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Information Modeling of Conceptual Design Integrated with Process Planning

Shaw C. Feng and Eugene Y. Song
Manufacturing Engineering Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

ABSTRACT

Information modeling is critical to the integration of conceptual design and process planning. An information model for conceptual design is provided in this paper. Conceptual design is a key activity in early product development. It determines product functions, form, and the basic structure. Major manufacturing cost is committed in early conceptual design process. The model presented in this paper includes activity model for the conceptual design process and object model for classes used in conceptual design. The activity model sets the context in which the objects are defined and used. The object model describes the data and functions used in conceptual design and integration with process planning. The main purpose of the model development is to initiate standard interface specifications that are necessary for design and process planning integration.

Key Words: Conceptual Design, Design and Planning Integration, Information Modeling, Product Design, Systems Integration.

1 INTRODUCTION

Influence of design on manufacturing cost is usually great. Errors made during the early stages of design tend to contribute as high as 70% to the cost of production [1]. Experienced designers are usually able to create successful initial designs because of their in-depth knowledge of common design practices, customer expectations, and manufacturing processes; however, less experienced designers often require input from experienced designers in all of these areas. Ideally, a designer should be able to access necessary manufacturing resource, design, customer requirement, and cost information during the design of a product. Even with the recent technological advances in software technologies for design, manufacturing, engineering analysis, process planning, and numerical control programming, making sound decisions in the early design phase is still rather difficult since it involves an understanding of many difficult to predict factors in manufacturability, quality, reliability, and serviceability [1, 2, 3]. Of these factors, the most substantial ones are the manufacturability of the design and the cost of fabrication.

Considerable research has been performed on detailed design automation. One problem with the current design and process planning software systems is the lack of integration between Computer Aided Design (CAD) data output and process planning input. For example, the primary focus of ISO 10303-203, informally the STandard for Exchange of Product model data (STEP) Application Protocol (AP) 203 [4], is the interoperability between traditional CAD systems. While, the focus of STEP AP 224 [5] (whose main emphasis is on machining features) has been on the input to process planning systems. These two APs alone cannot meet the needs of integrating conceptual design systems and conceptual process planning systems. Furthermore, most academic research is focused on generating manufacturing features from detailed geometry for unidirectional communication. As stated in the subsection of Engineering Tools for Design, Manufacturing, and Integration in a government report [6], the most important infrastructure needs and research areas to enable the necessary advances in design and manufacturing are alternate design concepts, conceptual phase tools, and improved simulation and modeling tools. In the conceptual phase tools, the need is on better models that can allow rough prediction from indefinite design parameter values, evaluation of processing alternatives, manufacturability, etc. Hence, interoperability between the various design and process planning phases is essential in the evolution of advanced manufacturing.

To achieve truly collaborative design and manufacturing, information representations of both design and process information must support multiple levels of abstraction for bi-directional (or multi-directional) communication. For example, during the early conceptual design phase, it is important to understand the trade-offs and implications of high-level design decisions. Symbolic descriptions of designs, which are not yet defined geometrically, can yield enough input to determine many characteristics of the manufacturing process with underlying cost estimates. Our work addresses the formal representation of such early design descriptions, and their utility in providing input to conceptual process planning and manufacturing applications. Our goal is to develop interface specifications for integrating design and manufacturing engineering.

This paper mainly provides an overview of various aspects of the information model that has been developed. Section 2 describes the current state of development of design and process planning software. Section 3 provides an overview of the model. Section 4 describes generic activities in conceptual design, which are represented in activity diagrams, and an object model, which is represented in class diagrams. Section 5 summarizes our efforts and describes future directions.

