Conceptual Process Planning - A Definition and Functional Decomposition

Shaw C. Feng
Y. Zhang
Manufacturing Engineering Laboratory
National Institute of Standards and Technology

Abstract: Conceptual process planning is an activity for designers to evaluate manufacturability and the manufacturing cost in the early design stage for mechanical parts production. Since major manufacturing costs of a product are committed in product specification and design, it is critical to be able to assess manufacturability and cost as early as possible in the design process. At the National Institute of Standards and Technology, the Design and Process Planning Integration (DPPI) project addresses the need for improving communication between conceptual design and conceptual process planning activities. Documenting the DPPI foundation, this paper provides a definition of conceptual process planning and describes its functions in an activity model. Also, this paper describes the conceptual process planning prototype system that has been implemented and integrated with a conceptual design system. The prototype system validates the definition, the activity model, and the integration between process planning and design in the early product development stage.

Keywords: Conceptual Process Planning, Conceptual Design, Cost Estimation, Integration, Manufacturing Process Selection.

1. Introduction

It is almost imperative to incorporate manufacturing considerations in new product design since primary manufacturing costs are determined in the design phase. In fact, 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. [1,2,3]. 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 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 a theoretical foundation to characterize the process of early product design and the integration of various functions and technologies for effective product design [1-3,17-23].

At the National Institute of Standards and Technology (NIST), an ongoing, multi-year project, named Design and Process Planning Integration (DPPI), addresses the need for improving communications between design and process planning activities in the early design phase [6]. One of its focuses is on the interoperability between conceptual design and conceptual process planning activities, as shown in Figure 1. A typical design process includes customer requirements analysis, functional decomposition, conceptual 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, form requirements (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 data are also captured in the messages and sent back to the conceptual design tools and designers. This paper defines conceptual process planning and describes the implementation of a prototype, which is integrated with a conceptual design system. The conceptual-process-planning-prototype system is implemented by using Adaptive Modeling Language (AML) [31]. It receives information from a conceptual design and feeds back feasible manufacturing process(es), required resources, and estimated cost for a better design decision.

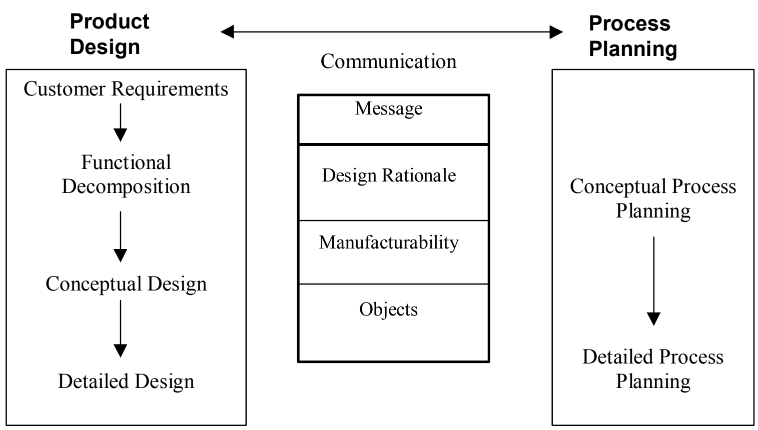

Figure 1 Design and Process Planning Message Exchange for Integration

This paper provides a fundamental definition of *Conceptual Process Planning* (CPP) and explains it in a detailed functional decomposition. In Section 2, the state of the art in conceptual design and conceptual process planning is introduced. Section 3 provides a definition of CPP and an activity model. Section 4 describes a high level communication strategy between conceptual design and conceptual process planning. Section 5 presents an implemented prototype system that realizes the CPP activity model. Finally, Section 6 contains concluding remarks and a description of future work.

2. Survey on Current Status on Conceptual Design and Process Planning Integration

As stated in the NIST Systems Integration for Manufacturing Applications (SIMA) program background study report [22], basic engineering activities have hardly changed in the last century, but the means of performing these activities, the knowledge needed, the degree of automation in them, and the technologies they use have all changed dramatically. Currently, most computer-assisted design and process planning tools handle geometry-related data, i.e., CAD, Computer Aided Engineering Analysis (CAE), CAM and Numerical Control (NC) Programming, Computer Aided Process Planning (CAPP), Design for Assembly and Design for Manufacturing (DFA/DFM), etc. [3,5,19]. There have been very few tools for assisting users to determine manufacturing methods and costs in the early design stage. There is no conceptual process planning software that would interoperate with conceptual design software in the early design stage.

