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Information Modeling of Conceptual Process Planning Integrated with Conceptual Design

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ABSTRACT

Conceptual process planning is a key activity for designers to evaluate manufacturability and manufacturing cost and time in the early product development stage. Since major manufacturing cost is determined in early design, it is critical to be able to assess manufacturability and cost as early as possible in the design process. The integration between process planning and design is critical to enable these analyses. A literature review of the current status of Computer-Aided Design (CAD) and Computer-Aided Process Planning (CAPP) software technologies reveals the lack of interface standards to enable the integration of these systems. In order to develop interface standards, information models have to be first developed to define the interfaces. An initial information model for conceptual process planning has been developed. This model includes an activity model and an object model for manufacturing process selection, resource selection, and cost and time estimation. The activity model sets the context in which the objects are used for information sharing and exchange. The object model defines classes used in conceptual process planning. The main purpose of developing this model is to initiate the development of standard interface specifications that are necessary for design and process planning integration.

Key words: Computer-aided Design, Computer-Aided Process Planning, Conceptual Process Planning, Cost Estimation, Design and Planning Integration, Information Modeling, Process Planning, 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 much as 70% to the cost of production [1]. It is better to consider manufacturing issues as early as possible in the product design process. However, making sound decisions in the early design phase is rather difficult since it involves many unpredictable factors in manufacturability, quality, reliability, serviceability, etc. [1,2]. Most Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) tools are applied to improve detailed design and detailed manufacturing planning, but not conceptual design, which usually does not include functions, behaviors, form, structure, tolerances, and surface conditions that determine manufacturing methods and cost. As technologies evolve, design engineers need to consider concurrently manufacturability in the design process [3-7]. In design engineering research, some researchers have proposed methods for cost estimation [7-10], material process selection [11-13], and basic manufacturing engineering processes and technology [14-17]. These research results lay a foundation for integrated design and process planning at a conceptual level. Nevertheless, computer-aided tools for integrated conceptual design and process planning are still far from being satisfactory in real-world applications. The reason is a lack of theoretical foundations to characterize the process of early product design and the integration of various functions and technologies for effective product design [21-24].

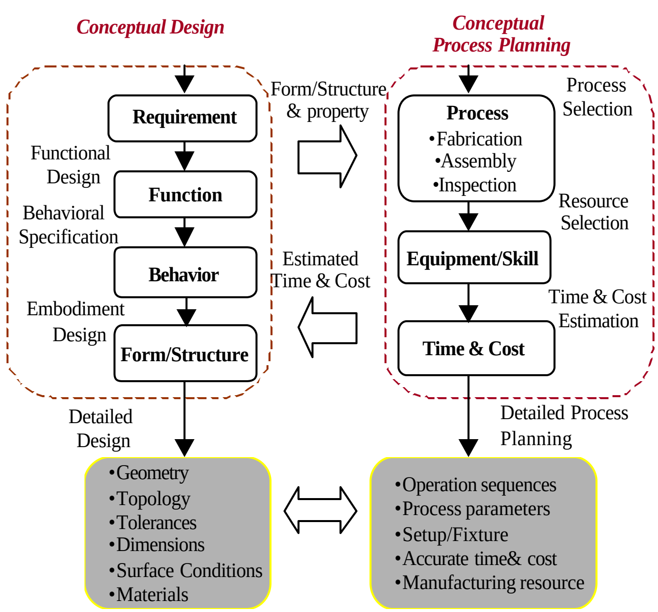

Figure 1 Design and Process Planning Message Exchange for Integration

The initial information model described in this paper addresses the need for improving communications between conceptual design and process planning activities in the early design phase. The focus is on the interoperability. Figure 1 illustrates many stages of communication that can exist when establishing interoperability between design and process planning. A typical design process includes customer requirements analysis, functional decomposition, behavioral specification, embodiment design, and detailed design. A corresponding manufacturing planning process includes conceptual process planning and detailed process planning. From conceptual design, data such as form, function, features, product quantity, and form properties (tolerances, surface conditions), are sent to a conceptual process planner. These data describe the product and the reasoning behind certain design decisions, also referred as design rationale. They are sent to conceptual process planning as messages. The outputs from conceptual process planning, including manufacturing processes, equipment, and cost, are the manufacturability data. These manufacturing data are also captured in the messages and sent back to the conceptual design tools and designers. Designers receive the feedback of feasible manufacturing process(es), required resources, and estimated cost and redesign as necessary for better products.