2 CURRENT STATE IN DESIGN AND MANUFACTURING INTEGRATION

CAD/CAM systems have been used in manufacturing industry for years. These systems have continually evolved. Traditional CAD systems handle wireframe geometry modeling, surface modeling, and solid modeling. CAD systems have been recently augmented to provide part assembly modeling, constraint representation [7, 8], and feature representation [9], tolerance definitions and analysis, and virtual reality capabilities. Researchers and vendors are still developing new capabilities for improving these CAD systems. More advanced CAD systems are being proposed and developed in academia. These advanced systems are largely knowledge-based. Hence, they have automated product generation capabilities and access to large-scale knowledge libraries [10]. In parallel to CAD technology development, Computer Aided Manufacturing (CAM) technology has evolved from handling prismatic parts (two-and-a-half-axis or three-axis) to parts with free-form surfaces (four- or five-axis machining). For concepual design, some knowledge-based design systems are available [12], such as ICAD and AML [25]. There is still no open interface specifications for integrating with process planning software.

Between design and machining, there are software tools – Computer-Aided Process Planning (CAPP) systems – for machining planning based on part design. CAPP systems are slowly evolving from traditional capabilities (finding volumes to be machined, cutting parameters selection, tolerance analysis and synthesis [13]) to modern capabilities (automated setup planning, interactive feature finding, equipment/tools selection, tool path generation, and machining simulation). CAPP serves the function of bridging the gap between design and manufacturing.

Although all of these tools can be very useful, they still rely primarily on geometric data. Moreover, they focus on detailed geometry. Currently, many CAPP systems acquire their data via feature recognition of a finished detailed geometric model from a CAD system. The CAPP system must interpret all of the design intent from the solid geometric model. Once the features have been found – a challenging research area – process plans can be created. This mode of operation does not provide any manufacturability feedback to designers. This can lead to inefficient product development cycles. Hence, there is a need for tools that provide feedback to the designer at every design stage.

In conceptual design, some commercial, rule-based design systems have been developed that allow routine design tasks to be automated. A designer can program knowledge into these systems to automatically generate a design using various input parameters. Although these systems can help a designer during he conceptual design stage (especially for routine design), they do not address many aspects of conceptual design, including functional decomposition and mapping from functions to the designed product. The design process has to be coded into the systems. Moreover, only geometry can be transferred into or out of the system. Academic researchers have also been developing conceptual design tools for many years. Several different synthesis systems have been implemented [14]. One such system developed, CONGEN (CONcept GENerator), is a domain-independent knowledge-based system framework that maps an evolving symbolic description of a design into a geometric one [15].

Process planning technology is also evolving as new analysis methods emerge. Process planning research [16] has been focused primarily on machining feature recognition, fixturing and setup parts, and NC tool path generation at the detailed level of process planning. These process planning technologies utilize detailed design data with detailed geometry, topology, dimensions and tolerances, material, and surface conditions completely specified. Only some of the research focuses on process selection [17, 18]. Research and development of commercial software for process selection and cost estimating at the conceptual design stage is still in an infancy stage.

The Systems Integration for Manufacturing Applications (SIMA) program [19] at NIST is addressing issues and developing solutions for interoperability among manufacturing systems. It was initiated as part of a Federal Initiative on High Performance Computing and Communications [20]. The SIMA program is supporting manufacturing system integration technologies; development and testing of interface specifications for manufacturing systems; remote access to scientific and engineering data; and research of collaborative manufacturing environments. As a result of some projects in the SIMA Program, several information models have been created for various manufacturing applications. A few examples of the diverse work being conducted via the SIMA program are activity models that describes functions and information flow among design, process planning, manufacturing execution [21]. Process Specification Language [22] which is design to capture operation sequences of manufacturing processes as an interchange format is also part of SIMA program. The development of conceptual design activity model and object model is within the scope of SIMA. An overview of the development project can be found in [23], and initial prototype development is described in [24].

3 CONCEPTUAL DESIGN INFORMATION MODELING FUNDAMENTALS

The information sharing and exchange between design and process planning applications (and other applications as well) occur at more than one stage. Figure 1 illustrates many stages of communication that can exist when establishing interoperability between conceptual design and conceptual process planning.

