A novel method for information rich costing in CNC manufacture

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A novel method for information rich costing in CNC manufacture

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Dedicated to my wife Wemimo Taiwo and my son Babafemi Taiwo

Abstract

Reliable cost estimation is important for economic production, cost control and maintaining competitive advantage in manufacturing contract bidding. Therefore, estimating the manufacturing cost of a machined part is of critical importance in CNC manufacture. Computers aided systems the link to manufacturers CAD systems and databases have been used since the 1980's to identify product cost and enable a company to evaluate resource utilisation. While the concept of an integrated costing system has made significant advances in integrating the design function with the cost estimation process, there are still major gaps in acquisition and application of detailed product data for generation of timely and reliable costing information feedback to engineers. Integrated costing systems are information intensive and require significant manufacturing data support.

A major obstacle is the bespoke nature of the available cost relevant data and their storage in company specific database tailored to individual company practices. Thus there is need to consider standardisation of information from the design of component through to their process planning and manufacture. This will allow seamless exchange of detailed, cost relevant, information between other computers aided systems and costing systems to facilitate automatic and reliable cost information feedback. In this research a novel framework is specified and designed for enabling detailed product information that exists across CNC manufacturing, to be utilised for generation of reliable cost estimates. The standards based costing proposed in this thesis framework facilitates high-level integration of various CAx resources and increases the availability of product creation process (PCP) data that are applicable in costing process. A prototype implementation of the

unified costing framework is utilised to demonstrate the capabilities of the framework. The demonstration is conducted using two industrially inspired prismatic test components where the components machining cycles were timed with a stop watch and the actual result compared with the prototype system estimated result to determine its reliability.

The research shows that implementation of manufacturing standard that contain structured representation PCP information together with an effective data retrieval mechanism and computational algorithms can provide a standard compliant framework to realise an information rich (detailed) costing system. The potential of the proposed framework is not limited to enabling the use of detailed information that exist within manufacturing facility to generate cost information; it also provides a standard compliant approach for the development of future generations of costing systems.

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Contents

List of Abbreviations

ADAM	Automated Drafting and Machining
AFNOR	Association Française de Normalisation
AIM	Application Integrated Model
ARM	Application Reference Model
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CAPP	Computer-Aided Process Planning
CAV	Computer-Aided Verification
CAx	Computer-Aided System
CIM	Computer Integrated Manufacturing
CNC	Computer Numerically Controlled
DSDL	Document Schema Definition Language
DTD	Document Type Definition
ERP	Enterprise Resource Planning
GUI	Graphical User Interface
IDL	Interface Definition Language
IGES	Initial Graphics Exchange Specification
IP	Internet Protocol
IP3AC	Integrated Platform for Process Planning and Control
LM	Layered Manufacturing NC Numerically Controlled
OMG	Object Management Group
OOT	Object Oriented Technology
PDM	Product Data Management
PCL	product creation lifecycle
PPC	Production Planning and Control
SBC	Standards based costing
SDAI	Standard Data Access Interface

STEP	Standard for the Exchange of Product data model
UDDI	Universal Description, Discovery and Integration
UML	Unified Modelling Language
URL	Uniform Resource Locator
VDA-FS	Verband der Automobilindustrie - Flächenschnittstelle (the organisation of the automotive industry - surface translation format)
VM	Virtual Manufacturing
VRML	Virtual Reality Modelling Language
WSDL	Web Services Description Language
XML	Extensible Mark-up Language

Definitions

Adaptability - The flexibility and agility of a manufacturing enterprise in handling changes in resources, jobs and strategies.

CAx - Computer aided systems utilised in a manufacturing enterprise. Includes CAD, CAM, CAV, CNC etc. In this thesis the term CAx has been used interchangeably with CAD/CAM/CNC as these are the most prevalent computer aided systems in prismatic part manufacture.

Class - A blueprint for creation of an object. An object is an *instance* of a class. The class specifies the attributes and methods associated with all objects that are instantiated from it.

Feature Based System - A CAx system that incorporates a library of pre-defined geometrical shapes or "features" to describe a product or manufacturing process

G&M Codes - The CNC machine programming language standardised in ISO6983. The term "G&M codes" has occasionally been used in this thesis to refer to all "machine axis movement description" languages.

Inheritance - A class can be the subtype of another class. In this case, the child class *inherits* all of the parent class‟s attributes and methods and can overwrite or amend them.

Integration - The process of incorporating parts, components, elements into a larger defined unit, set, whole.

Interface - The contact point between a class and the outside world. When a class *implements* an interface, it promises to provide the behaviour defined in that interface.

Interoperability - The ability to seamlessly transfer information from one computer system to another, while maintaining the integrity of the information.

Object - A packaging of related state and behaviour in software. Object-Oriented programming utilises objects to model the real-world objects and encapsulate data and actions in them. The state is captured in an objects *attributes* and its behaviour is defined using *methods.*

Object Persistence - The ability to store an object‟s state to disk or another persistent information storage system to be retrieved later.

Prismatic Part - A mill machined part is defined to be prismatic when all of the planes defining the part‟s surface geometry are either parallel or perpendicular to the spindle axis of the milling machine used in its manufacture. In this research the term is only used for parts that can be machined using one tool axis direction (i.e. can be manufactured on a 3-axis milling machine in a single setup).

Semantic Interoperability - In order to obtain mutual understanding of interchanged data, the actors have to share a model of what the data represents. Semantic interoperability is achieved when such mutual understanding exists.

Semantic Interpretation - The process of discovering semantics conveyed through a specific syntax of data.

Semantics - The implied meaning of data within a specific context with respect to their role in a system.

Standardised Input / Output - Data transferred from/to a CAx resource where the semantics and syntaxes have been homogenised with those of the manufacturing Interlinuga.

Syntax - The rules that regulate the format of representation of information within a context.

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1 Introduction

In manufacturing industry, cost estimation is of utmost importance as it influences production policies, resource utilisation and bidding strategies that are relevant to economic success of the manufacturing enterprise. Early, manufacturing cost estimation approaches were based on past experience. The advent of a computer aided manufacturing philosophy paved the way for computer based costing systems (Ben-Arieh, 2000). A number of integrated costing systems that interface with computer aided design (CAD) system and provide product cost information to support decisions on design alternatives have been developed over the years. This costing system provides cost information based on product design but the process plan and resource utilisation effect on cost are not accounted for. As a result many cost estimates of questionable reliability are generated because manufacturing processes and resources are not considered(Staub-French et al., 2003). The manual, labour intensive, manufacturing process of yesteryears has given way to a computer aided process where most activities are now performed by CAx systems and hardware. As a result the manufacturing process and resource utilisation impact on product cost is on the increase(Fischer et al., 1994). For the development of costing system capable of generating consistent and reliable estimate, it is essential to review, and where necessary augment, the conventional costing method according to these changes.

Integrated costing systems have been developed and are continuously being enhanced as tools to meet these evolving demands. The automation and reliability of this integrated costing system can be a critical enabler in realising process improvement in manufacturing cost estimation domain.

Researchers have presented integrated cost estimation that utilised process model and a database of process parameters for automatic generation of cost estimate(Geiger and Dilts, 1996). Subsequent extensions to the work have significantly augmented the costing system capability(Geiger and Dilts, 1996). This costing system has evolved from a simple data processing computer to multi-faceted system that effectively interfaced with a CAx system. This added complexity has made the estimation process a more expensive and time consuming effort(Roy et al., 2011). The implementation of integrated costing system requires considerable capital and time investments for the gathering, sorting and storage of applicable product creation process (PCP) data (Shehab and Abdalla, 2002).

According to literature, researches have tried to solve this problem by improving the capability of costing systems for direct linkage with relevant CAx systems that output product design and process plan information. However, CAx manufacturers develop their systems using proprietary languages with the results that a conventional manufacturing environment comprises plethora of CAx chain each with its own computer language for communication with other CAx systems. As a result costing systems do not have a unified link with CAx chains to utilise their PCP data output for cost information feedback.

A unified link is the ability to seamless exchange information with CAx chains for cost information feedback across product creation lifecycle. Information feedback across the entire product creation lifecycle is a key factor for optimum resource utilisation. In today's highly competitive global economy with product creation been increasingly automated to reduce cost and lead time, optimum resource utilisation is critical for survival of a manufacturing enterprise.

The current costing systems fall short of delivering this requirement and therefore a major paradigm shift towards a more information rich framework has become necessary.

In this research a novel vision for a new costing method has been outlined and a unified framework based on manufacturing standards has been realised to support and enable this leap.