Section 2 provides a summary of the state of the integration art in conceptual design and conceptual process planning. Section 3 defines the conceptual process planning and an activity model. Section 4 describes an object model, which can be used for prototype development and interface specification. Finally, Section 5 contains concluding remarks and a description of future work.

2 A SUMMARY OF THE STATE OF THE ART IN INTEGRATING CONCEPTUAL PROCESS PLANNING INTO CONCEPTUAL DESIGN

Pioneering research and some developed prototypes involved computational function design and conceptual design. Gorti and Sriram developed a software framework for conceptual design, which could map an evolving symbolic description of design into a geometric description [19]. Mukherjee and Liu presented an abstraction for conceptual design by using function-form relation matrices. The relation matrices provided a link between purely functional and purely geometric representations, and a means to carry out domain-dependent manufacturability evaluations [13]. Theodoracatos and Ahmed described an expert system for conceptual design that interprets functional structures, searches engineering solutions, and evaluates concepts [34]. Anderson and Makkonen described the development of the CANDLE modeling language to support the early design phases of mechanisms and manipulator systems [25]. Tomiyama, Umeda and Yoshikawa proposed a methodology – Function-Behavior-State (FBS) to model functions and introduced a computerized tool to support functional design based on the FBS modeling [26]. Kimura and Suzuki attempted to capture and to represent product background information, which includes requirements, specifications, assumptions, constraints, decision history, trial-and-error processes, and other rationale rules [27]. Wong and Sriram developed an object-oriented framework for storing product and design processes. It allowed the representation of multiple versions of parts; relations between function, form, and behavior for each part; part attributes; constraints; and assembly relationships [17]. Hsu and Woon conducted a survey of the current state of research and development of conceptual design activities, and also compared the advantages and disadvantages of various techniques and tools [28]. These efforts were important in conceptual design process automation. Nevertheless, these techniques and tools were still far from being available for real industrial applications because they do not provide realistic assessment of manufacturability of conceptual products developed in early design stage.

Compared to conceptual design, the idea of integrating conceptual process planning has just been developed. Until recently, Computer-Aided Process Planning (CAPP) research and development efforts have focussed on metal removal, particularly NC machining, almost to the exclusion of other applications [20,29]. Actually, manufacturing process planning covers a wide range of technologies, i.e., casting, forming, metal removal, welding, inspection, and assembly [14-16,20]. Haudrum developed an approach to consider production methods in design stage [11]. Lenau presented a method for the selection of manufacturing processes and materials based on a computer tool that inspired the designer to examine materials/processes [30]. Giachetti described a prototype material and manufacturing process selection system that integrates a formal, multi-attribute decision model with a relational database [12]. Boothoyd and Dewhurst introduced another systematic approach to select manufacturing processes according to material and shape [1]. Evbuomwan and Sivaloganathan developed a design function deployment (DFD) software tool to support material and process selection [31]. Manufacturing cost estimation in the early design stage is an important topic for conceptual process planning and it is a critical element for decision making in design [7-10,32]. Only a definition and a reference architecture for conceptual process planning have been introduced [6].

From the literature review, we found that both computerized conceptual process planning and the high-level integration between conceptual design and conceptual process planning are at the initial stage of research and application. There lacks an effective integration mechanism to support the interoperability between these two functions. The required integration mechanism is the interface that can unambiguously transfer information among different systems. The interface software is usually developed based on a standard interface specification. The interface specification has to be defined in information models. This paper describes an activity model and an initial object model for the future development of the standard interface specification that supports the integration of conceptual design and conceptual process planning.

3 CONCEPTUAL PROCESS PLANNING INFORMATION MODELING FUNDAMENTALS

Conceptual Process Planning (CPP) is an activity of assessing the manufacturability and estimating the cost of conceptual design in the early product design stage. This activity aims at determining manufacturing processes, selecting resources and equipment, and estimating manufacturing costs and time. Conceptual process planning supports product design to optimize product form, configuration, and material selection to minimize the manufacturing cost.

One of closely related activities to conceptual process planning is detailed process planning. In contrast to CPP, detailed process planning is an activity based on a detailed design and the results from conceptual process planning to specify operations, determine operation sequences, select machines and tools to be used, depict setups, define process parameters, and estimate process time and manufacturing cost. Based on the definition of CPP, an activity model in IDEF0 [33] methodology is developed to describe the functions and data flow in the CPP activity in detail.