Pioneering research and some developed prototypes involve computational function design and conceptual design. For example, Gorti and Sriram developed a software framework for conceptual design, which could map an evolving symbolic description of design into a geometric description [18]. Mukherjee and Liu present an abstraction for conceptual design by using function-form relation matrices. The relation matrices provide a link between purely functional and purely geometric representations, and a means to carry out domain-dependent manufacturability evaluations [13]. Theodoracatos and Ahmed describe an expert system for conceptual design that interprets functional structures, searches engineering solutions, and evaluates concepts [34]. Anderson and Makkonen describe the development of the CANDLE modeling language to support the early design phases of mechanisms and manipulator systems [24]. Tomiyama, Umeda and Yoshikawa propose a methodology – Function-Behavior-State (FBS) to model functions and introduce a computerized tool to support functional design based on the FBS modeling [25]. Kimura and Suzuki attempt to capture and to represent product background information, which includes requirements, specifications, assumptions, constraints, decision history, trial-and-error processes, and other rationale rules [26]. Wong and Sriram developed an object-oriented framework for storing product and design processes. It allows 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 have a survey of the current state of research and development of conceptual design activities, who also compare the advantages/ disadvantages of various techniques and tools [27]. These pieces of work are important in conceptual design process automation. Nevertheless, they are 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 conceptual process planning has just been developed. Until recently, CAPP research and development efforts have focussed on metal removal, particularly NC machining, almost to the exclusion of other applications [19,28]. Actually, manufacturing process planning covers a wide range of technologies, i.e., casting, forming, metal removal, welding, inspection, and assembly [14-16,19]. Haudrum developed an approach to consider production methods in design stage [11]. Lenau presents a method for the selection of manufacturing processes and materials based on a computer tool that inspired the designer to examine materials/processes [29]. Giachetti describes a prototype material and manufacturing process selection system that integrates a formal, multi-attribute decision model with a relational database [12]. Boothoyd and Dewhurst introduce another systematic approach to select manufacturing processes according to material and shape [3]. Evbuomwan and Sivaloganathan developed design function deployment (DFD) to support material and process selection [33]. 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 [7~10,35].

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 stages of research and application. A clear definition and a reference architecture for conceptual process planning are needed. This paper describes a conceptual process planning definition, an activity model, and a high level object model for interface specification that supports the integration of conceptual design and conceptual process planning.

3. Conceptual Process Planning Definition and Activity Model

Some technologies and theories for detailed process planning are available, as described above. However, industry needs methods and tools to evaluate product concepts as soon as function and form are described in the conceptual design. Kalpakjian points out seven criteria to select high level manufacturing processes [14]. Alting[15] and Halevi[16] introduce a similar classification and a way to select primary process and secondary process. ElMaraghy outlines process planning in four levels: generic planning, macro planning, detailed planning, and micro planning [19]. However, a distinct definition of conceptual process planning is necessary for new technology development to help designers evaluate their early design.

3.1 A Definition

Based on the need of conceptual process planning and its relationship to conceptual design and detailed process planning, a definition can be given as follows:

> **Definition: Conceptual Process Planning (CPP)** is an activity of preliminary manufacturability assessment of conceptual design in the early product design stage. It aims at determining manufacturing processes, selecting resources and equipment, and estimating manufacturing costs roughly. Conceptual process planning supports product design to optimize product form, configuration, and material selection and to minimize the manufacturing cost.

A closely related activity 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 is developed to describe the functions and data of CPP in detail.

3.2 An activity model

Starting from the basic manufacturing process planning activities specified in [3,14-16,19,32], this paper classifies the main tasks of conceptual process planning into manufacturing process selection, manufacturing resources selection, and manufacturing cost estimation. An activity model of conceptual process planning has been developed in the context of the product realization model in the NIST SIMA program [22]. The top level activity is *Develop Conceptual Process Plan* (A0), which is decomposed into a series of three activities shown in Figure 2.