Conceptual design is an activity in the early design stage in which the concept of a product is formulated. The concept of a product includes product requirements, functions, possible

Properties include material, assembly-level tolerance, critical surface roughness and hardness parameters, and critical dimension. Functional design generates product major functions and decomposed them into detailed functions from requirements. Behavioral design maps detailed functions into behavior models. Embodiment design specifies product form and structure based on functions and behaviors. Detailed product information is derived from the conceptual design.

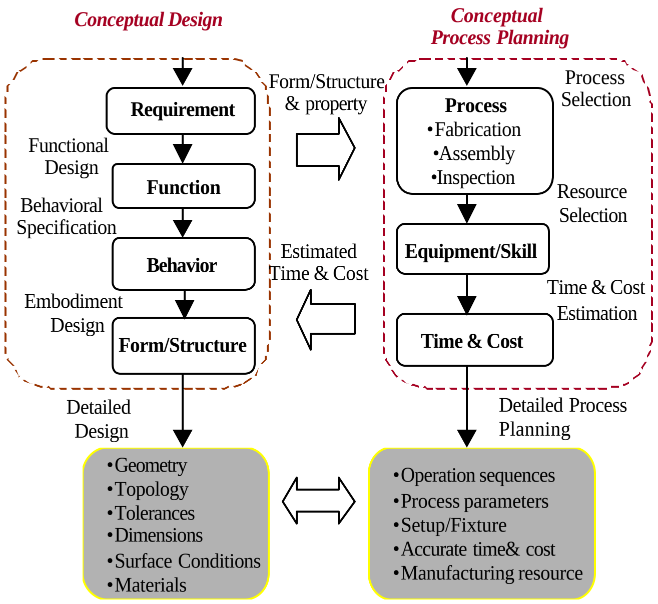

Figure 1: Integration of conceptual design and process planning

behaviors, form/structure (layout), and associated properties.

The conceptual process planning is an activity of preliminary manufacturability assessment and cost estimation on conceptual design. More details are in [25]. Conceptual design information is used in the detailed design process, geometry, topology, tolerance, and dimension specification. Likewise, conceptual process planning information is used in the detailed process planning activity, such as operation sequences, process parameters, and setup specification. However, both detailed design and process planning are out of the scope of this paper. The goal of this information modeling is to model the information about conceptual design so that conceptual process planning can be performed. In order to set the context in which the information is used, an activity model is developed. This model decomposes the main idea into more detailed levels. Additionally, the model is a specialization of the preliminary design activity described in the SIMA activity model [18].

The conceptual design activity (A1) is decomposed into five subactivities. Figure 2 shows subactivities A11 to A15 and the data flow. Activity A11 is to defined product functions and constraints based on the input, engineering requirements. This activity is called functional design and can be further decomposed, as shown in Figure 3. Activity A12 is to generate product behaviors based on product functions and constraints, output from A11. This activity is to generate behaviors. For those products that do not have behaviors, such as static structural objects, this activity should be skipped. Activity A13 is to decompose functions, constraints, and behaviors so that each part, subassembly, and assembly of a product has its own functions, constraints, and behaviors (if it has). With decomposed functions, constraints, and behaviors, parts can be designed and product can be configured by these parts in A14.