The conceptual process planning activity (A2) is decomposed into three subactivities. (Activity A1 is Conceptual Design.) Figure 2 shows subactivities A21 to A23 and the data flow. Activity A21 is to Determine Manufacturing Processes. Depending on conceptual product information, such as material, form, structure, and tolerances, primary manufacturing processes are selected, such as casting, forging, molding, and machining. This activity also includes the subsequence of processes to complete the manufacturing of the product. Activity A22 is to Select Manufacturing Resources. Based on the selected manufacturing processes, choose appropriate manufacturing resources including both physical resources and human resources. Resources include machines, tools, and labor skills. Activity A23 is to Estimate Manufacturing Cost. Based on overhead, selected manufacturing processes, and resources, A23 estimates manufacturing cost and time. Manufacturing cost covers material, purchased parts, labor, tooling, capital, machine usage, and overhead.

Activity A22 covers a series of resource selection functions and can be further decomposed into three subactivities in Figure 3. Activity A221 is to Select Machines. Based on the selected manufacturing processes, machines available in the factories are selected for manufacturing the designed product. Machines include machines tools, forging machines, casting machines, material handling and assembly machines, and measuring machines. Activity A222 is to

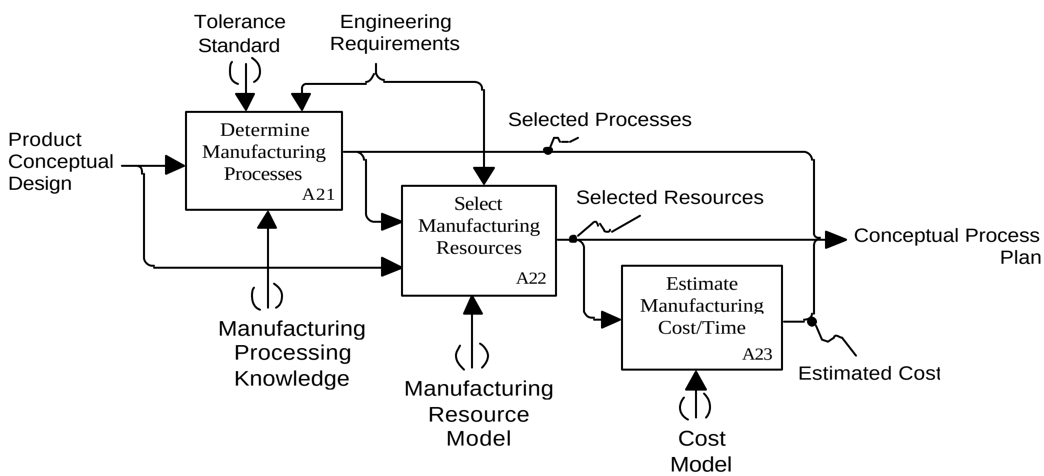

Figure 2 Functional Decomposition of Conceptual Process Planning

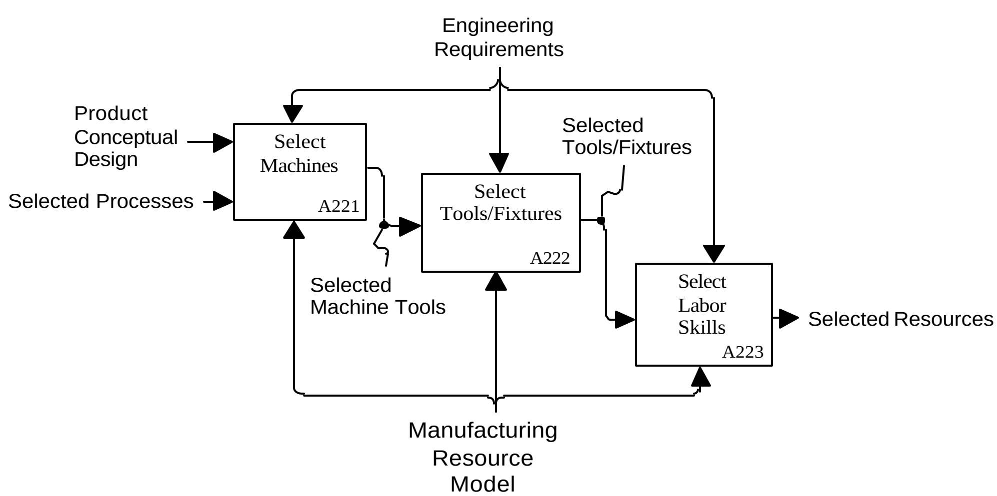

Figure 3 Manufacturing Resource Selection

Select Tools and Fixtures. Based on the selected machines, tools and fixtures that are necessary for supporting manufacturing processes are selected. Activity A223 is to Select Labor Skills. Based on the machines and tools, labor skills to operate the machines and use tools for production are selected in A223.