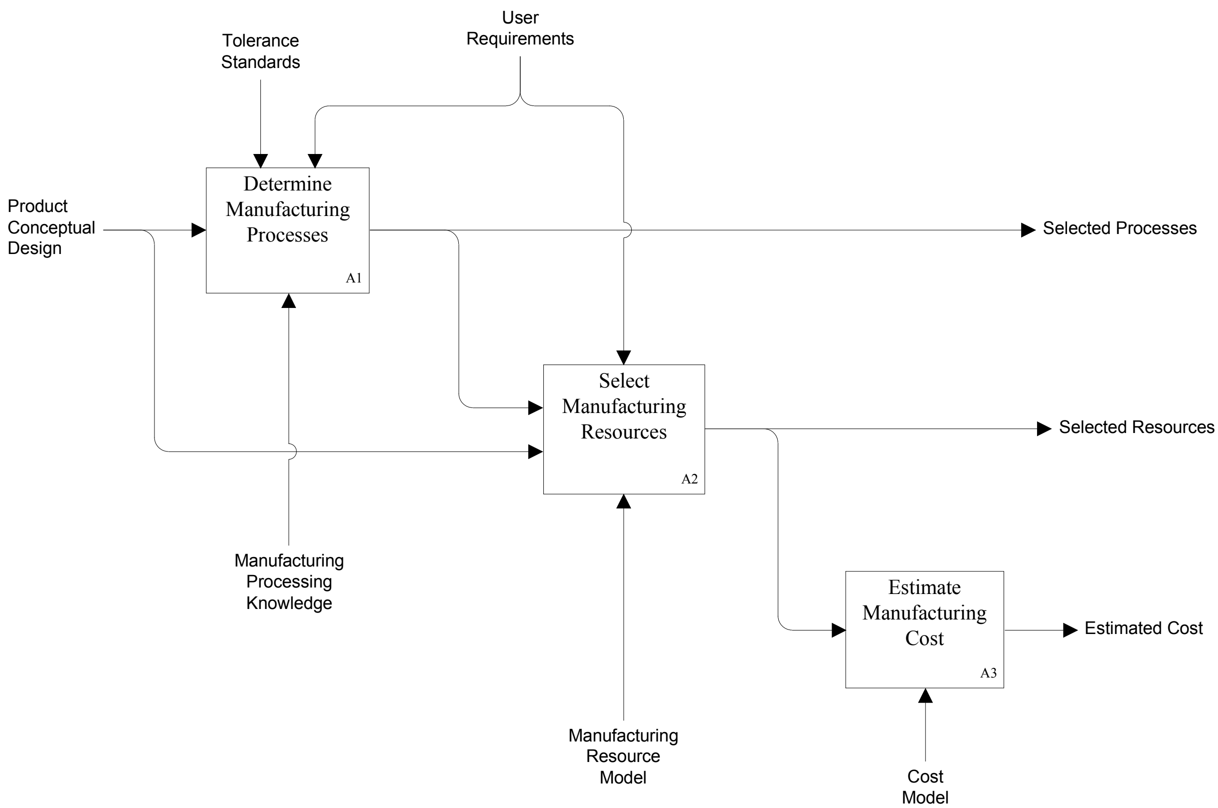

Figure 2 Conceptual Process Planning Activity Model

Product Conceptual Design is the input to CPP from a conceptual design activity. Both *Tolerance Standards* and *User Requirements* (of a product) are control data. *Manufacturing Process Knowledge*, *Manufacturing Resource Model*, and *Cost Model* are mechanism data. *Selected Processes, Selected Resources,* and *Estimated Cost* are output data resulted from CPP and fed back to conceptual product designers.

A1 – Determine Manufacturing Processes

Depending on high level product information, such as material, forms, and tolerances, select primary manufacturing processes, such as casting, forging, molding, and machining. This activity also includes the subsequence of processes to complete the manufacture of the product.

A2 – Select Manufacturing Resources

Choose appropriate manufacturing resources including both physical resources and human resources, based on the selected manufacturing processes. Resources include machines, tools, and labor skills. By referring to a predefined manufacturing resource capability model, some of the selected manufacturing processes may be deselected.

A3 – Estimate Manufacturing Cost
Estimate manufacturing cost based on the selected manufacturing processes and the use of selected manufacturing resources. Manufacturing cost covers material, purchased parts, labor, tooling, capital, and overhead.

Activity A1 covers a series of process selection functions and is further decomposed into four subactivities shown in Figure 3.

A11 – Determine Processes Based on Material
Select manufacturing processes based on material characteristics and properties. A set of possible materials for a product should be initially specified by designers in the conceptual design stage.

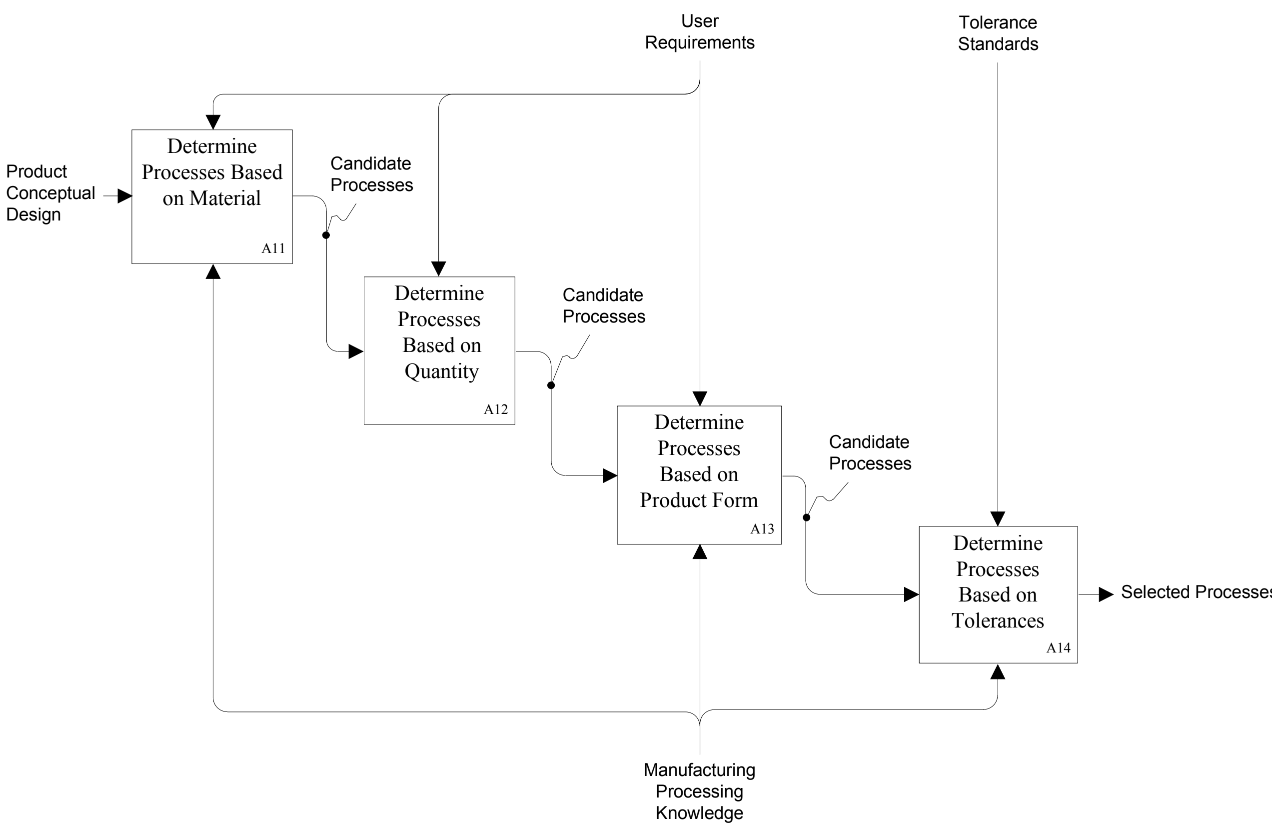

Figure 3 Manufacturing Process Selection

A12 – Determine Processes Based on Quantity

Select the manufacturing processes from A11 based on the quantity of a product to be produced. Large production volumes require high production rates and involves special machinery and less skilled labor. Small production volumes need more sophisticated labor skills and more general equipment.