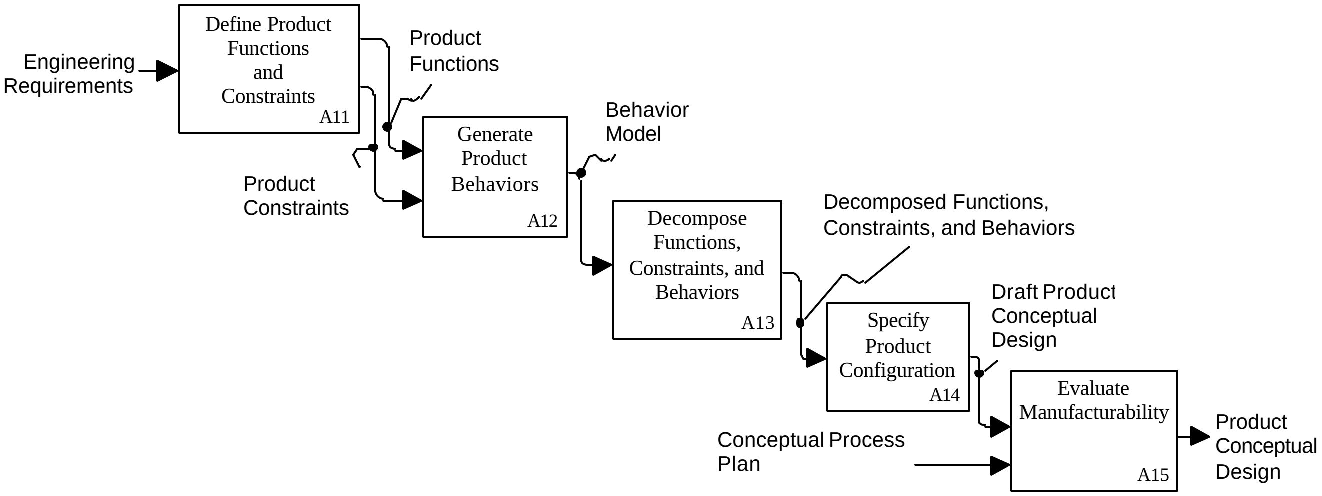

Figure 2 Functional Decomposition of Conceptual Design

The output is the concept of a product, the product conceptual design. Finally, The conceptual design is evaluated by manufacturability in A15. The manufacturablity analysis takes input from both conceptual process planning and conceptual design.

Activity A14 can be decomposed into two subactivities. Activity A141 is to specify product structure based on function, constraint, and behavior decomposition. The form and structure of the product is conceptualized in this subactivity. Activity A142 is to specify detailed information about artifact. The detailed information is necessary for process planning, such as manufacturing process selection, resource selection, and cost estimating.