4 OBJECT MODELING FOR CONCEPTUAL PROCESS PLANNING

The object model contains information on the data flow in conceptual process planning, described in the activity model above. In this section, the object modeling of processes, resources, and cost structure for a conceptual design is described. The model is represented in the class diagrams in the format of the Unified Modeling Language (UML) [34].

Figure 4 shows classes related to manufacturing processes. ArtifactToBeMade has a sequence of ManufacturingProcess objects. ManufacturingProcess represents a generic process, which can be specialized further. The first level specialization includes Setup, Handling, Processing, LoadUnload, and Idling. Setup represents the activity of machine setup, tool setup, or workpiece setup. Handling captures the information on material

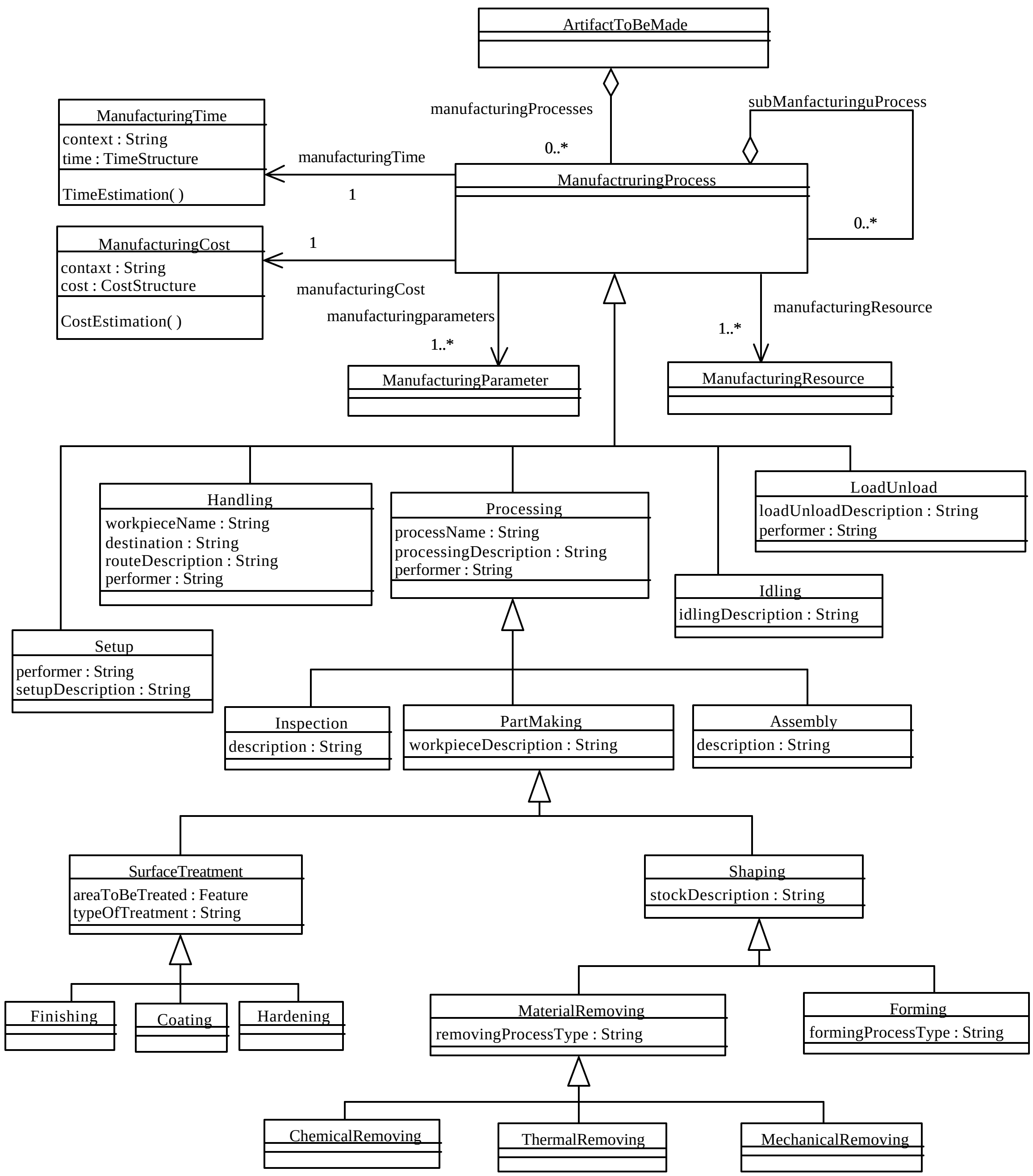

Figure 4 Class diagram for Manufacturing Process