A13 – Determine Processes Based on Form

Select the manufacturing processes from A12 based on main shape and feature characteristics and properties. Shape is a factor to determine primary processes and features, which influence the selection of subsequent processes.

A14 – Select Processes Based on Tolerances

Select the manufacturing processes from A13 based on the tolerance requirements of the design in early stage. Tolerances control the forms of parts and the shape relationships between parts in a product. Tight tolerances usually require high precision machinery and skilled workers, thus, tolerances further narrow down the choice of manufacturing processes.

Activity A2 covers a series of resource selection functions and is further decomposed into three subactivities shown in Figure 4.

A21 – Select Machines

Select machines available in factories for manufacturing the designed product. Machines include machines tools, forging machines, casting machines, material handling and assembly machines, and measuring machines.

A22 – Select Tools and Fixtures

Based on the selected machines, select tools and fixtures that are necessary for supporting the selected manufacturing processes.

A23 – Select Labor Skills

Based on the select machines and tools, select labor skills to operate the machines and use tools for production.

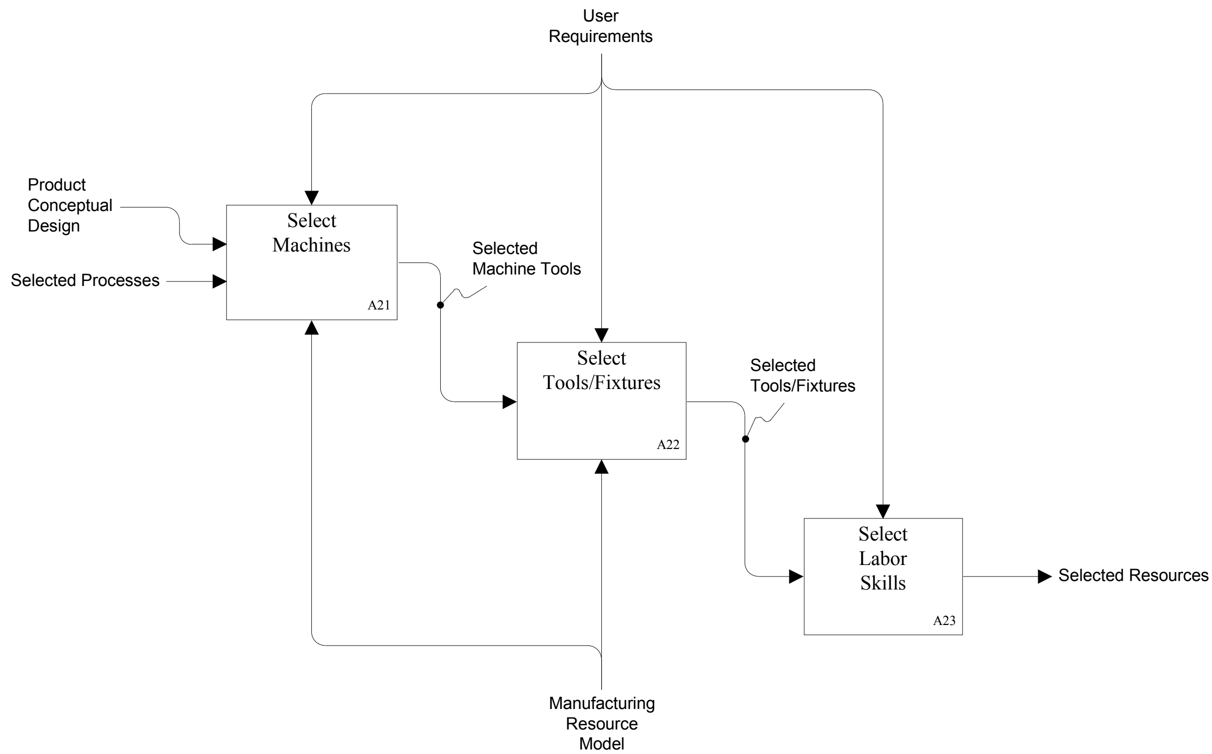

Figure 4 Manufacturing Resources Selection

4 Conceptual Process Planning in the Early Stage of Product Design

Conceptual process planning is an activity, which aides design and manufacturing integration. It enables product developers: (1) to assess manufacturability by determining and selecting available manufacturing processes and manufacturing resources, (2) to estimate manufacturing cost for affordability assessment, and (3) to reduce product development time by preparing production activities and acquiring necessary manufacturing resources as early as the concept of a product is sketched and the critical parameters of the conceptual product are defined.

The integration of conceptual design and conceptual process planning facilitates the information exchange between the two functions. As described in Figure 5, conceptual design takes in engineering requirements and defines functions of the product and its modules and parts. The material, form (usually approximated), product configuration, features, tolerance requirements, quantity, and date of delivery are defined based on product functional requirements and transferred to the conceptual process planning software. The conceptual process planning software performs process and resource selections and cost estimating. It outputs process sequences, resource lists, and estimated cost. The outputs are fed back to the conceptual design. The designer can modify the design to increase manufacturability and decrease the cost.

