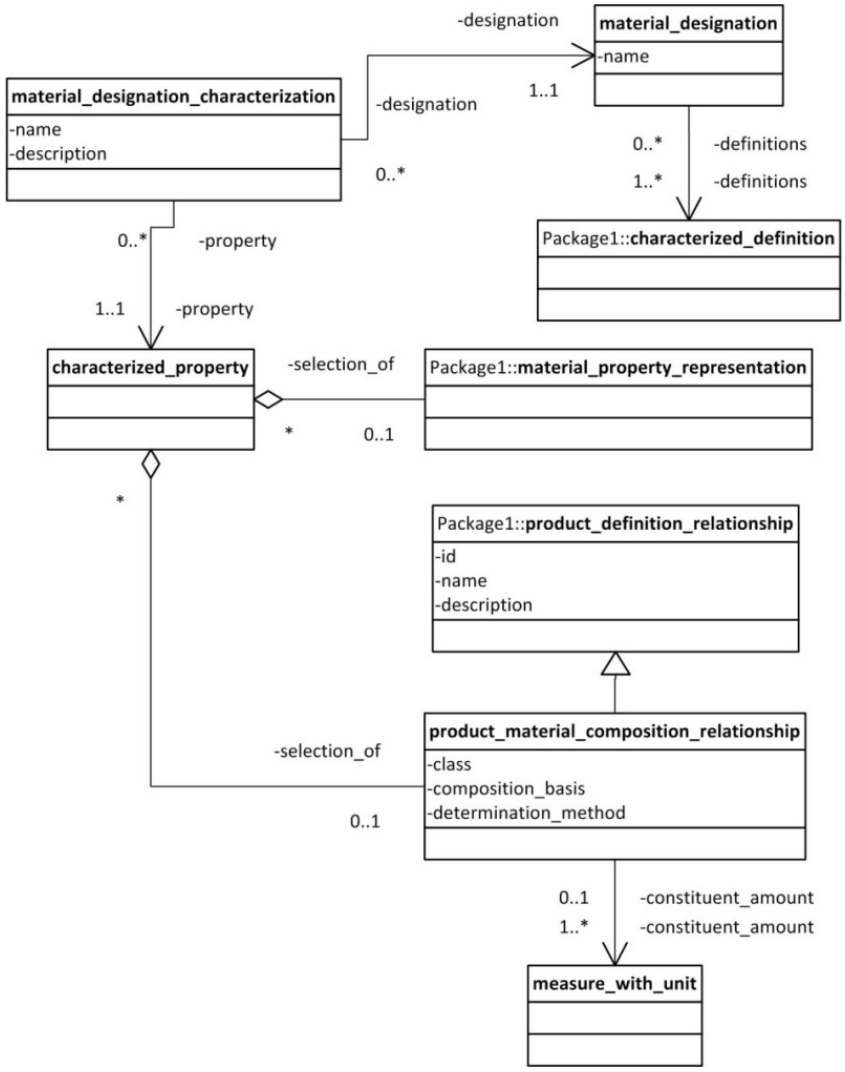
Figure 10 Representation of behaviour, function and artifact



In STEP Standard (particularly in Part 45), the mass of any material, constituents of any material and the mass of any substance have different ways of representation. In Part 45, either a material property definition or the product material composition relationship definition can be associated with a material designation (Figure 11). This association is represented by the entity **material_designation_characterisation** in Part 45. In order to define the constituents of a material product, an instance of the **material_designation_characterisation** has to be created for each constituent substance of a product. Each constituent is then identified by the **product_material_composition_relationship**. This object aggregates the class information for the kind of relationship between a constituent and a product (e.g., mixture, alloyed, chemically bonded, etc.), the amount of constituent, the basis of composition (e.g., volume, weight, mole, atoms, etc.) and the method of determining the amount of constituent. This object is a subset of the **product_definition_relationship** and it inherits five attributes: *id*, *name*, *description* (optional), *relating_product_definition* and *related_product_definition*. The *relating_product_definition* attribute should be connected to the base material product definition. The *related_product_definition* attribute should be connected to the

constituent material product definition. The constituents of a product that are defined through the **product_material_composition_relationship** can be used as the substance representation at the product level for IPC-1752. The *constituent_amount* attribute represents the amount of substance and the unit of measure. For each constituent material, a **material_designation** should be instantiated to define the ID of the constituent.