Activity model describes functions and their input and

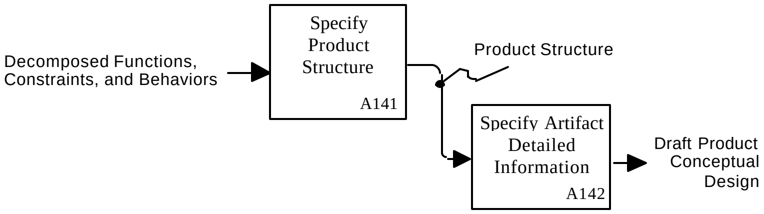

Figure 3 Specify Product Configuration

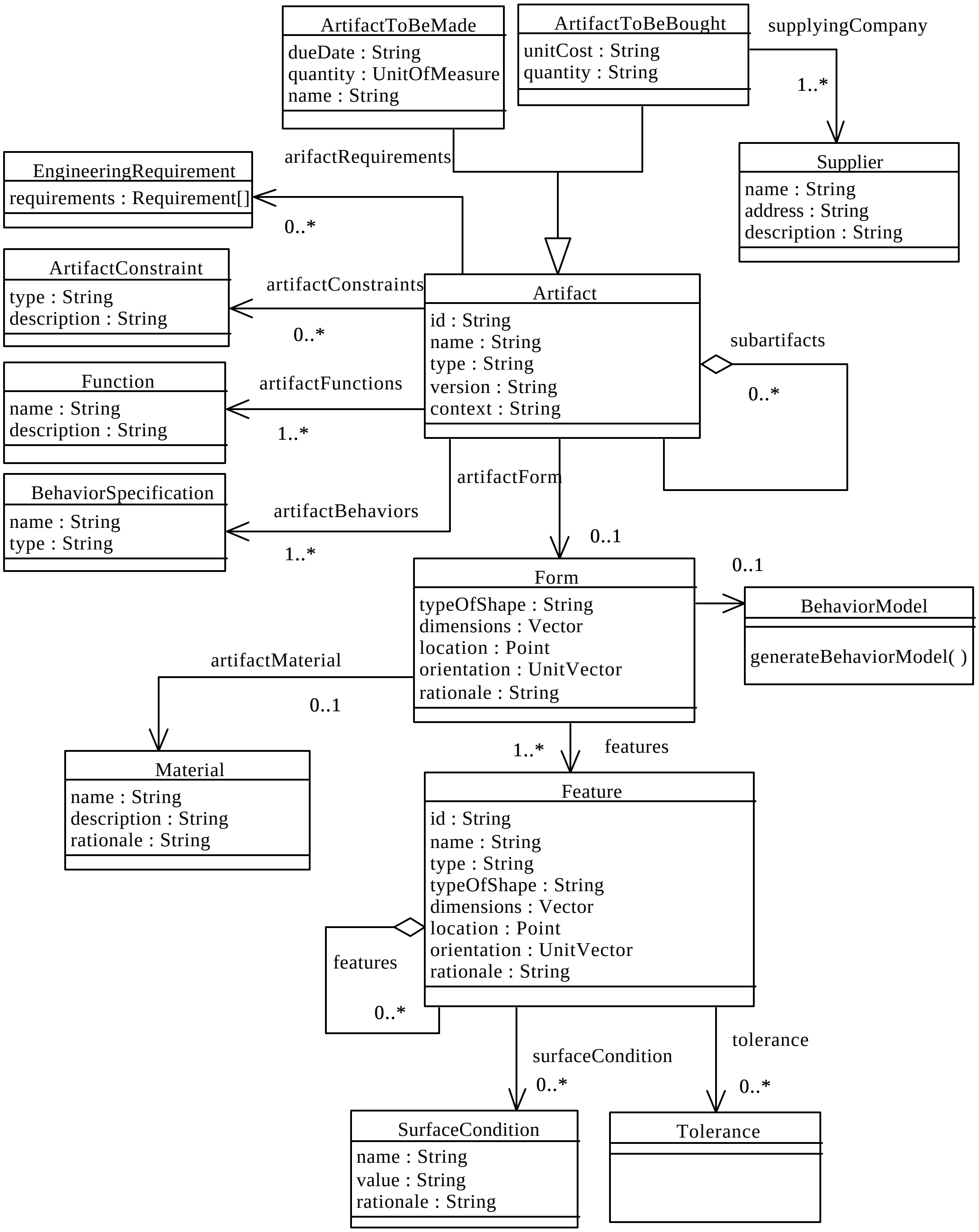

Figure 4 Class diagram for Artifact

output data in conceptual design, based on the concept of integrated design and process planning. We will collaborate with industry to make sure that the model does reflect real world cases and situations. The activity model provides a context in which object model is developed.

4 OBJECT MODELING FOR CONCEPTUAL DESIGN

The object model contains many aspects in conceptual design, described in the activity model. In this section, the modeling of artifact, its function, and the assembly relationships is described. The classes pertaining to product requirements are omitted from this section because conceptual design starts from functional design. The model is represented in the class diagrams in the format of Unified Modeling Language (UML) [26]. Some classes related to information on product are derived from a core product representation model, currently being developed at NIST. The concept of the following clasese are adopted from the core: Artifact, Function, and Constraint. The following classes are derived from the core: Behavior, Material, Requirement, and Constraint. The rest of the classes are specific to the conceptual design integrated with conceptual process planning. The intended uses of this model are as follows: (1) to be a reference architecture for the next-generation conceptual design, (2) to serve as a basis for developing standard interfaces, and (3) to be used as database schema. The whole model is described as follows.

Artifact is a general term for referring to an individual component in a product hierarchical structure, such as a part, subassembly, assembly, or the product. Specific information includes material parameters, tolerances, dimensions, surface roughness parameters, surface hardness parameters, and texture parameters.