The organisation of the research is such that first the aims, objectives and the scope have been presented, before reviewing the existing literature on product creation process and integration standards. A review of literature on cost estimation methods and systems followed. The research gaps and opportunities have then been identified. In the theoretical phase of the work, the novel framework for realising unified costing has been specified, envisioned and developed. The framework consists of a number of elements that have then been presented in full detail. In the experimental phase, a prototype implementation of the unified cost framework has been realised and evaluated. A number of topics of discussion raised in the course of the research then follow. Finally the conclusions drawn in the course of the research together with areas with potential for future research have been presented. Figure 1.1 shows the organisation of the different chapters and their contents within the context of the research

1.1 Thesis structure

The structure of this thesis in relation to stages of research development is illustrated in figure 1.1. The thesis is structured into ten chapters. There are five main functional parts: preliminary; review of subject's areas; description of unified costing method; implementation of prototype software, practical evaluation of prototype and conclusions. The first and second chapters deal with preliminary issues. The first chapter introduces the thesis topic, its significance and the conceptual framework for the thesis. The second chapter explains the theoretical context of the research within the fields of integrated product development.

The third and fourth chapters deal with the review of the literature in the research fields. This is an essential step before attempting to specify an improved methodology. The third provides a review of product development in an integrated environment. The fourth chapter provides another literature review, this time on manufacturing cost estimation methods and systems. The 5th review is on information models in relation to costingThese reviewed chapters not only provide a better understanding of the research area they also informs on research gaps in cost estimation domain.

The sixth and seventh chapters are concern with the description of the unified costing framework. The fifth chapter specifies the framework and the seventh chapter provide the description of the developed computational mechanism and algorithms for cost calculation. This provides relevant insight into the standard based methodology and set the scene for a test component case study.

The eighth chapter discusses the variety of methods that were used to validate the prototype unified costing system with milled components case study.

The ninth and ten chapters discuss the findings of the research and the conclusions. Chapter nine compare the result of the milled components case study with practical experimentation and existing cost estimation system. The purpose of this comparison is to observe whether the novel methodology improves cost estimation process and/or provides an improvement, in terms of accuracy, over existing systems. Finally, the tenth chapter concludes the thesis and summarises the lessons that may be drawn from the research. All of these chapters are built around a research design.

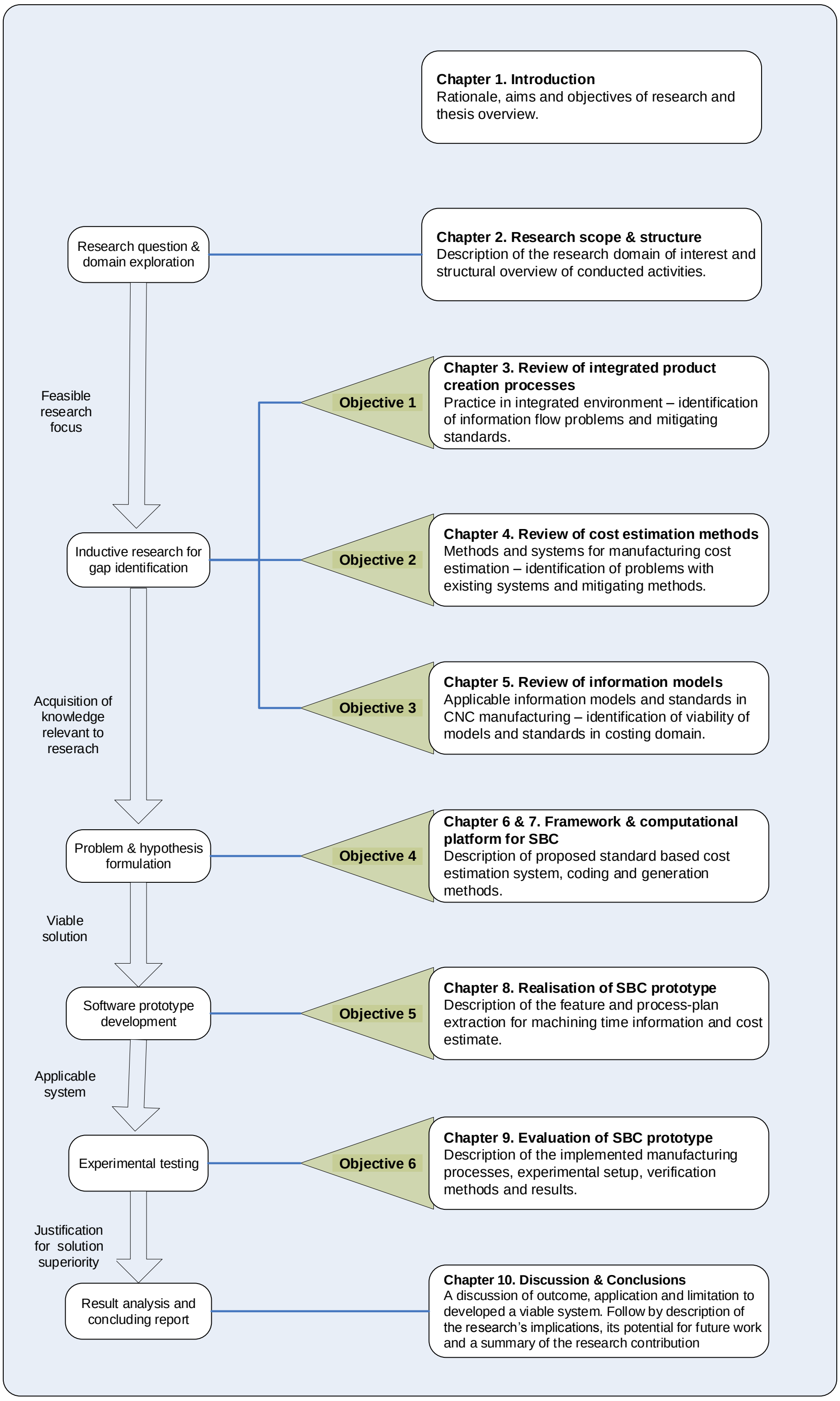


Figure 1.1 – Thesis structure in relation to research development stages

2 Research aims, methodology and context

This chapter outlines the aims, scope and boundaries of the research. To do this, the boundaries of an integrated product creation process will be established and the aims in enabling unified costing process in such an environment are identified. The scope of the research specifies the particular perspective of the author in determining the relevant issues pertaining to the development of reliable costing system and positions the work in relation to other research on costing methods.

2.1 Research aims

Manufacturing enterprises have access to a wide range of costing methods and integrated software tools to estimate the cost of a product at the early stage of product development. The utilisation of cost estimating relationships to quantify the likely cost of a new product is an example of a parametric method. Feature based costing systems that utilised design geometry output of a CAD system for cost feedback is an integrated systems example. These individually useful methods and tools relied on availability of detailed product information from CAx to generate reliable cost feedback. The diverse programming languages, and the multi-format file, with which PCP information are communicated and stored in integrated environment however, have prevented access to detailed product information that are available for costing process.

Due to this multi-standard environment, the integration of costing system with majority of the CAx used in product creation has been slow and a costing system capable of using detailed product information that exist within integrated manufacturing environment is almost nonexistent. Currently costing systems rely on past cases and utilise low level geometry information from the design stage of product development with little or no focus given to downstream product creation processes where product information exists in increasing detail. This lack of consideration for downstream processes constitutes a hindrance in achieving a high-level integrated costing method where available detailed information from across the CAx chain were utilised to generate cost feedback.

The main hypothesis of this research is that it is possible to move towards high-level integrated costing in CNC manufacturing by adopting the unified framework based on standardised information models.

The key enabler for this is standardisation of PCP information and semantic retrieval of cost relevant data. Detailed information from across the PCP lifecycle can be made available for the costing process by replacing the proprietary file format for uni-directional communication of information with a neutral file format that support bi-direction information exchange. This change is depicted in Figure 2.1.

Standardisation allows the heterogeneous PCP information stored using various proprietary language across CAx systems to be unified and expressed using a single neutral format representation.

The aim of this research is to conceptualise, design, implement and realise a unified costing framework based on a neutral file representation of detailed product information and utilisation of the actual cost parameters to prove the hypothesis. This method will allow high-level integration of costing system with existing computer software and hardware systems (CAx) in CNC manufacturing environment