Figure 11 UML representation of material designation and material composition representation available in part 45

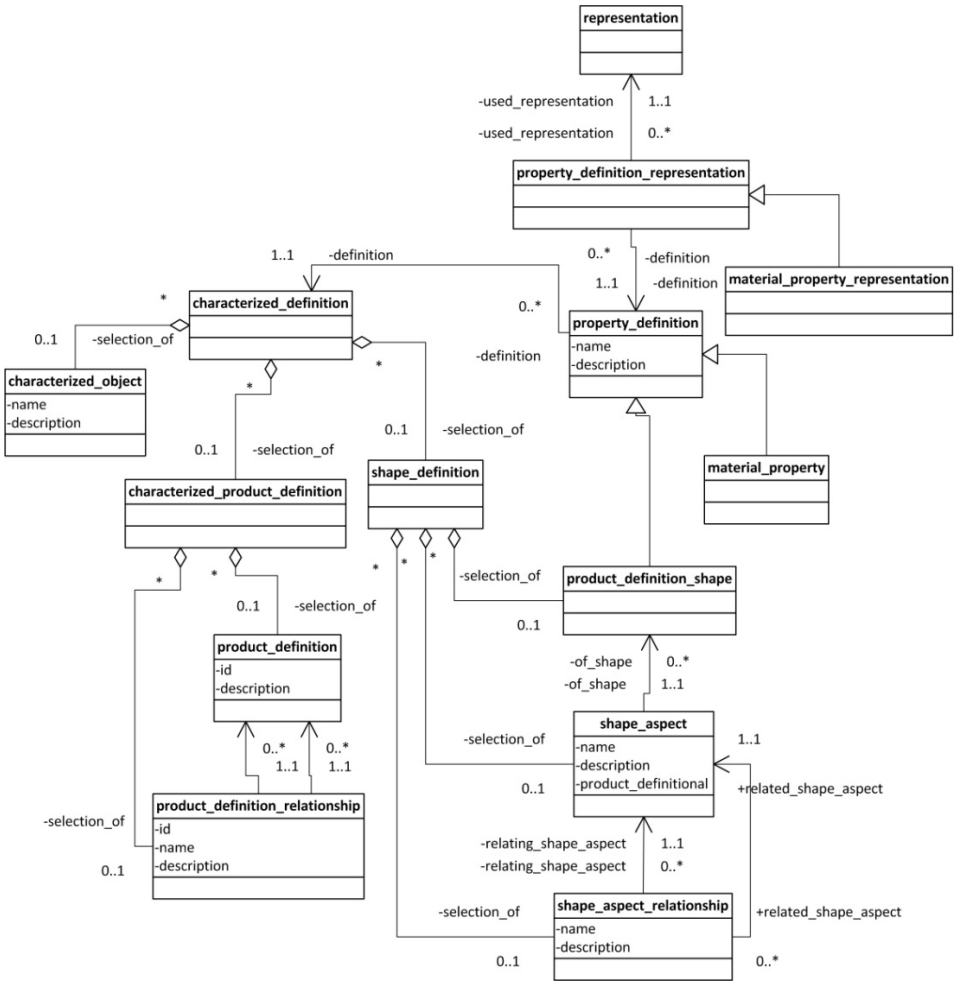


In order to represent the mass of a material or a product in Part 45, the **material_property** in Figure 12 will be used. It is a subset of the **property_definition** which has *name*, *description* and *definition* attributes. The *definition* attribute connects to the **characterised_definition**. The **product_definition** (Figure 12) will be

instantiated as the *definition* attribute of the **material_property** through this object for the product or material for which the mass has to be defined. Then, the **material_property_representation** which is a subset of **property_definition_representation** has to be instantiated. It inherits two attributes from the superset entity: *definition* and *used_representation*. The *definition* attribute will be connected to the instantiated **material_property** and the *used_representation* attribute will be connected to the **representation**.