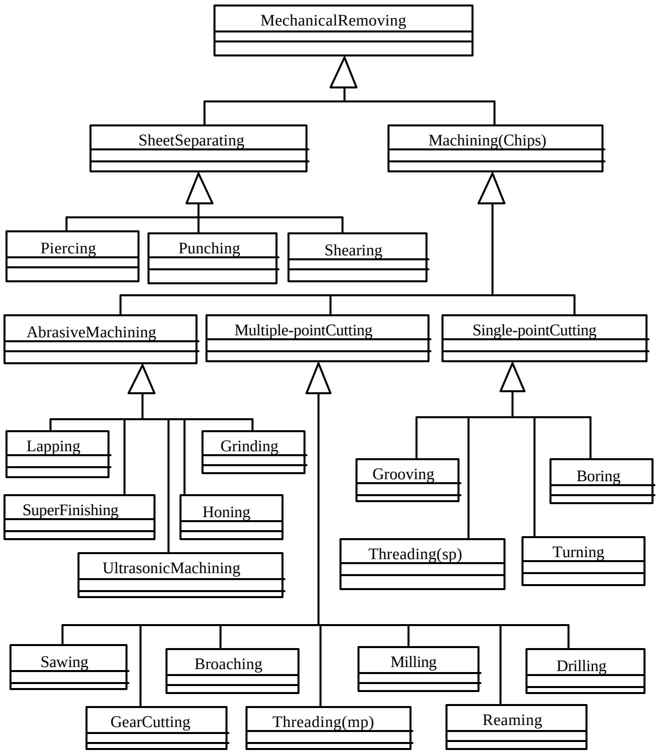

Figure 5 Mechanical removing object model

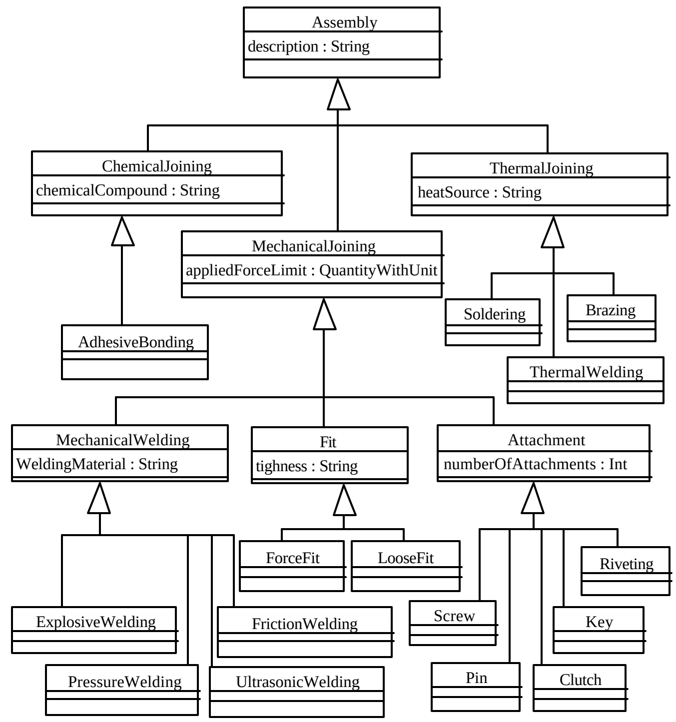

Figure 7 Assembly Process Object Model

handling including transferring materials or tools from one place to another. LoadUnload represents the activity of loading and unloading workpieces or tools onto a machine. Idling represents the idling time between two activities. Processing represents a manufacturing activity, which includes Inspection, PartMaking, and Assembly. Inspection [35] is out of the scope of this paper. Assembly-related classes are in Figure 7 and will be discussed later. PartMaking represents a part fabrication activity, which can be further specialized. The derived classes from PartMaking are SurfaceTreatment and Shaping. SurfaceTreatment is an activity of treating surfaces of a workpiece for meeting tolerance, surface roughness, and surface