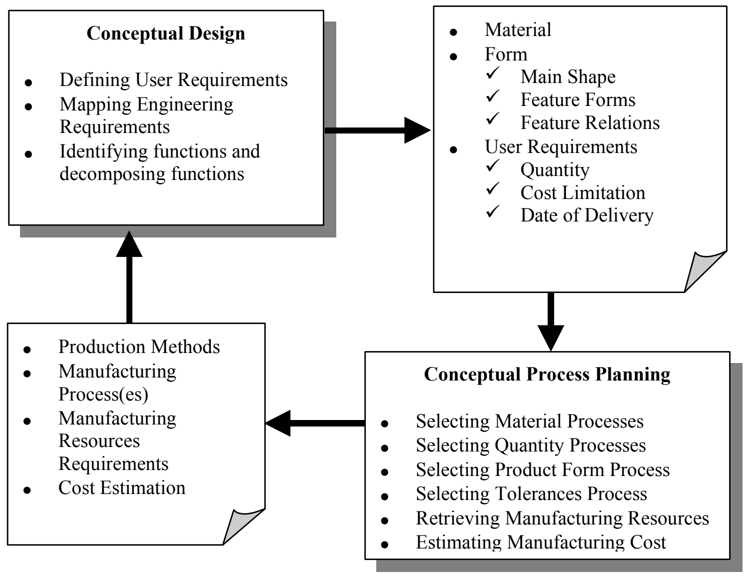

Figure 5 Information Exchange Between Conceptual Design and Conceptual Process Planning

5. Conceptual Process Planning Prototype Implementation

A prototype conceptual process planning system has been developed. Two kinds of gearboxes – planetary gearboxes and parallel axis gearboxes – are used as test cases. Process selection and resource selection rules have been developed and implemented. The prototype is built based on the Adaptive Modeling Language (AML) [31]. To describe the software organization of the implemented prototype, a class diagram in Unified Modeling Language (UML) [36] is shown in Figure 6. It contains three main classes: the *Part* class, the *CPP_interface* class, and the *Conceptual_process_planning* class. The *Part* class receives high level information from the conceptual design side and makes the information available to other objects. The *CPP_interface* class is an interface for a manufacturing engineer to specify shape and identify possible feature types contained in the high level conceptual design model. It provides interactive dialogue between manufacturing engineers and the prototype so that the engineers can decide which manufacturing process is more suitable. The *Conceptual_process_planning* class accepts high level product information from the *Part* class to synthesize manufacturing processes and their sequence. Also, it retrieves available manufacturing resources from simplified and pre-defined manufacturing resource capability objects. Finally, manufacturing cost will be qualitatively estimated for all potential manufacturing processes. Processes, resources and costs will be fed back to designers from the conceptual design side.

Although there are many knowledge representation methods, conceptual process planning knowledge is classified and coded in tables, production rules, and capability objects in this prototype. By referring to available process capability tables and diagrams, e.g., Table 40.3 in [14] and Figure 2.7 in [3], a material-based process selection table is deduced in the prototype system. Similarly, a shape-based process selection table and a feature-based process selection table have been implemented. Manufacturing resource capability knowledge has been defined in

AML objects, which specify working space, precision limitation, operation capability, power, etc.