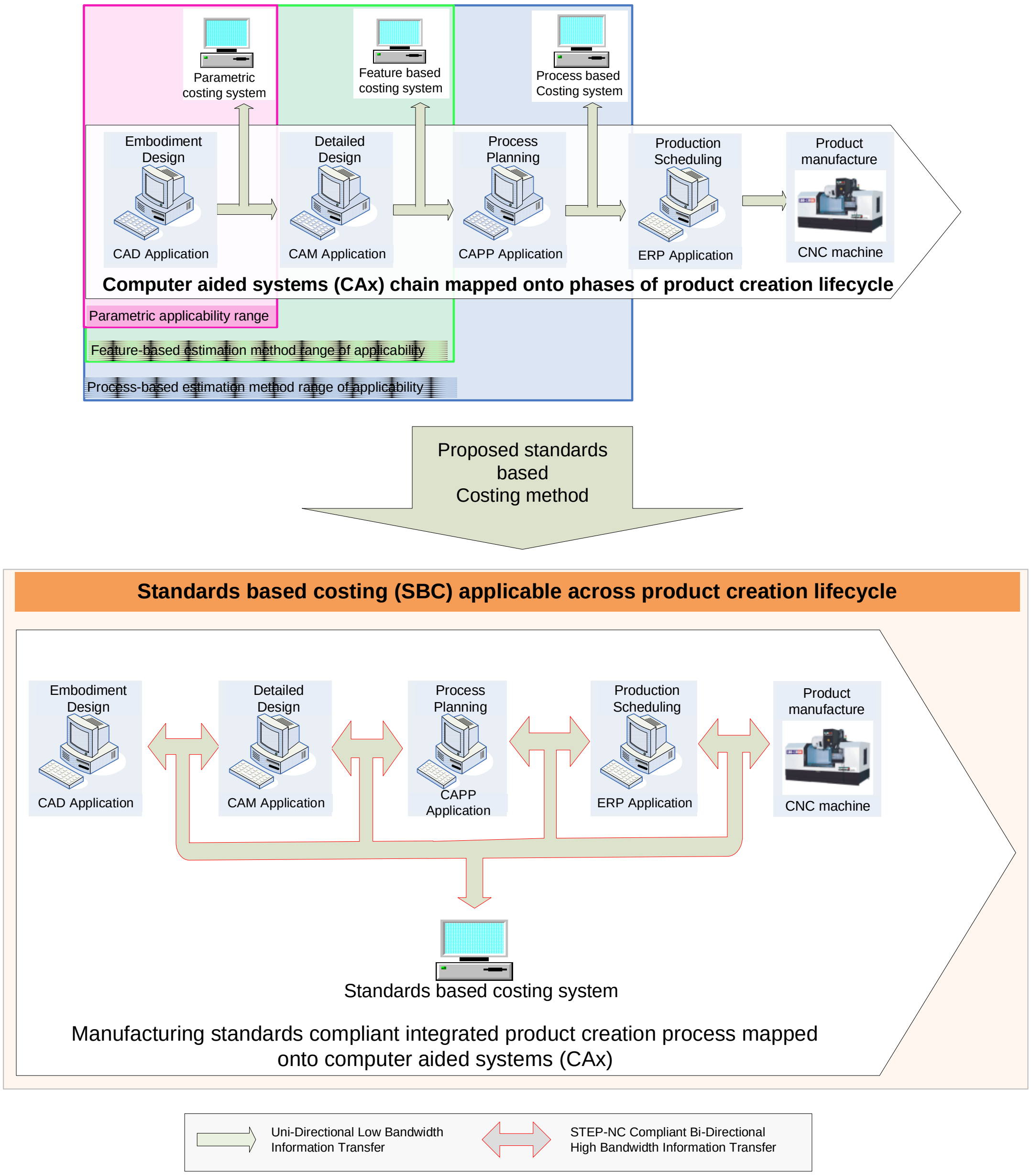


Figure 2.1 – Facilitating detailed product information availability for costing

2.2 Research methodology and objectives

A deductive approach has been chosen as the research methodology to achieve the above stated aim of this research. A deductive approach requires the establishment of a theory followed by provision of observations and practical findings to validate the theory (Bryman, 2007). The lack of high-level integration of a cost estimation system with computer aided system utilised in product development is clearly defined as the research problem, the research can be considered as being constructive (Lukka, 2003). Constructive research is a follow-up to an explorative research where the problems within a specific domain are defined. The results derived from the research are applicable to future empirical research. A novel software prototype is the main outcome of this research and its validity is demonstrated utilising a test component comprising industrially informed manufacturing features.

The following objectives have been defined toward the realisation of this research methodology:

- Reviewing manufacturing cost estimation methods and applicability in relation to integrated product development environment to derive the high-level integration problem within the research scope and boundaries.
- Reviewing the state-of-the-art of CNC manufacturing in relation to manufacturing standards system to understand standardised representation of information/data flow in integrated product development environment (Chapter 3).
- Specifying and designing a novel methodology for realisation of high-level integrated cost estimation system. The methodology will facilitate the utilisation of product cost-driving data, which exist throughout

product development stages, for automatic estimation of product cost and introduce a cost estimation system that is applicable at all product development stages.

The following objectives have been defined toward the realisation of this research aim:

- Reviewing the product creation process together with applicable costing systems and methods in integrated environment to devise integrated costing problems within the research scope and boundaries.
- Specifying and designing a novel framework for realisation of standard compliant costing in CNC manufacture. The framework will facilitate access to detailed product information that exist in an integrated manufacturing environment and introduce methods for generating cost information feedback from standardised information. This objective can be achieved by:
    - Identifying effective manufacturing standards that support structured representation of detailed product creation process (PCP) information.
    - Retrieval of actual cost parameters that are required for computation of product cost.
    - Realising a prototype standard compliant costing method based on the requirements.
- Evaluating the prototype standard compliant costing system by comparing its machining time estimation results, for industrially inspired prismatic components, with those obtained from a commercial costing system and from actual machining operation.

2.3 Research context and boundaries

The context of this research is costing within an integrated CAD/CAM/CNC manufacturing environment. The scope of this research is illustrated in Figure 2.2 to indicate an overlap between manufacturing technologies and cost estimation researches. Relevant areas reviewed to gain broad knowledge of the research field but not implemented in this research defined the scope of this work as indicated by the horizontal lines outside of the research boundary lines.

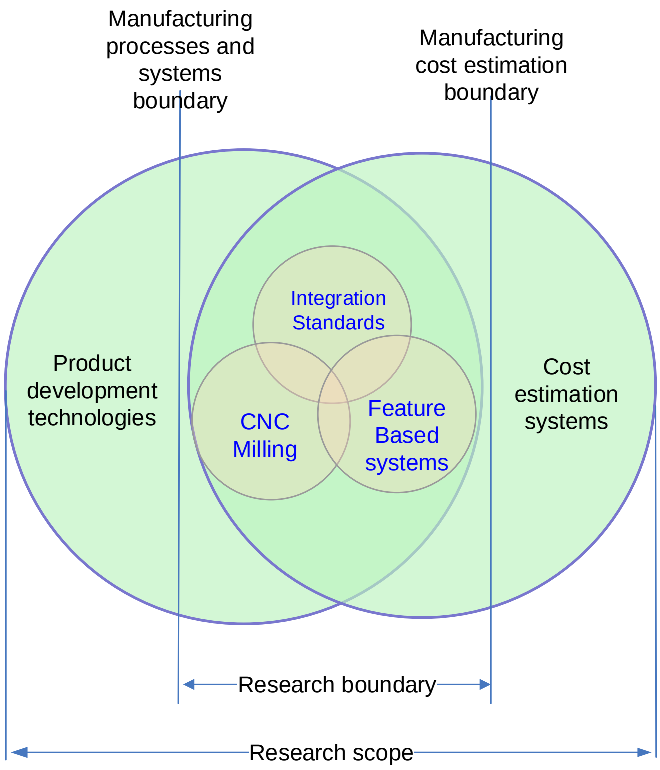


Figure 2.2 - Research boundary

The inner vertical lines in figure 2.2 shows the research boundary that has been identified within the research scope to enable the research focus on key issues in application of detailed product creation processes information to generate reliable cost information feedback. The identified research boundary area are defined as follows:

2.3.1 **Integration standards**

Today a vast number of manufacturing standards and proprietary information models are being used to provide neutral language format for product creation systems integration. The ISO14649 (STEP-NC) is an evolving standard that has been proposed to facilitate high-level integration of CAx chain in CNC manufacture (ISO (2003a)).

This standard has been chosen as the basis of this research as it provides suitable hierarchical data structures for representation of product design, process, and resources information in CNC manufacture. STEP-NC is extensively utilised in Chapter 6 as the data source for costing process and reference were made STEP standards, ISO10303 (ISO 1994), where it provides the necessary constructs to achieve the research objectives.

2.3.2 **CNC milling**

In Computer Numerically Controlled (CNC) manufacture, CAD/CAM/CNC technology is widely employed to manufacture varieties of designed component using a number of machining processes. CNC manufacture ranges from 3-axis milling used to machine prismatic parts to 5-axis turn/mill for asymmetric rotational parts to wire-EDM to rapid manufacturing (Xu and Newman, 2006). Given the time constraint and avoiding the complexity of dealing with multiple manufacturing processes costing of prismatic component manufactured by 3-axis milling processes have been chosen as the main area of interest within the integrated product creation process.

2.3.3 **Feature based systems**

Various costing methods are now used for product costing in CNC manufacture. Some costing methods relied on past cases to generate estimates; other methods are based on features and/or process recognition. To focus on the challenge of using actual cost parameters for CAx chains, feature recognition, has been chosen as the method of interest for integrated costing process.

2.4 The Scope of the Research

To achieve the objectives defined in 2.2 the following sections are identified as the research scope:

2.4.1 **Review of integrated product creation process and costing methods**

A number of methods and various tools have been used in manufacturing industry and by researchers to tackle product cost estimation in an integrated product creation environment. Literature on the product creation process (PCP), integration standards and cost estimation (costing) methods have been reviewed and assessed in chapter 3, 4 and 5 to identify potential methods for achieving unified costing in CNC manufacture. These literature reviews have been utilised to identify the research gaps and current research requirements.