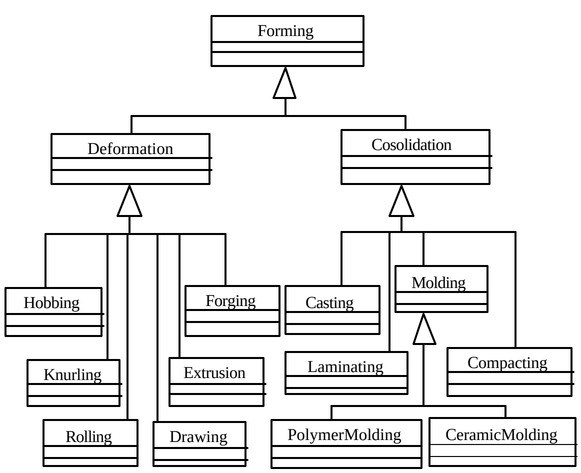

Figure 6 Forming Object Model

hardness specifications. Three derived classes from SurfaceTreatment are Finishing, Coating, and Hardening. Shaping represents an activity to transform workpiece into a certain shape. These classes has two derived classes: MaterialRemoving and Forming. Forming is the activity of molding, casting, or forging material into a certain shape. Figure 6 shows the details in Forming. MaterialRemoving is a shaping activity that removes material from a workpiece to get the anticipated shape. It can be ChemicalRemoving, Thermal-Removing, or MechanicalRemoving. ChemicalRemoving can be photochemical milling, electrochemical machining (ECM), or chemical milling. ThermalRemoving can be high energy beam machining, electrical discharge machining (EDM), or torch cutting.

Figure 5 shows the mechanical removing-related classes. MechanicalRemoving [36] is an activity of removing material from a workpiece using mechanical methods, such as machining and shearing. There are two derived classes: SheetSeparating and Machining. SheetSaparating uses shearing methods to cut metal sheets. Specific methods are piercing, punching, and shearing. Machining is a metal cutting activity using a machine tool and has three derived classes: SinglePointCutting, Mul-tiplePointCutting, and Abrasive. SinglePointCutting includes boring, turning, grooving, and single-point threading. Mul-tiplePointCutting includes drilling, reaming, milling, multiple-point threading, broaching, gear cutting, and sawing. Abrasive includes grinding, honing, ultrasonic machining, super finishing, and lapping.

Figure 6 shows the forming-related classes. Forming has two derived classes: Deformation and Consolidation. De-formation is a class that represents the activity of changing the shape of a workpiece. Specific processes are forging, extrusion, drawing, rolling, knurling, and hobbing. Consolidation is a class that represents the activity of shape forming with mold or die. Specific processes are casting, polymer molding, ceramic molding, compacting, and laminating.

AssemblyProcess, as in Figure 7, is a class represents the activity of joining components into a product. The derived classes are MechanicalJoining, ThermalJoining, and Chemical-Joining. ChemicalJoining is a class that represents the activity of joining components using chemical methods, such as adhesive bonding. ThermalJoining is a class that represents the activity of joining components using thermal bonding methods, such as brazing, thermal welding, and soldering. MechanicalJoining is a class that represents the activity of joining components using mechanical methods, such as fit, attachment, and mechanical welding. Fit can be either force fit or loose fit of two components in a product. Attachment can be riveting or using keys, pins, or screws. Mechanical welding includes friction welding, explosive welding, ultrasonic welding, and pressure welding.

ManufacturingResource, as in Figure 8, is a class that represents a physical object or a labor skill that is used in a manufacturing process. ManufacturingEquipment is a class that represents a piece of equipment (a physical entity) that is used in manufacturing processing. Examples are machine, tool, fixture, and gauge. A piece of equipment has a set of parameters that describe the piece of equipment. Equipment-Parameter is a class that represents parameters. The derived classes from ManufacturingEquipment are Machine, Tool-ForMachining, Mold, and Die. Machine can be a machining center, forging machine, EDM machining, etc. Tool for machining is a tool used in the machining process, such as cutter, extender, holder, and gauge.