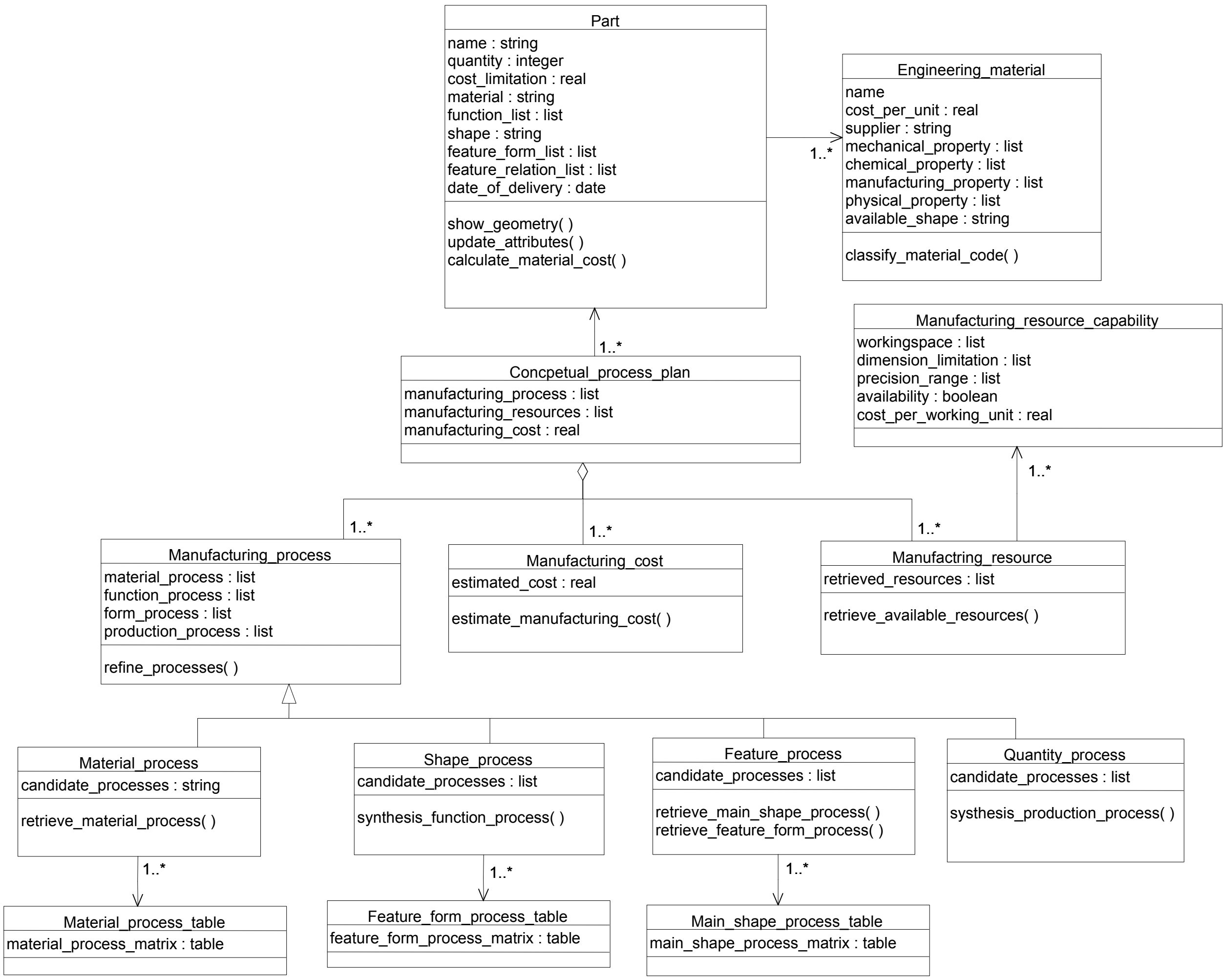

Figure 6 Conceptual process planning objects

Cost estimation is built upon a series of methods and functions by referring to literature on cost estimation [1,3,7,9,32]. Quantitative cost estimation is described in the following equations. The estimated cost per part (C) is the sum of the cost of materials (C_m), the cost of capital in using and purchasing equipment (C_c) per part, the cost of labor per unit time (C_l) per part, and overhead (C_{np}), as formulated in Equation 1. The material cost (C_m) consists of the cost of material, which is the result from multiplying workpiece volume by material density and unit cost per weight plus the cost of scrap generated in the primary process, secondary process, tertiary process, etc., as formulated in Equation 2. The capital cost is the sum of tools, machines, auxiliary equipment, and some other capital investment, as formulated in Equation 3.

$$C = C_m + \frac{C_c}{N} + \frac{C_l}{N'} + C_{np} \qquad (1)$$

$$C_m = V_w * \rho * C_{unit} + \sum_{i=0}^{P} VS_i * \rho * C_{unit} \qquad (2)$$

$$C_c = \Upsilon_{i=1}^{P}(\sum_{j=1}^{O} C_{tool}, \sum_{j=1}^{O} C_{mach}, \sum_{j=0}^{O} C_{aux}, C_{capt}) \qquad (3)$$

Where:

Vw – workpiece volume
ρ - material density
C_{unit} – unit cost per weight
P – total number of processes
O – total number of operations in each process
VS_i – scrap volume in each process
C_{tool} – tooling cost of each operation in each process, including jigs, fixtures, cutting tools, molds, and other parts specifically manufactured or purchased for this operation
C_{mach} – rate of depreciation of machine tool in each operation
C_{aux} – rate of depreciation of auxiliary equipment in each operation
C_{capt} – capital cost in each process, including power, space, etc.
C_{np} – non-production cost, normally 5%~15% of (C_m+C_c/n+C_l/n')
C_l – labor cost per unit time
N – number of workpiece to be manufactured
N' – number of workpiece manufactured per unit time

C_{tool}, C_{mach}, C_{aux} and C_{capt} are determined by the complexity of parts, and they depend on manufacturing time and resource availability. Currently, the qualitative estimation assumes a complexity index for a part to just make the equations work.

With equations to estimating cost, five steps are used to select processes in the prototype. The algorithm used to plan manufacturing processes and estimate manufacturing cost is described as follows:

Step 1 [Initialization]. Load material specification, quantity, main shape, feature types, tolerance requirements on features, and dimension range of the workpiece into the CPP prototype system from the housing object developed in conceptual design.

Step 2 [Initial processes synthesis]. There are four substeps.

Step 2.1 [Select material processes]. Retrieve a pre-defined material-process table by using the material specification. All the processes that can process the material are selected in a list, named A.

Step 2.2 [Select processes based on the shape of product and its parts]. Retrieve a pre-defined shape-process selection table and select those processes that are capable of making the shape characteristics. All the processes that can make the shape are selected in another list, named B.

Step 2.3 [Select feature types processes]. Retrieve a pre-defined feature-process selection table and select processes that are capable to make all the features. The selected processes are listed in List C.

Step 2.4 [Synthesize initial processes]. Find the common processes in Lists A and B and find the common processes in Lists B and C. The common processes are jointly selected. These processes can produce the shape and features in the specified material. Store these synthesized processes into an initial processes list for further usage.

Step 3 [Process selection refinement] There are two substeps.

Step 3.1 [Refine the initial processes by production methods]. Eliminate some processes in the initial processes list by the production quantity criterion.

Step 3.2 [Refine the initial processes by precision]. Eliminate or extend some processes in Step 3.1 according to the tolerance requirements and dimension range to determine a final process list.

Step 4 [Manufacturing resources selection] Select manufacturing resources according to the process list obtained in Step 3.2 based on a pre-defined manufacturing resources capability model.

Step 5 [Cost estimation]. Estimate manufacturing cost using the final process list, and the selected manufacturing resources, shape, material, and quantity. Equations 1 to 3 are used to calculate the estimated manufacturing cost.

The prototype system interface is shown in Figure 7. Using the housing of a planetary gearbox as an example, the system reads a data file generated by conceptual design, classifies main shape and feature types, generates manufacturing process(es), selects resources, and estimates manufacturing cost. The results are fed back to conceptual design for a designer to evaluate.