2.4.2 **Framework for unified costing in CNC manufacture**

A theoretical framework based on 2.4 which utilises standardised PCP information has been developed in chapter 6 and 7 to establish the functional requirements for unified costing. The potential benefits and the viability of generating cost information feedback based on established manufacturing standards, ISO14648 (STEP-NC), has also been introduced. A process to retrieved cost relevant parameters from standardised representation of product design, process planning and manufacturing resources are proposed and explained, using IDEF0 and flowchart methodologies to represent the framework operation.

2.4.3 **Implementation of a Prototype unified costing Framework**

In order to enable the application of the structured PCP information represented by STEP-NC, a computational platform has been explored. Java objects, data retrieval mechanisms and costing algorithms have been developed to implement a prototype unified costing system for CNC manufactured part in chapter 8.

2.4.4 **Evaluation of the unified costing Prototype Framework**

In chapter 9, the system has been evaluated using prismatic components consisting of manufacturing features similar to those in industrial practice. The reliability of the developed costing prototype’s estimate results has been assessed by comparing it with a commercial cost estimation system and actual experimental results.

3 Review of integrated product creation process

In this chapter the stages of product creation lifecycle (PCL) in CNC manufacture and a number of standards that are used to integrate the product creation processes have been presented. Various methods and tools that are used to generate cost feedback information during product creation processes are investigated. A review of the existing literature for each method is then provided with a critique to highlight the advantages and disadvantages of each approach. As shown in Figure 3.1, this knowledge is then used to identify the research gaps that exist in the current costing solutions in CNC manufacture.

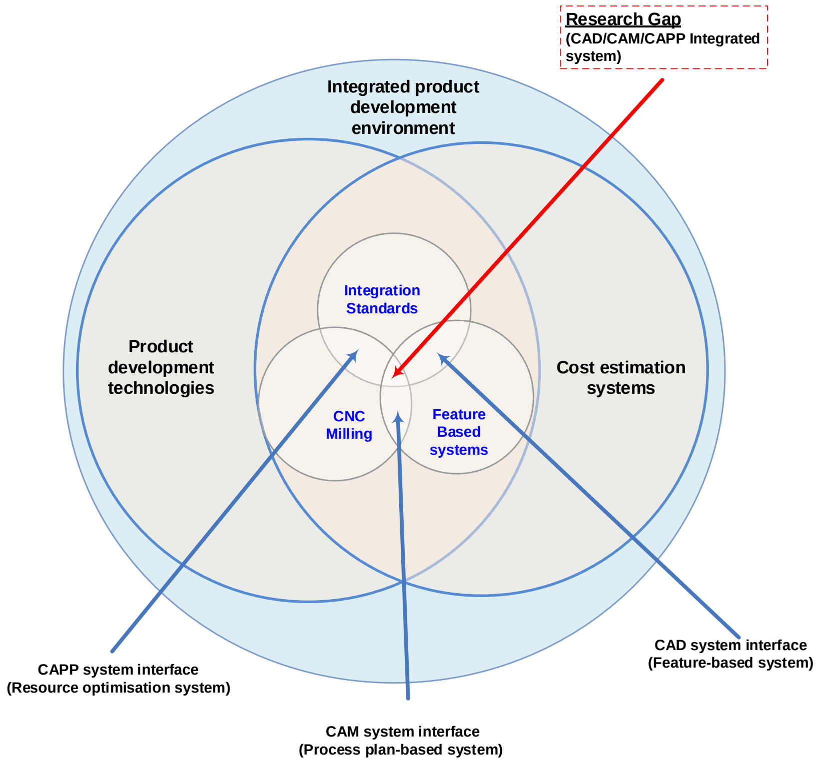


Figure 3.1 - Research gap identification area

3.1 The product creation phase in life cycle engineering

Life cycle engineering has been proposed as an effective solution to improve product creation and to reduce both cost and lead time (Keys, 1990). This approach supports consideration for products' complete life cycle through simultaneous treatment of product, processes and the service system(Asiedu and Gu, 1998). A product's life cycle starts with needs identification at the product planning phase and progressed to the product creation phase where the product is realised; the subsequent phases of product life cycle after product creation phase are product use, service, and finally disposal (Alting, 1993, Ehlenspiel et al., 2006). The product creation phase is the critical stage where costing is applicable for cost based decision support. Therefore, this research focus is on the product creation phase of the life cycle engineering. In this thesis, the term product creation lifecycle (PCL) has been used to refer to the beginning of the product creation processes (conceptual design) through to assembly. Figure 3.2 shows stages of the product reaction lifecycle for a typical CNC manufacture that is the domain of this research.

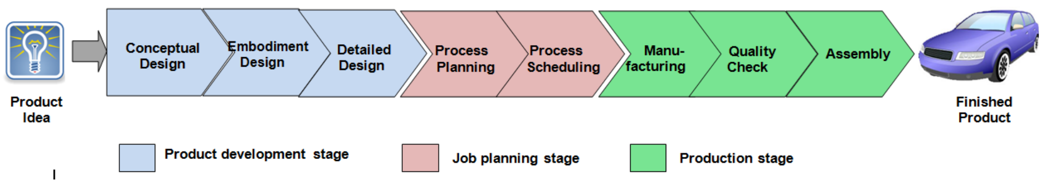


Figure 3.2 – Stages of the product creation lifecycle (adapted from Pahl and Beitz 1996)

Product planning is initiated by perceived market need or placed order and it is the stage at which logical identification of applicable ideas and product development approach, whether a new or adaptive product can be profitably introduced into the market, decision are taken. Determination of areas to be search for product ideas, analysis of the company potentials and comprehensive evaluation of developed idea for new product are conducted at product planning stage. Furthermore, consideration is given to interdependent systems, such as manufacturing capability and legislation, to identify achievable objectives that are realised throughout the stages of product creation lifecycle (PCL).

During the Product development stage new product's property is defined to meet production and customer requirements as set out at the product planning stage and decisions concerning product characteristics are made. The specifications generated are elaborated to ensure that technical requirements are met. Both the product geometry and associated product information are gradually refined from conceptual design, into embodiment design and into detailed design. The conceptual design process provides the basic concept and engineering structure to inform the search for suitable physical principles (Layer, 2003). Embodiment design process maps the basic structure onto a realizable product structure consisting of a number of sub-modules and components. The final process at product development stage is detailed design, where modules, component, and part designs are further refines to achieve higher level of specification after which the next stage, job planning, of the product creation lifecycle begins (Pahl and Beitz, 1996). Researchers have concluded that up to 80% of product cost becomes in-built by the distinguished activities at the product development stage of product life cycle (Corbett, 1986a, Mileham et al., 1992, Dowlatshahi, 1992, Hundal, 1993, Ullman, 2003). Base on this, existing cost estimation methods and system were developed to support decision on alternative design at the product development stage.

Job planning is the stage in PCL where detailed design information from the product development stage is utilised to determine production processes and manufacturing resources requirements. Process planning and process scheduling have been classified as key activities at the job planning stage (Giebels, 2000). Process scheduling consists of all the activities require for order execution and focus on sequential allocation of jobs for optimum utilisation of available resources (Giebels, 2000). Process planning activity defines the require process to transform detailed design to a finished product (Halevi and Weill, 1995). In CNC manufacture, process planning involve activities to determine machining processes, operation sequence and available resource. The specification of machining condition and technological parameters such as feeds and speeds are also carried out during process planning. The detailed information about the product that is available at this process planning are utilised in analytical costing methods to generate reliable product cost estimate.

Finally, production stage in CNC manufacture consists of manufacture, inspection and assembly activities that are performed with consideration to optimal technological and economic conditions. Manufacturing activity turned product design into actual product in line with product development guidance. Manufacturing process that shape production depends on the type of engineering design (Pahl and Beitz, 1996). Different types of manufacturing systems (e.g. flexible or cellular manufacturing systems) and practices (e.g. digital manufacturing and virtual enterprise) are applied to economically produce the desired product. Engineering costing methods that are capable of supporting not just decision on design and process alternatives but also supports decision on alternatives resources can be develop to provide cost information feedback across the product creation lifecycle (PCL).

In practice the PCL is not always sequential as feedback to activities at previous stages may be required to support necessary alteration. A predefine sequential practice during PLC increases the time and cost for correcting mistakes (Sohlenius, 1992). Manufacturers have replaced the traditional time and labour intensive practices with modern computer aided systems (CAx) to support simultaneous product creation processes (Sohlenius, 1992). In modern manufacturing, CAx chains are integrated for efficient performance of the product creation process, from product design through to manufacturing and beyond. Manufacturing standards that facilitate efficient information exchange are implemented to support CAx chain integration and a number of existing standards can be used to improve costing process in integrated product creation environment.