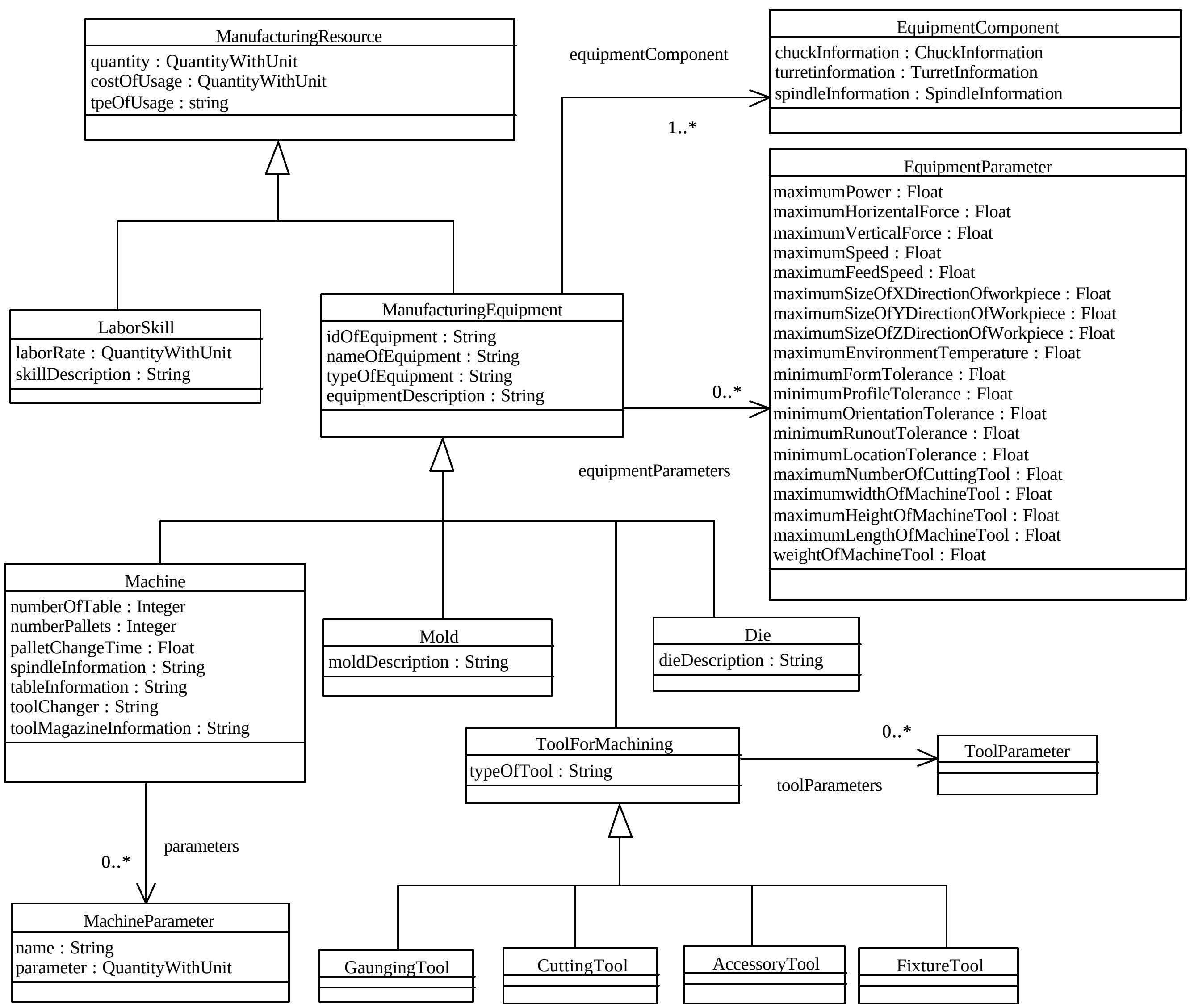

Figure 8 Manufacturing Resource Object Model

Manufacturing cost and time estimations have been built into the object model. Activity Based Costing (ABC) methods and results from research [37, 38, 39] based on ABC are adopted to form the basis for estimating cost and time described in this paper. Each manufacturing activity can be one of many processing activities, such as setup, load/unload, handling, processing, and idling. Each processing activity involves cost of using any resources and overhead cost. Cost and time estimating equations are described in the following equations.