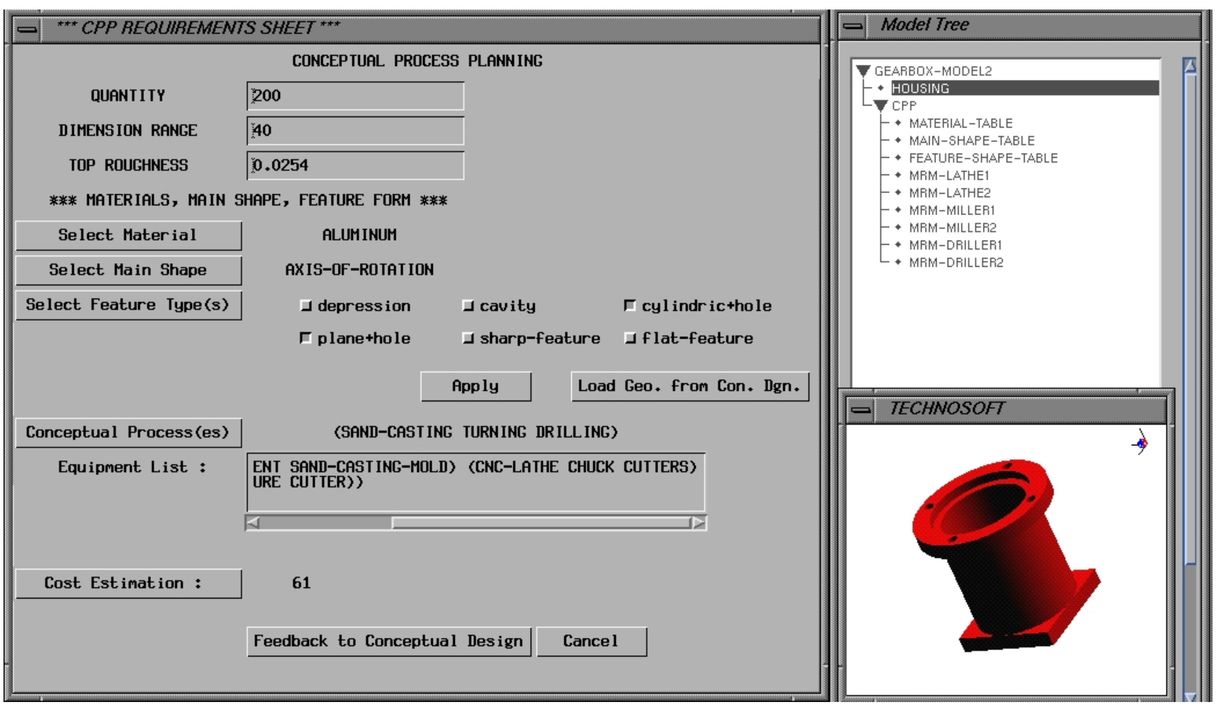

Figure 7 Interface of the prototype conceptual process planning system

6. Conclusion and future work

In this paper, conceptual process planning was defined as an activity that assesses manufacturability and estimates the manufacturing cost of the concept of a product developed in the early design stage. Subactivities involved in selecting manufacturing processes, resources, and cost estimation were modeled in an activity model, which further described the conceptual process planning in detail. Furthermore, an initial prototype was developed based on the definition and functional decomposition for validating the definition and proving that the integration with conceptual design is feasible. Most of the knowledge, engineering rules and data were implemented using a knowledge-based design system. However, further development of the idea is necessary. Possible future work includes (1) extending the prototype using more industrial cases, (2) specifying interfaces for conceptual process planning software, (3) formally representing manufacturing process knowledge, (4) improving cost estimating methods to increase accuracy, and (5) develop an initial specification for information sharing between design and process planning according to the NIST Initial Manufacturing Exchange Specification development procedure [37].

Acknowledgements
Many interesting discussions and suggestions from Drs. Steven Ray, Ram Sriram, Walter Nederbragt, and Robert Allen are gratefully acknowledged.

Disclaimer
No approval or endorsement of any commercial products by the National Institute of Standards and Technology is intended or implied. Certain commercial software systems are identified in this paper in order to facilitate understanding. Such identification does not imply that these software systems are necessarily the best available for the purpose.

References

[1] D. G. Ullman, The Mechanical Design Process, 2nd Edition, McGraw Hill Companies, Inc., 1997.
[2] G. Pahl and W. Beitz, Engineering Design – A Systematic Approach, 2nd edition, Springer-Verlag, 1996.
[3] G. Boothroyd, P. Dewhurst and W. Knight, Product Design for Manufacture and Assembly, Marcel Dekker, Inc., 1994.
[4] J.R. Dixon and C. Poli, Engineering Design and Design for Manufacturing – A Structured Approach, Field Stone Publishers, Conway, Massachusetts, 1995.
[5] J.J. Shah and M. Mäntylä, Parametric and Feature-based CAD/CAM, John Wiley & Sons, New York, 1995.
[6] W. Nederbragt, R. Allen, S. Feng, S. Kaing, S. Sriram, and Y. Zhang, "The NIST Design/Process Planning Integration Project," the Proceedings of AI and Manufacturing Research Planning Workshop, Albuquerque, New Mexico, August, 1998, pp. 135-139.
[7] P. Dewhurst and G. Boothroyd, "Early Cost Estimating in Product Design," Journal of Manufacturing System, Vol.7, No.3, 1989, pp. 183-191.