3.2 Integrated product creation in relation to costing

In this thesis the term costing refers to system of predicting product and production costs based on resource utilisation. In integrated product creation environment, costing broadly relates to the economic resources required to accomplish a product and, (Stewart and Wyskida, 1995). Resources are physical entities such as materials, operators, machine tools, cutting tools and fixtures utilised for product realisation. Costs are caused and fixed by engineering processes at different phases of product lifecycle (Wierda, 1990).

Figure 3.3 illustrates the effect of processes, at various lifecycle phases, on product cost; to indicate that while design phase only accounts for 10% of the product cost, 70% of the product cost is however fixed at this phase. On this basis researchers have argued that it more effective to perform cost reduction process at the design stage of product creation phase than at the manufacturing stage (Corbett, 1986a, Mileham et al., 1992, Dowlatshahi, 1992, Hundal, 1993, Ullman, 2003) and that accurate costing at this stage can help the designers engineers and estimators to improve product designs in terms of performance and cost(Shehab and Abdalla, 2001).

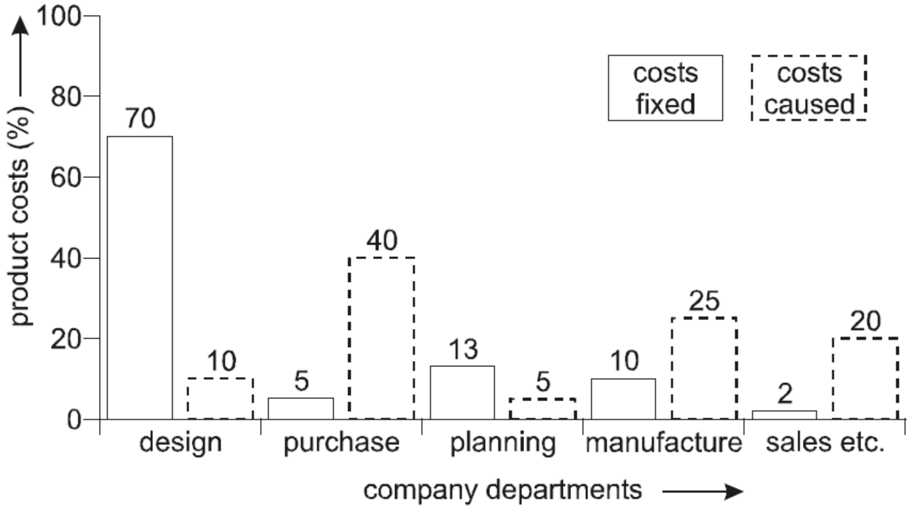


Figure 3.3 – Departments influence on product cost (Wierda, 1990)

The cost fixed at the product development stage are caused by interrelated cost elements, such as, geometry, material, production process and production planning (Weustink et al., 2000). The interrelationships of these cost elements influence cost, such that any decision to lower the cost of one aspect of the design product can increase the cost of another. For instance, the selection of cheap material to reduce unit cost may results in having to perform additional operation to meet a given surface roughness or tolerance requirement, and consequently increase production cost. Accurate estimation of the production cost will depends on the availability of detail product information and applicable costing method.

4 Costing methods and systems in manufacture

In this chapter various methods of generating product cost estimate (costing) in manufacturing industry have been presented. The importance of information availability for applicability of costing methods at various stages of product development has been investigated. The accuracy and uncertainty in costing at the different stages of product creation lifecycle (PCL) are also discussed, followed by a review of the state-of-the-art solution to improve costing process and integration of costing system with other product creation CAx. Finally, a critique of existing solution to integrated costing is then provided to highlight methods shortcomings. This knowledge is then used to identify the research gaps that currently exist in the costing research. Additionally a list of the author's publications in the research area can be found in appendix A.

4.1 Introduction

The focus of this research is costing in CNC manufacture. The term manufacturing in this thesis refers to a series, or parallel (as practiced in concurrent engineering environment) interdependent activities and operations that involve designs, material selection, process planning and CNC machining of product. Concurrent engineering is a philosophy where product creation processes are performed simultaneously, in other to improve quality and reduce production time span (Carter and Baker, 1992). Machining is the inter-related series or parallel processes by which a product is physically make from specified materials.

The term cost in this thesis refers to the sum of money spent on making a product including labour, materials, and manufacturing resources utilisation. The selling price refers to the asking monetary value for a given product. Manufacturing Cost Estimation (refers to as 'costing' in this thesis) was defined as "an attempt to forecast the expenses that must be incurred to manufacture a product" (Wilson and Harvey, 1963). As the name implies, costing primarily uses cost as an evaluation criterion to support design-to-cost or design-for cost product creation practice (Asiedu and Gu, 1998).

Cost is used as evaluation criterion in a design-to-cost or design-for cost context (Asiedu and Gu, 1998). Design-for-cost is the conscious use of engineering process technology to reduce life cycle cost; whereas design-to-cost obtains a design satisfying the functional requirements for a given cost target (Dean and Unal, 1992). Analysis of a product's total life cycle cost (LCC) enables the differentiation of estimated cost that is associated with various phases of product life cycle (Asiedu and Gu, 1998). Figure 4.1 shows the lifecycle costs components for a product's lifespan and includes the total manufacturing cost. The lifespan, or lifecycle of a product, starts from the initial concept through to product disposal and the cost of the product through this lifespan is the life cycle cost (BNET 2003). The Life cycle cost (LCC) is the sum of two distinct cost sections, the manufacturer's costs and user's costs (Ehlenspiel et al., 2006). The user's cost includes the acquisition, maintenance, operation and disposal of the product (Barringer, 2003), whereas the Manufacturer's costs consists of material cost, development cost, production costs and the overhead costs (Ehlenspiel et al., 2006).

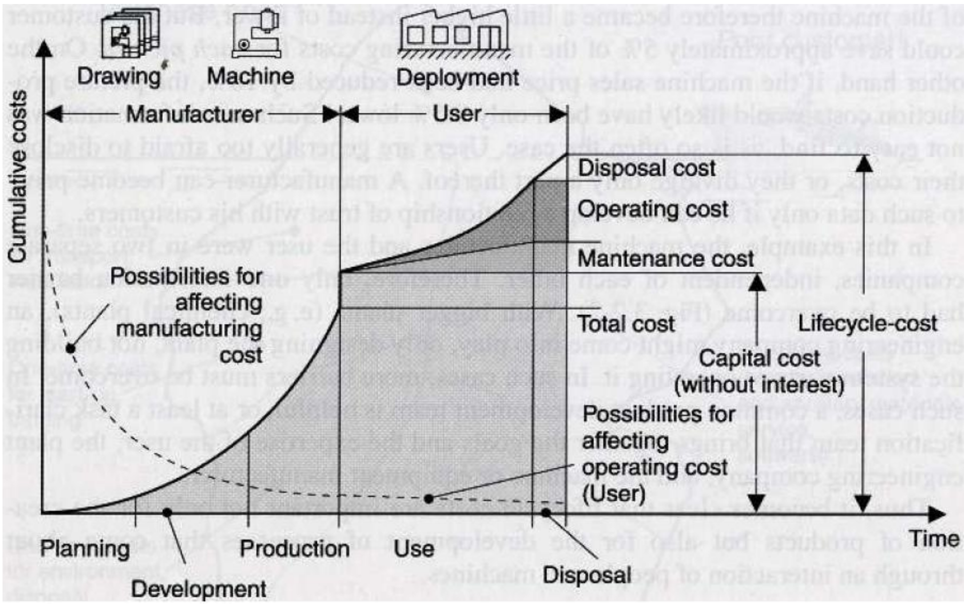


Figure 4.1 – Total lifecycle costs for an individual product (Ehlenspiel et al., 2006)

There are a number of methodologies that have been proposed for life cycle costing (Refs) (Ehlenspiel et al., 2006); however, this research focus is on estimation of manufacturing cost and costing methods that can be used to support cost effective product creation efforts. Various methods exist for generation of product cost estimate at different stages of product creation lifecycle (PLC). Researchers agrees that no one costing method is conclusively superior to other (Hicks, 2002, Hicks et al., 2002), since the suitability of a method depends on the manufacturer data gathering practice and the stage of PLC the method is applied (Farineau et al., 2001). Though different terminologies have been used by researchers to classify costing methods, a common view is that existing methods can be classify into parametric, analogy, intuitive and analytical approaches (Farineau et al., 2001, Ben-Arieh and Qian, 2003, Roy, 2003, Camargo et al., 2003, Cavalieri et al., 2004, Feldman and Shtub, 2006) that were categorised as either qualitative or quantitative techniques (Niazi et al., 2006).

4.2 Qualitative estimation techniques

Qualitative techniques consist of costing approaches that were used at the conceptual design of product development stage and relied on the identification of similarities between past and new products for cost analysis. This techniques is sub-divided into intuitive and analogical approaches (Niazi et al., 2006).