In order to represent the homogeneous level substance information of IPC-1752, the **material_designation** has to be instantiated for the substance in scope (Figure 11). The *definitions* attribute of this object should be connected to the **shape_aspect** (Figure 12) through the **characterised_definition**. The **shape_aspect** defines an element of the shape which is identifiable for a product. By this object, the homogeneous material region can be identified and the substance information can be assigned through the **material_designation** as explained above.

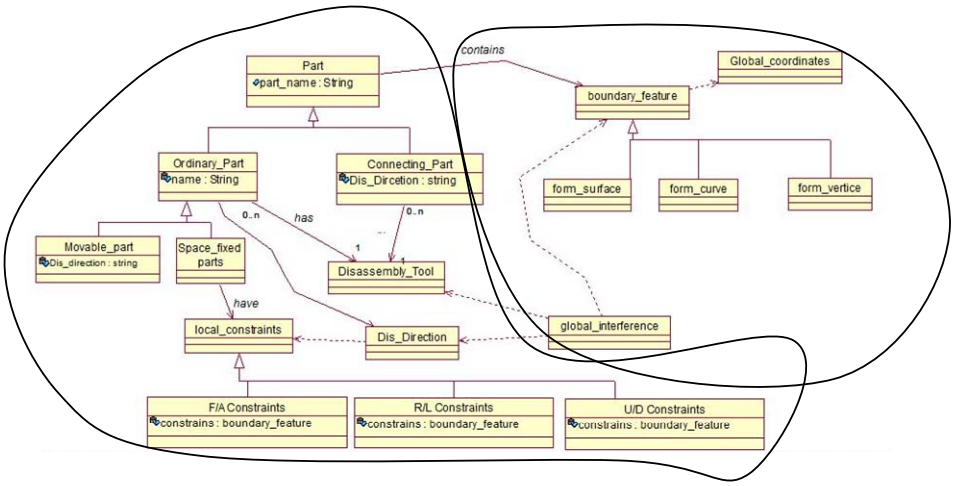
Figure 12 UML representation of material property representation available in part 45



4.3 The disassembly sequence information model

The structural schema of the information model required for the disassembly sequencing operation is created in UML as shown in Figure 13. A detailed explanation is available in (Zhu et al., 2012).

Figure 13 Structural schema of disassembly sequence information model (see online version for colours)



The schema consists of basic information regarding followings:

1 disassembly directions

2 spatial constraints

3 disassembly tools.

4.3.1 Disassembly directions

Disassembly direction is crucial in verifying feasibility of a certain disassembly operation. However, this information is not known for all the parts in the product. The disassembly directions of some parts such as screws are known regardless of the state of domain. Some parts are fixed just because of constraints by spatial positioning of other connected parts. Thus, the disassembly direction of these parts can change based on the removal of the constraints. The disassembly information model thus separates these two kinds of parts into connecting part and ordinary part. The disassembly direction of an ordinary part is null at the beginning and will be determined by the behavioural schema of the model during a stage changing event.

All the classes in the left circle help generate the disassembly direction for an ordinary part. The model has three classes, **F/A** *(front and after)* ***constraints***, **R/L** *(right and left)* **constraints**, **U/D** *(up and down)* **constraints**, and each of which holds a boundary feature instance. These boundary features could be boundary surfaces or boundary curves. They are special kind of boundary features because they are the reasons why the ordinary part is spatially fixed.

4.3.2 Spatial constraints

Spatial constraints are considered to represent the relationships between a part and other parts, some of which are linked locally while the other parts may not be directly linked. In order to capture this information, boundary representation technique is used. A solid model is represented by the bounded surfaces. The bounded surfaces are represented by bounded curves. The bounded curves are represented by vertices. The classes in the right circle of the model handle this information.