[8] C. Ou-Yang and T.S. Lin, "Developing an Integrated Framework for Feature-based Early Manufacturing Cost Estimation," International Journal of Advanced Manufacturing Technology, Vol. 13, 1997, pp. 618-629.
[9] W. Winch, Realistic Cost Estimating for Manufacturing, 2nd Edition, published by the Society of Manufacturing Engineers, 1989.
[10] A. R. Mileham, G.C. Currie, A.W. Miles, & D.T. Bradford, "A Parametric Approach to Cost Estimating at Conceptual Stage of Design," Journal of Engineering Design, Vol.4, No.2, 1993, pp. 117-125.
[11] Jan Haudrum, Creating the Basis for Process Selection in the Design Stage, Ph.D. dissertation, the Institute of Manufacturing Engineering, Technical University, Denmark, 1994.
[12] R.E. Giachetti, "A Decision Support System for Material and Manufacturing Process Selection," Journal of Intelligent Manufacturing, Vol. 9, No. 3, 1998, pp. 265-276.
[13] A. Mukherjee and C.R. Liu, "Conceptual Design, Manufacturability Evaluation and Preliminary Process Planning Using Function-Form Relationships in Stamped Material Parts," Robotics & Computer Integrated Manufacturing, Vol.13, No.3, 1997, pp. 253-270.
[14] S. Kalpakjian, Manufacturing Engineering and Technology, 3rd Edition, Addison-Wesley Publishing Company, 1995.
[15] L. Alting, Manufacturing Engineering Processes, Marcel Dekker, Inc., 1994.
[16] G. Halevi and R.D. Weill, Principles of Process Planning – A logical approach, Chapman & Hall, Inc., 1995.
[17] A. Wong and D. Sriram, "SHARED: An Information Model for Cooperative Product Development," Research in Engineering Design, Vol.5, 1995, pp. 21-39.
[18] S. R. Gorti and R. D. Sriram, "From Symbol to Form: A Framework for Conceptual Design," Computer-Aided Design, Vol.28, No.11, 1996, pp. 853-870.
[19] H. ElMaraghy, "Evolution and Future Perspectives of CAPP," The Annals of the CIRP, Vol. 42, No.2, 1993, pp. 739-751.
[20] R. Anderl and R. Mendgen, "Modeling with constraints: theoretical foundation and application," Computer-Aided Design, Vol.28, No.3, 1996, pp.155-168 .
[21] V. Allada, S. Feng, and S. Ray, "Development of a Message Model to Support Integrated Design and Manufacturing," Advances in Industrial Engineering Applications and Practice II, 1997, pp. 867-872.
[22] E.J. Barkmeyer (editor), *SIMA Reference Architecture Part 1: Activity Models*, The National Institute of Standards and Technology Internal Report 5939, Gaithersburg, Maryland, 1996.
[23] Pugh. S., Creative Innovative Products Using Total Design, Addison-Wesley Publishing Company, Inc., 1996.
[24] K. Andersson, P. Makkonen, and J.G. Persson, "A Proposal to Product Modelling Language to Support Conceptual Design," The Annals of the CIRP, Vol. 44, No.1, 1995, pp. 129-132.
[25] T. Tomiyama, Y. Umeda, and H. Yoshikawa, "A CAD for Functional Design," The Annals of the CIRP, Vol.42, No.1, 1993, pp. 143-146.
[26] F. Kimura and H. Suzuki, "Representing Background Information for Product Description to Support Product Development Process," The Annals of the CIRP, Vol.44, No.1, 1995, pp. 113 – 116.

[27] W. Hsu and I. Woon, "Current research in the conceptual design of mechanical products," Computer-Aided Design (Vol.30, No.5, 1998), pp. 377-389.

[28] R. R. Wu and Y. Y. Zhang, "The Research of a CAPP Framework and its Methodology," International Journal of Advanced Manufacturing Technology, Vol.14, No.4, 1998, pp. 255-260.

[29] T. Lenau, "The Missing Element in Design for Manufacture," The Annals of the CIRP, Vol. 45, No.1, 1996, pp. 105-108.

[30] T.C. Chang and R.A. Wysk, An Introduction to Automated Process Planning, Prentice-Hall International Series in Industrial and Systems Engineering, 1985.

[31] *Adaptive Modeling Language Reference Manual: Version 2.0* (Technosoft Inc., 8589 Beechmont Ave., Cincinnati, OH 45255, 1997)

[32] E. M. Malstrom, editor, Manufacturing Cost Engineering Handbook, Marcel Dekker, Inc., 1984.

[33] N.F.O. Evbuomwan, S. Sivaloganathan, and A. Jebb, "Concurrent materials and manufacturing process selection in design function deployment," Concurrent Engineering: Research & Applications (Vol.3, No.2, 1995), pp. 135-143

[34] V.E. Theodoracatos and M.F. Ahmed, "ECDEX: A Knowledge-based approach to conceptual design of engineering systems," Robotics & Computer-Integrated Manufacturing, Vol.11, No.3, 1994, pp. 137-166.

[35] C.S. Park and G.T. Kim, "An economic evaluation model for advanced manufacturing systems using activity-based costing," Journal of Manufacturing Systems, Vol.14, No.6, 1995, pp. 451-439.

[36] M. Fowler, with K. Scott, UML distilled: Applying the standard object modeling language, Addison-Wesley, 1997.

[37] S. Kemmerer and J. Fowler, "Initial Manufacturing Exchange Specification (IMES): IMES Concept Document for Manufacturing Systems Integration," NISTIR 5978, the National Institute of Standards and Technology, Gaithersburg, Maryland, 1997.