4.2.1 **Intuitive approach**

This approach is use to capture expert reasoning that is applicable to future product costing validation and improvement. Expert knowledge is stored as rules or decision tree for use in future costing (Niazi et al., 2006). This approach relies on the skill and experiences of the expert; as such estimates vary from one expert to the next even on the basis of the same data/information. Case-based and decision support systems methods are classified as intuitive approach (Niazi et al., 2006).

i). Case-based reasoning (CBR) method

Case-based reasoning method involves organisation and storage of past cases solutions into knowledge base in anticipation of their use for new product costing. Figure 4.1 illustrates the CBR costing process. For every new case (new product), the knowledge base is search to locate similar past cases and once found, a function is applied that adapts the previous case to the attribute of the new product for which costing is required. Provision of quick estimate and alternative solutions based on previous cases to mitigate against lack of formal knowledge of process planning and production (Duverlie and Castelain, 1999) are advantages of this method. A major disadvantage is that CBR relies on past cases for effective performance (Niazi et al., 2006, Gu et al., 2005, Aamodt and Plaza, 1994). In a highly innovative company new cases share little or no similarity with past cases, therefore CBR has limited use in such innovative environment, (Aamodt and Plaza, 1994, Duverlie and Castelain, 1999). Also, CBR method is based on defined part's features and therefore suffers from the limitation imposed by lack of consensus across manufacturing industries on what constitute a feature (Roy, 2003).

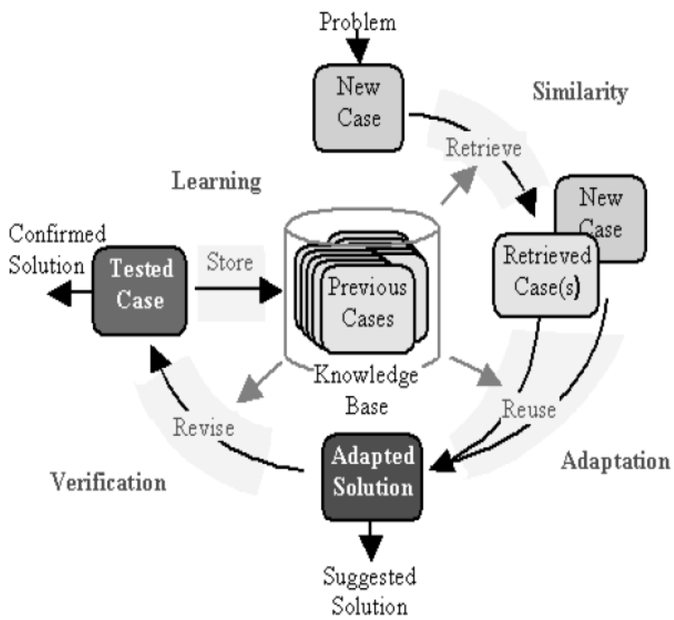


Figure 4.2 - The case based reasoning (CBR) process
(Aamodt and Plaza, 1994)

ii). Decision support system

A Decision support systems, also known as the expert costing method, utilised domain expert knowledge to assist task holder toward making satisfactory decision during costing process (Niazi et al., 2006). The domain expert's knowledge is stored in the form of rules, decision trees, judgements, etc, at a specified database to help the task holder improve the decision-making and costing processes based on certain information input(Niazi et al., 2006). The applications of decision support system for production planning and scheduling activities have been reported in literature (Er and Dias, 2000, Jahna-Shahi et al., 2001, Metaxiotis et al., 2002).

4.2.2 **Analogical approach**

This approach make use of similarities in products, the inference of analogical methods is that similar product are likely to incur similar cost to produce. Therefore by comparing the similarity in any two products, and adjusting for any cost-driving differences, a valid cost estimate can be derived. There is however a requirement to have a means of identifying the similarities and differences of products. Expert knowledge and historic product database are often employed to achieve these (Avramenko and Kraslawski, 2006). The analogy approach is capable of generating timely and reliable estimates even when there is no detail information about the product, therefore it is applicable at the early stage of product creation (Avramenko and Kraslawski, 2006). The degree of similarity used to retrieve past cases and the number of cases stored in the database however determines the quality of the estimate (Klinger et al., 1992). Analogy based cost models are quick and have high degree of transparency compare to parametric methods. The implementation of database facilitates the retention of expert's and collective knowledge in manufacturing environment. A key disadvantage of analogy methods is the high degree of reliance on expert judgement. Complete familiarity with product and process is also required to identify similarity and to make adjustment for difference in product. Regression analysis and artificial neural network (ANN) are categorised as analogy based methods (Duverlie and Castelain, 1999)

i). Artificial neutral network

Neural Networks (NN) or Artificial Neural Networks (ANN) method involves a network of simple processing elements which can exhibit complex global behaviour by connecting the processing elements and element parameters. The system of NN in CE takes the form of developing a computer programme that is capable of understanding how certain product attributes, (e.g features, tolerance, surface roughness etc) impact product cost. Usually this requires the use of data from a past case to train the NN on generating functional relationship between the cost element parameter and the cost value. A trained NN can then accept product parameters or its attributed values, and applied the approximated function to generate cost estimate for a new product. Neural networks can be constructed to simulate the action of a human expert in a complicated decision situation (Ayed, 1997) and are particularly effective for complex costing problems where the relationships between variables cannot be expressed by simple mathematical expressions. The general structure of neural networks (NN) is depicted in figure 3.4

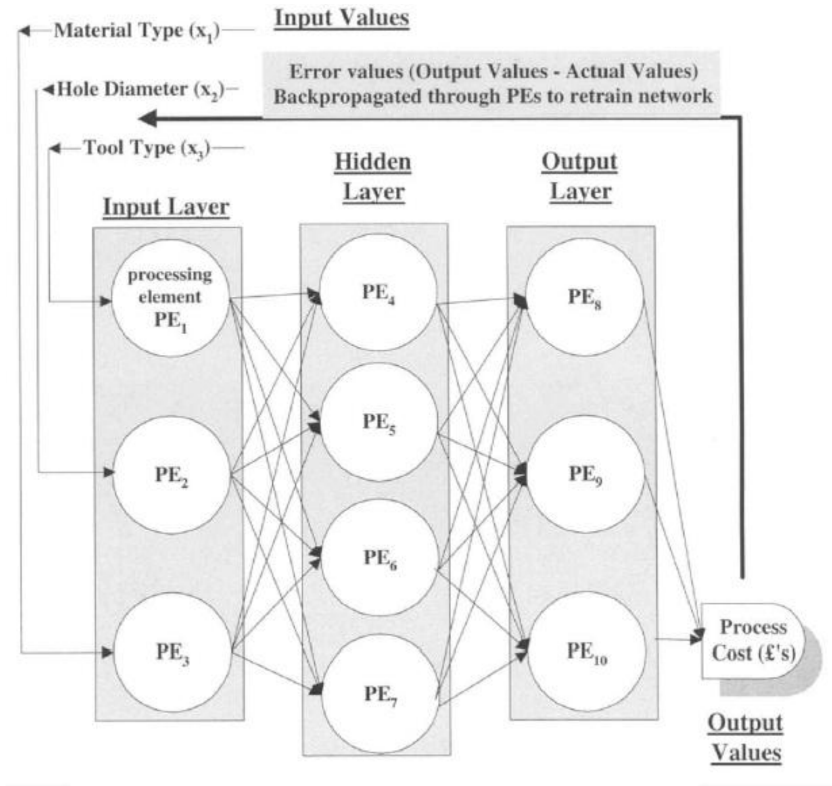


Figure 4.3 – General structural of an artificial neural network (Stockton and Wang, 2004)

Although ANN has the advantage of been applicable, to generate product cost estimate, at the conceptual stage of product development, some of the disadvantages of this method include the need for a considerable past cases to effectively train the programme, therefore, manufacturers that produce limited product ranges would find it unsuitable. Also, past cases have to have a high degree of similarity to the new product for a satisfactory estimate to be achieved. As is the case with most analogy methods, NN is not a suitable method for estimating novel or innovative product cost. The illogical nature of the resultant equation for product cost estimation makes NN a black-box; therefore, it is not effective for presenting the reasons and assumption on which a cost estimate is based (Asiedu and Gu, 1998). The application of any work analysis tools is not supported because the logic behind the data use for cost estimation is not transparent, and there is no explicit set of rules to determine whether a given learning algorithm is suitable for a particular system(Wong et al., 1997).

4.3 Quantitative costing techniques

Quantitative estimation methods involve the detail analysis of cost attributes associated with product design and processes for product realisation. Parametric and analytical approaches are consider Quantitative techniques (Niazi et al., 2006).

4.3.1 Parametric approach

Parametric costing is the computation and utilisation of equations that define relationships between product cost and measurable attributes of a product that must be realised (Dean and Unal, 1992, Stewart and Wyskida, 1987). In parametric costing, regression analysis based on historical cost and technical information is used to predict the impact of various process, e.g. design or manufacture, on product's cost (Cavalieri et al., 2004). Statistical correlation of costs with parameters that define the product culminates in a set of formulae known as cost estimation relationships (CERs). Applicable parameters may include product weight, performance requirement, design familiarity and product complexity. For instance, in the development of a new aircraft the relation between the cost of engine and the thrust requirement is a simple CER.