Figure 4 shows the class diagram of Artifact. The Artifact class has a recursive definition. Artifacts are in a hierarchical structure, which can capture the product structure, in a hierarchical structure. Artifact has the following associated classes. Constraint relates to those factors that prohibit product to function, such as physical limitations, environmental concerns, and safety regulations. Behavior captures the motion of a product. The motion is calculated or simulated in the method generateBehaviorModel() in the class. Function captures product functions, translated from engineering requirements. Detailed Function object model, which is linked to the Artifact model, is in Figure 6. Form has the conceptual/sketched shape of the product and its components.

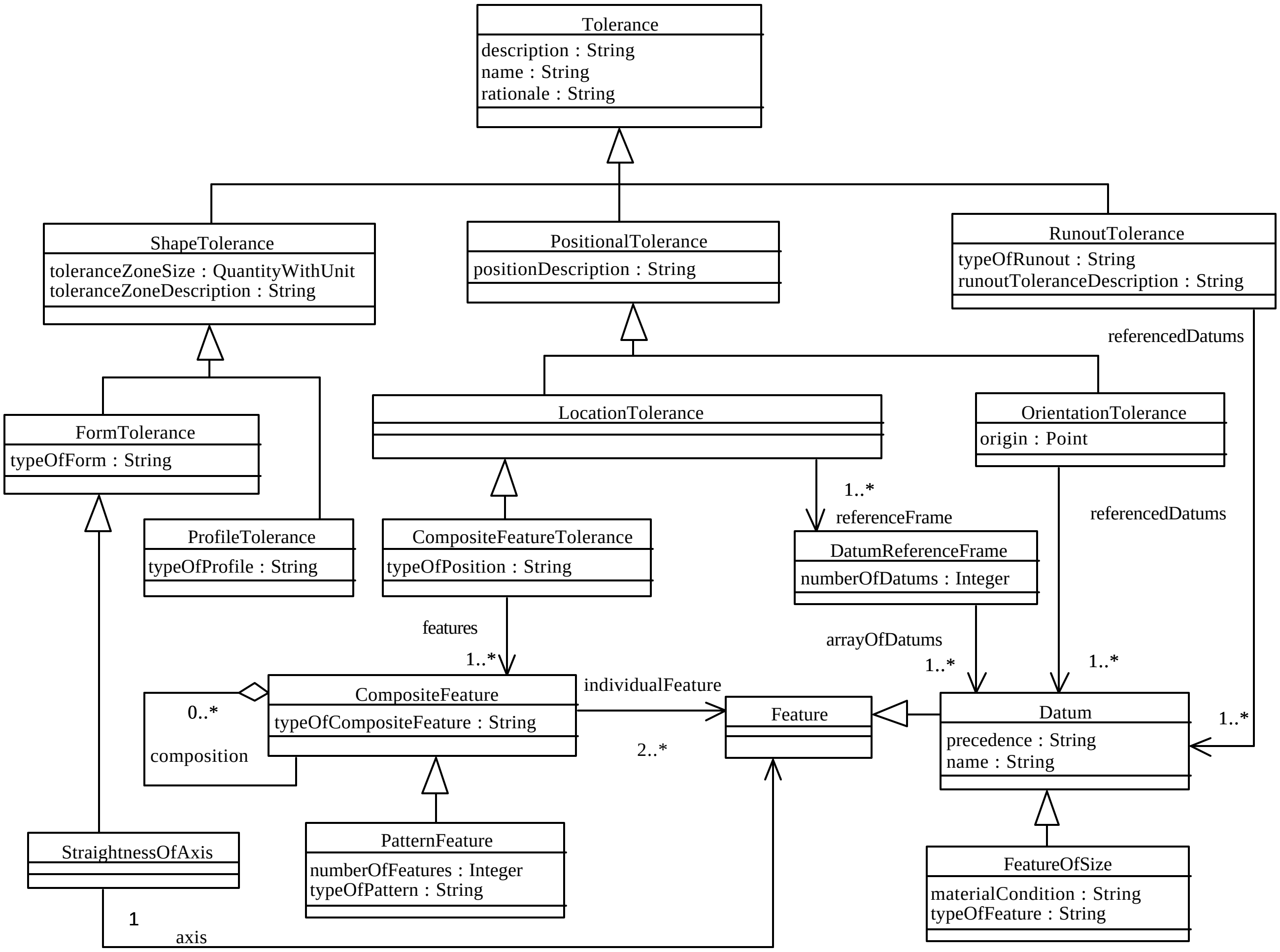

Figure 5 Class diagram for Tolerance

Form consists of Material, Feature, Tolerance, SurfaceCondition, and Rationale. Material represents the information of material properties relating to the realization of product shape. Feature is a portion of the form and is also in recursive definition. A feature can consist of many subfeatures, which are in a hierarchical structure. For example, a screw hole consists of a countersink feature and a hole feature, and the hole feature consists of a cylindrical feature (hole) and a thread feature. The class can also represent