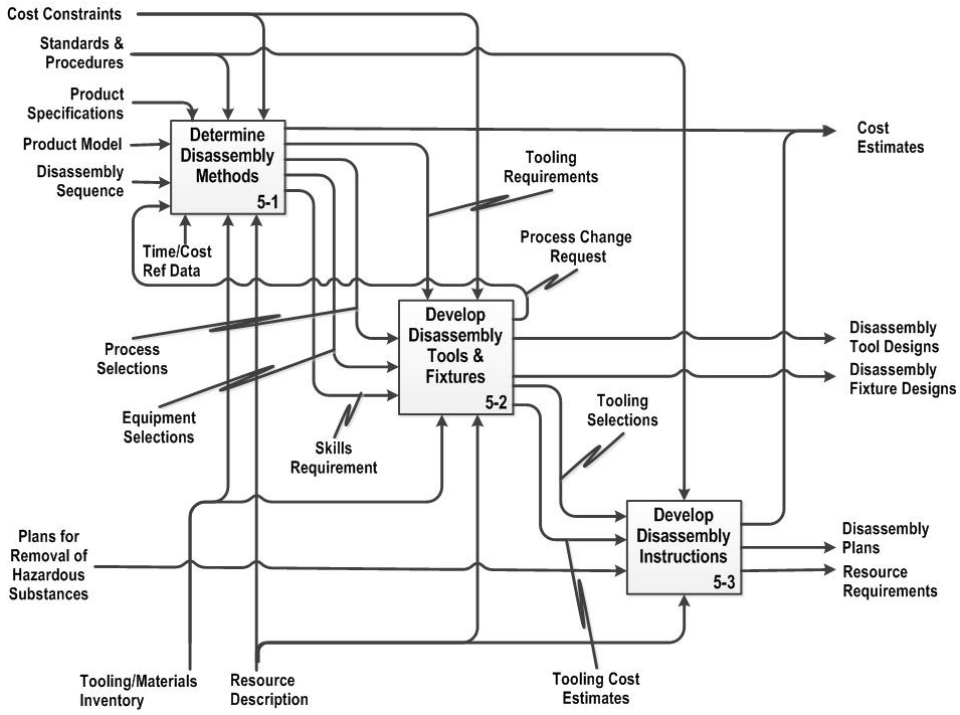
4.3.3 Disassembly tools

Disassembly tool is also simplified as bounded surface for validating the disassembly operations. This information is in the class disassembly tool.

4.4 The disassembly plan information model

The activity, 'develop disassembly plans' in Figure 5, has been further broken down into sub-activities. The decomposition is given in Figure 14.

Figure 14 Decomposition of the 'develop disassembly plans' process model



In order to develop disassembly plans, the first activity is to determine the disassembly methods. Cost constraints, standards & procedures and product specifications dictate how to determine the disassembly methods. Tools/materials inventories, resource descriptions and time/cost reference data are used for this process. Outputs are disassembly process selections, tooling requirements, equipment selections and skills requirements. With this

information, disassembly tools and fixtures are developed, and finally the disassembly instructions are generated. It further helps determine the cost estimates, disassembly tool designs, disassembly fixture designs, disassembly plans and resource requirements.

5 Conclusions

It is very important to understand the role of disassembly in the context of any product's overall life-cycle activities. Disassembly, being the precursor to any repair, replacement and maintenance operation, or any product recovery operation at the end of the product life-cycle, is the most important activity in EOL management. Almost every recovery option involves some amount of disassembly. It necessitates the study of developing a comprehensive disassembly information model that can help maximise recovery of possible value-added materials from the product.

The work that has been developed and reported has several important characteristics. The informational framework is domain-independent, generic meta-models which could be easily implemented in Protégé (2012), an OWL-based system for supporting automated decision making mechanisms for any product. The framework could be further embellished to incorporate product design, analysis, manufacturing and EOL – specific information to record product history that would be useful in determining any product sustainability related information throughout the product supply chain. The framework is fully capable of supporting semantic interoperability among CAD, CAE, CAM and other interrelated systems.

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