Systematic information gathering and analysis process that is require to ensure applicable CERs are up to date in parametric costing involves considerable efforts (Asiedu and Gu, 1998, Scanlan et al., 2002), once the relevant data are compiled product cost feedback can be rapidly generated (Greves and Schreiber, 1993). Parametric costing methods are applicable at the early stage of product creation life cycle that is characterised by lack of detail information (Farineau et al., 2001, Fad and Summers, 1988) and in cases where cost driver and parametric functions can be readily identified (Farineau et al., 2001, Niazi et al., 2006, Cavalieri et al., 2004).

Other advantages of parametric costing includes: enabling the user to quickly generate product cost estimates without a great deal of detailed information (Long, 2000, Camargo et al., 2003) and, provision of insight and understanding on product cost driving parameters (Kwak and Watson, 2005). One such parametric costing systems developed for this purpose and widely used commercially is the Lockheed Martin PRICE system (Asiedu and Gu, 1998). PRICE is implemented by a number of high profile companies that include British Aerospace Corporation (Daschbach and Apgar, 1988), the European Space Agency (Greves and Schreiber, 1993) and NASA (Dean, 1989).

Disadvantages of this method include the requirement for a significant volume of historical data to establish statistically meaningful CERs (Scanlan et al., 2002). The lack of relevant parametric variables to develop satisfactory CERs introduces certain degree of uncertainty that reduces estimate reliability in the costing process(Duverlie and Castelain, 1999). The parametric approaches is also not suitable for estimating the cost of products that require significant technological changes and new manufacturing processes (Farineau et al., 2001).

4.3.2 **Analytical approach**

The term analytical cost estimation approach is used interchangeable with detailed cost estimation in literature (Layer et al., 2002). The analytical approach is when product cost is estimated by taking into account all the operations and resources require for producing a finish product. The output is a cost estimate that is the sum of all the cost associated with constituent parts of the product. This approach often resulted in the generation of new model estimate, and as a result is capable of handling changes in manufacturing processes and technological development. By depicting detailed cost drivers, it allows for specific conclusion and effective cost adjusting decisions (Layer et al., 2002). Activity based costing (ABC), feature based (FB) method and Process based (PB) method are categorised as analytical approaches (Niazi et al., 2006)

i). Process-based method

Process-based (PB) cost estimation relies on detailed engineering analysis and calculation to determine an estimate (Niazi et al., 2006). The method is based on the premise that the processes which produced the desired finished part have a cost associated with them. The individual cost of the performed processes is summed up to obtain the cost estimate for a given product. PB methods accounts for overhead and materials as well as labour expenses, and it is primarily aimed at enlarging the range of cost attributes so as to broaden the scope of engineering activities to which product cost can be linked. The advantage of this method is that accurate cost estimate is generated because every process is accounted for. Its drawback includes the requirement for detailed product information and need manufacturing expert to determine material and processes for product realisation. The method could also be tedious and not permitting a quick way to generate product cost estimate.

ii). Feature-based method

Feature based costing is based on the products individual part's characteristics. The entire features present in the parts that comprise a product are identified and the cost of operation to produce individual feature is estimated. This type of cost estimation method is well researched. Feature-based costing (FBC) is a useful method that design engineer use to consider the implication of their design decision on product manufacture and lifecycle (OuYang and Lin, 1997, Hicks et al., 2002). In FBC the need to determine part features such as holes, slots, etc. necessitate the use of CAD system (Hicks, 2002, Roy and and Sackett, 2003, OuYang and Lin, 1997). Recent advances in the computer aide systems (CAx) integration has facilitated development of FBC system that is integrated with CAD system(Philpott et al., 2004). However, the lack of consensus on the definition of features across manufacturing industry meant practitioners have to implement company specific feature definition in FBC. This may result in lack of confidence among collaborating manufacturers as each generates different cost estimate for a given product.

iii). Activity-based costing

Activity-based costing (ABC) is a method used for cost evaluation of activities performed on a product. Performed activities such as inspection, production, administrative processes are accounted for to obtain product estimate (Ben-

Arieh and Qian, 2003, Ahmed and Abdalla, 2002, Aderoba, 1997). In this method each of the activities within an organisation is identified and average associated costs derived for a given activity. Once this is established, the cost estimate for a product is determine by analysing the amount of activities a product is likely to require.

In theory, ABC should be the most accurate method for cost prediction, as it takes all business activities that goes into a finished product into account and thus eliminate distortion arising from indirect cost, or variability in measure of activities (Niazi et al., 2006). The method's reliability and speed of development, as well as its transparent depiction of cost drivers are also advantageous. However, since the processing times and labour handling times must be estimated based on the experience of a manufacturing engineer or a cost estimating engineer, and given the difficulty to accurately break down the various overhead costs incurred on manufacturing a part, the ABC approach often provides inaccurate cost estimates, is very time consuming (Philpott et al., 2004) and requires high capital investment for its implementation (Niazi et al., 2006).

4.4 Costing accuracy and uncertainty during product creation

4.4.1 Accuracy of costing methods

Accuracy of cost estimate is important for manufacturing companies economic survival. In a competitive bidding scenario if a manufacturing company submit an estimate that is unrealistic low, that is underestimated, the order maybe won but there is likelihood of financial loss. This is because the resources plan on which the underestimate is based may not be feasible and as the project progresses the cost targets are missed. To address the issue resource restructuring is conducted and extra resources may even be added, the consequence of which is eventual cost increase (Daschbach and Apgar, 1988). Overestimation on the other may cause the company to lose the bid but if the bid was awarded cost reducing practice becomes less of a priority and as a result the anticipated higher profit is not realised (Daschbach and Apgar, 1988).

A reliable cost estimate are not only important for external bidding on manufacturing contracts, it is also essential for cost control during internal product creation and for product cost reduction.

Figure 4.4 Is the Freiman curve that illustrate the relationships between the overestimate, underestimates and products cost. The curve shows that both underestimate and overestimate results in higher actual spending but a realistic estimate leads to cost effective project.

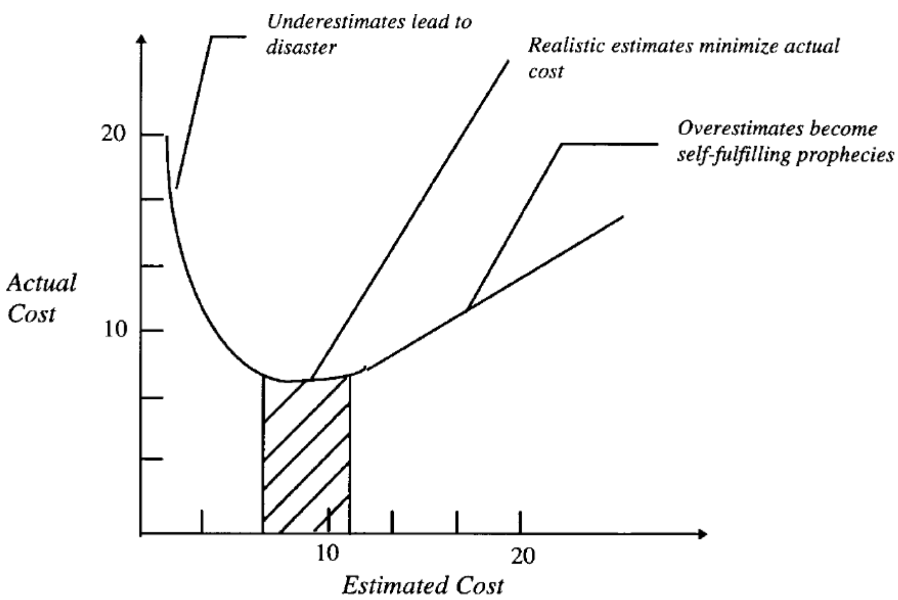


Figure 4.4 - The Freiman curve (Daschbach and Apgar, 1988)

The costing methods requirements for generating cost estimate varies according to the stage of the product creation lifecycle (PCL) at which cost analysis is to be performed and the type and depth of the analysis to be carried out (Fabrycky and Blanchard, 1991). During the conceptual and embodiment designs of product development stage, there are limited data about a product and various parametric costing approaches are used to generate cost estimate. At this level the accuracy of cost estimates ranges from -30 to 50% (Creese and Moore, 1990b). At the detailed design of the product development stage, more information about the product becomes available and, where historical cost data exist, cost estimates are generated using analogous approaches that compare the characteristics of the new product with similar past cases (Fabrycky and Blanchard, 1991). Analytical (Detailed) approaches are also applicable at this point for detailed cost analysis. Cost analysis for budgetary reason are performed at this point and estimates accuracy is within the -15 to +30% range (Creese and Moore, 1990b). As the product creation process progressed from the detailed design, and more comprehensive information about the product, process and resources requirement becomes available, analytical costing approaches are often used at this stage to generate realistic cost estimate with -5 to +16% accuracy (Creese and Moore, 1990b).