composite features, composed features from different artifacts. Tolerance defines the limits within which a feature can vary. Tolerance includes form tolerance, location tolerance, profile tolerance, and runout tolerance.

Figure 5 illustrates classes that relate to tolerance. SurfaceCondition specifies the hardness, roughness, and texture requirements on a feature of a form. Rationale captures the reasons that tolerance is defined, material is selected, and form and feature are design. Additionally, Artifact has two derived classes: ArtifactToBeMade and ArtifactToBeBought. Some components (artifacts) can be purchased from supplies. Others have to be made by the company in which the product is designed.

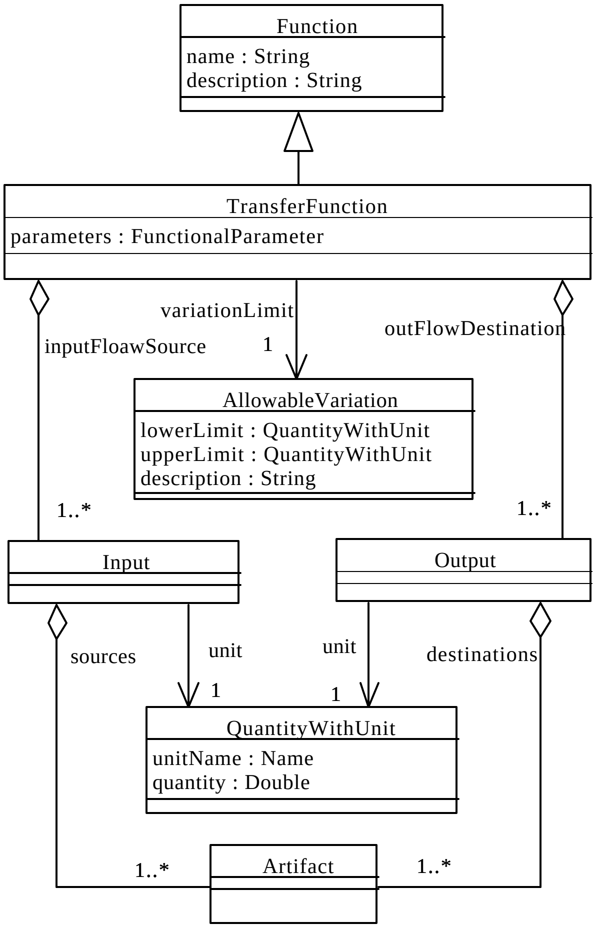

Figure 6 Class diagram for Function

TransferFunction, as in the Function model in Figure 6, is a derived class from Function. It captures those functions that have input and output of information, material, and/or energy. Input has a type of input, quantity, and the source. Similarly, Output has a type, quantity, and the destination. The functions of manufactured parts do vary and have to be constrained by AllowableVariation, which sets the limits for which a function of an artifact can vary. The allowable functional variation can be converted into tolerances on certain feature parameters using, for instance, Taguchi methods.