Manufacturing cost estimating:

$$C_m = \sum_{i=1}^{N} C^i_{activity}$$

$$= \sum_{i=1}^{N} \left(C^i_{processing} + C^i_{setup} + C^i_{handling} + C^i_{load-unload} + C^i_{idling} + C^i_{overhead} \right)$$

- C_m is manufacturing cost of an artifact.
- i is an index.
- N is the total number of manufacturing activities applied to manufacture an artifact.
- $C^i_{activity}$ is the manufacturing cost of activity i.
- $C^i_{processing}$ is processing cost of activity i.
- C^i_{setup} is setup cost of activity i.
- $C^i_{handling}$ is handling cost of activity i.
- $C^i_{load-unload}$ is load and unload cost of activity i.
- C^i_{idling} is idling cost of activity i.
- $C^i_{overhead}$ is overhead cost of activity i.

- **processing cost:**

$$C^i_{\text{processing}} = C^i_{equipment} + C^i_{labor} + C^i_{material} + C^i_{tool}$$

- $C^i_{equipment}$ is the equipment cost of activity i. Equipment cost is decided by the time the equipment being used and the cost per unit time.
- C^i_{labor} is the labor cost of activity i.
- $C^i_{material}$ is the material cost of activity i.
- C^i_{tool} is the tool cost of activity i.

- **Tooling activity cost:**

$$C^i_{tool} = C^i_{fixture} + C^i_{cuttingTool} + C^i_{gaugeTool} + C^i_{accessoryTool}$$

- C^i_{tool} is the tool cost of activity i
- $C^i_{fixture}$ is the fixture cost of activity i
- $C^i_{cuttingTool}$ is the cutting tool cost of activity i
- $C^i_{gaugeTool}$ is the gauging tool cost of activity i
- $C^i_{accessaryTool}$ is the accessory tool cost of activity i

Tool cost is decided by the time the tool being used and the cost per unit time.

- **Setup activity cost:**

$$C^i_{setup} = C^i_{s-machine} + C^i_{s-tool} + C^i_{s-workpiece}$$

- $C^i_{s\text{-}machine}$ is the machine setup cost of activity i.
- $C^i_{s\text{-}tool}$ is the tool setup cost of activity i.
- $C^i_{s\text{-}workpiece}$ is the workpiece setup cost of activity i.

Manufacturing time estimating:

$$t_m = \sum_{i=1}^{N} t^i_{activity}$$

$$= \sum_{i=1}^{N} \left(t^i_{processing} + t^i_{setup} + t^i_{handling} + t^i_{load-unload} + t^i_{idling} \right)$$

- t_m is the estimated manufacturing time of an artifact.
- i is an index.
- N is the total number of manufacturing process of an artifact.
- $t^i_{processing}$ is the processing time of activity i.
- t^i_{setup} is the setup time of activity i.
- $t^i_{handling}$ is the handling time of activity i.
- t^i_{load} is the load and unload time of activity i.
- t^i_{idling} is idling time of activity i.

- **Setup activity time:**

$$t^i_{setup} = t^i_{s-machine} + t^i_{s-tool} + t^i_{s-workpiece}$$

- $t^i_{s\text{-}machine}$ is the machine setup time of activity i.
- $t^i_{s\text{-}tool}$ is the tool setup time of activity i.
- $t^i_{s\text{-}workpiece}$ is the workpiece setup time of activity i.

5 CONCLUDING REMARKS

Conceptual process planning is a manufacturability analysis activity, which includes selecting manufacturing processes based on conceptual design, selecting manufacturing resources, and estimating manufacturing cost and time. Incorporating manufacturing analysis into design can ensure that the design is manufacturable and within cost limits. Manufacturability analysis and cost estimation are important to minimize production cost. However, there is currently a lack of software tools in conceptual process planning. Manufacturers need new software tools that will effectively support translating conceptual design into manufacturing process and resource selection and, then, to estimate 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 process planning activity model and an object model developed based on the activity model to enable the integration. The process, resource, and cost/time types of data that are necessary for conceptual process planning have been collected and modeled using both IDEF0 and UML. The models are still in draft form. They are expected to be further enhanced by modification, expansion, and extension to meet industrial needs.

Future work includes the following tasks: (1) validate the draft models using more industrial cases, (2) formally represent manufacturing process knowledge, and (3) develop an 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. For the near future work, we plan to obtain a state-of-the-art knowledge-based system that 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 new design and manufacturing planning information exchange mechanism. This work should give us the background necessary to specify, with the help of software vendors and industrial users, standard interface requirements for next-generation software tools --integrated CAD and CAPP systems.

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