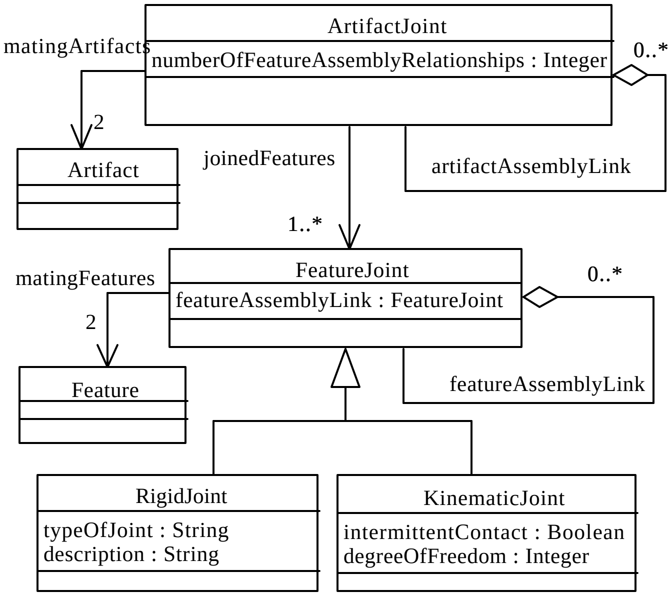

Figure 7 Class diagram for Joining

The artifact joining, also referred as assembly, model describes how two artifact are assembled, as shown in Figure 7. ArtifactJoint describes the joining relationship of two artifacts. The class has recursive definition. This generates an assembly hierarchy, the lower pair in the hierarchy the earlier they should be joined with each other. Thus, the hierarchy indicates the assembly sequence. Each pair of joined artifacts is connected with each other in some portions, features, of the artifacts. FeatureJoint captures assembly relationship of two features and type of joint, rigid or kinematic. This class is also in a recursive structure to describe the joining relationships of features of a feature. Like in ArtifactJoint, the feature assembly sequence is captured in the hierarchical structure.

The model has been manually populated using a gearbox example. The gearbox consists of a sun gear, three planetary gears, a ring gear, an input shaft, an output shaft, two pieces of housing, two bearings, and two seals. Functions, forms, product structure, tolerances, and the assembly relationships of the gearbox conceptual design were able to be represented using the model [24, 25]. Certainly, more tests of the model using varieties of examples that will thoroughly test the model are definitely necessary and will be conducted in the near future.

5 CONCLUDING REMARKS

The conceptual design is a product design activity to define product functions, behaviors, form, materials, and necessary tolerances. Incorporating manufacturing analysis into design can ensure that the design is manufacturable and within cost limits. Manufacturablity analysis and cost estimation are important to minimize production cost. However, there currently lack integrated tools for designers to evaluation conceptual design. Manufacturers' need new software tools that will effectively support translating production requirements to functions and functional decomposition, translating functions to behaviors, translating functions and behaviors to production forms, selecting manufacturing processes, selecting manufacturing resources, and estimating manufacturing time and cost. To develop these new tools information models are necessary to support the tool development and the integration of the tools.

This paper has described a conceptual design activity model and an object model that have been developed to serve the purpose of integration. The design information that is necessary for conceptual process planning has been collected and modeled using UML. The models are still in draft form. They are expected to be further enhanced by modification, expansion, and extension in the future.

Future work includes the following tasks: (1) validate the draft models using more industrial cases, (2) formally represent manufacturing process knowledge, and (3) develop initial prototype system of integrated conceptual design and conceptual process planning to further test the object model.

Industrial collaborations are critical to the success of the project. During the next year, we plan to obtain a state-of-the-art knowledge-based system which will be incorporated into our prototype system and collect industrial parts as the test cases. Using the information models and the test cases, we will implement a more advanced design and manufacturing planning information exchange mechanism. This work should give us the background necessary to specify, with the help of software vendors, the interface requirements for next-generation, integrated CAD and CAPP systems.

DISCLAIMER:

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