4.4.2 **Uncertainty in costing**

According to the National Aeronautics Space Administration, “Cost estimation is the art of approximating the probable cost, extent, quantity or character of something based on information available at the time”(NASA 2002). This suggests that cost estimation (costing) depends on cause and effect relationship to decide likely product cost. The resulting cost estimates are decisions about what costs will be in the future and therefore there is inherent uncertainty in costing. A decision under uncertainty is one in which each action may result in more than one outcome, depending upon the state of nature but each state of nature has an unknown probability(Jelen and Black, 1983).

Uncertainty is “a potential deficiency in any phase or activity of the modeling process that is due to lack of knowledge which causes model-based predictions to differ from reality”(Oberkampf et al., 1999). For instance, a designed product due for manufacture months after can include uncertainty about changes in technology, manufacturing processes, materials, and resources logistic. This makes the analysis of cost related to such product difficult (Asiedu and Gu, 1998). Costing (cost estimation) process at the early product development stage have to relied on cost information from similar past cases and historical database, this introduce a degree of uncertainty into the process as the actual requirements such as final product attribute (e.g surface finish) and manufacturing resources are unknown this stage.

Accurate cost estimation plays a significant role in a manufacturing company’s product creation effectiveness and market performance. Availability of more detailed information about a product reduces uncertainty in cost estimation process(Corbett, 1986b), and improve estimate accuracy (Creese and Moore, 1990b). In view of this, the availability of design, process and manufacturing resource information about a product and the development of costing system capable of using the information from across the product creation lifecycle (PCL) will provide grounds for improving the cost estimation accuracy, and therefore, offer distinct engineering and business advantages (Kleyner and Sandborn, 2008). A number of analytical (detailed) costing methods have been developed to utilised product creation information that is available with integrated manufacturing environment.

4.5 The state-of-the-Art on integrated costing research

The current body of research on analytical costing are subset of methods to access available data from the product creation processes. In this section an overview of the literature together with a categorisation and critique of the methods utilised by the researchers is provided.

4.5.1 **CAD/CAM integration based solution**

A number of researches have been conducted to improve cost estimation process at various stages of the product creation process by linking costing system to computer aided, CAD/CAM, systems that output design and process information necessary for cost analysis.

Geiger and Dilts, (1996) developed a prototype estimation system that implements an automated design-to-cost method to facilitates the integration of manufacturing and accounting concepts for feature-based, process-based and activity based costing (Geiger and Dilts, 1996). Their work provides a good understanding of how a design will lead to manufacture and the identification of product creation cost attribute but lacks integration with CAx chain downstream the product creation lifecycle.

Feng et al., (1996) presented a mathematical algorithm model to determine the minimum cost design in which the cost evaluation was based on part features (Feng et al., 1996). The emphasis was on calculating machining time for a component. That is, the time taken to complete a machining cycle, the changeover, and set-up. The presented model shows that changeover and set-up time were the significant components of machining time, as the shorter the changeover and the set-up time, the lower the machining cost.

OuYang and Lin, (1997) developed a cost estimation system based on design feature but also take the part’s shape and require precision in account for improve estimate accuracy (OuYang and Lin, 1997). The system generates manufacturing processes from a CAD based geometric features. The process plan is generated using a rule-based approach to allocate machining operation to design feature, the system then generates estimate, based on the volume of material removed and specified surface roughness. Though OuYang and Lin, (1997) methodology was an improvement on previous systems, its rule-based approach makes it more difficult to integrate valuable knowledge and to apply the method for complex product.

Ben-Arieh, (2000) presented a methodology to deatermine manufacturing process by assessing features of detailed design and apply variant approaches to calculate the manufacturing time and estimate the final cost of the part with a detailed model(Ben-Arieh, 2000). The accuracy of this method is questionable as the product cost estimate result is based on computed values and not on actual cost elements information.

Maropoulos and Baker, (2000) developed a system that used designed part features to determine the operations necessary for the machining process. A capable resources for the require operation is then determine by the system and manufacturing time, which can be used to estimate cost, calculated (Maropoulos and Baker, 2000). However, the methodology was based on a specific tool selection module which does not cover the whole product life cycle.

Arezoo et al. (2000) developed an integrated system to support decision on optimal process based part design and candidate tool characteristic. Manufacturing cost calculation is based on the selected process, cutting tools and machining conditions (Arezoo et al., 2000). This method was based on expert system and exhibits estimate's inconsistency inherent to expert based system.

Tang et al. (2003) present a rule based integrated system that link cost associated with product feature to process requirement for product cost estimation. (Tang et al., 2003). The presented system is primarily applicable for decision on alternatives design and process, as well as cost tracking studies but lacks capability to support decision on alternative resources.

Philpott et al., (2004) presented a novel Feature Based Costing (FBC) methodology for automatically estimating the manufacturing cost of parts in real time by extracting parametric features of a product design from CAD model (Philpott et al., 2004). Product creation process cost attributes are identified on the basis of design's parametric features, and computed to generate product cost estimate. The capability of the FBC system to provide fast feature by feature cost association, as a part is being designed, was reported following a case study commercial application for an extrusion process (Nieto, 2010). The developed FBC method interfaced with manufacturer CAD system but it does not have the capability to interface with CAM, CAPP and machine tools systems therefore cannot effectively be utilise for cost based decision on process and manufacturing resource alternatives.

Newnes, et al (2007) developed an estimation system that integrate parametric costing process with a design system and processing database (Newnes et al., 2007). As an extension of an integrated estimation framework proposed in (Hosseini-Nasab et al., 2003) and (Mileham et al., 2005), the Newnes, et al (2007) system utilised CAD package to assist design engineers during conceptual product design to support decision on design alternatives, however, it does not address the confidence of cost estimates and how the lowest possible cost for each concept can be achieved.

4.5.2 **Knowledge based solution**

Allen and Swift (1990) develop a knowledge-based expert methods capable of integration with design package for automatic costing n and selection of manufacturing processes at the early design phase of PCP (Allen and Swift, 1990). Their method uses mathematical rule to select manufacturing process and the resulting nominal values are used to generate cost estimate. The methodology makes product information available for costing but the use of nominal values calls the estimate accuracy into question.

Luong and Spedding (1995) reported the implementation of a generic knowledge based framework for the unification of process sequence and cost estimation into an integrated system (Luong and Spedding, 1995). Though the system has integrated process planning and cost estimation capability, it however lacks a CAD/CAM systems interface capability for effective support on design and process alternatives.

Cunningham and Smart, (1993) developed an expert system with feature-based cost estimation capability that was commercially implemented to calculate the manufacturing costs of parts for the Ford company in Europe (Cunningham and Smart, 1993). The system comprises of an information platform for production planning cost calculation and a knowledgebase of process models to support decision on process alternatives. The system implements a combination of heuristic, fuzzy logic and object orientation methods to generate detailed cost estimate but require high capital investment for its implementation.

Aderoba (1997) proposed an ABC method applicable to product's manufacturing cost estimation and orders evaluation (Aderoba, 1997). Another analytical model based on the ABC method was proposed and implemented in a Motorola electronic components assembly plant (Locascio, 2000). The proposed methodologies lacks high level integration capability with actual manufacturing systems and are therefore not adequate as sole system for manufacturing cost estimation.

Bouaziz et al. (2006) presented a database system that combine analogical and analytical estimation methods to generate relatively accurate cost estimate for machined dies (Bouaziz et al., 2006). However the proposed methodology will requires high capital investment for its implementation and operation.

4.5.3 **Generic information model based solutions**

Jiao and Helander(2006) proposed a digitally integrated system that facilitate the configuration of product features and has a cost calculation module to support pending decision and cost calculation (Jiao and Helander, 2006).

Venkatadri et al., (2006) propose a generic model oriented toward decision support at the request for quote (RFQ) phase in manufacturing supply chain. The system calculate manufacturing time to support decision on alternative supplier or sub-contractor(Venkatadri et al., 2006).

Jin et al. (2012) presents a digital manufacturing based method for integrated cost estimation (Jin et al., 2012). The presented work set out a knowledge database for part costing that is consistent with a defined digital manufacturing structure. The system's capability to integrate product assembly time and parts manufacturing cost estimate within a digital environment was demonstrated with a software prototype.

Other researchers have proposed the application of virtual manufacturing models (VM) to for cost analysis. Virtual Manufacturing is the digital representation of physical, logical schema and the characteristics of manufacturing systems including products, process, manufacturing resources and environments (Noh et al., 2003). Stockton et al (2012) proposed a methodology that is based on virtual manufacturing (VM) model and data mining techniques to generate cost estimate (Stockton et al., 2012b). In the second part to this research alternatives data mining algorithms were examine for their capability to provide a high level of estimating accuracy and represent actual causal costing relationship (Stockton et al., 2012a). Though, the validity of the methodology was demonstrated using an automated painting process case study data, a key shortcoming of the methodology is that it is not fully automated as the use of virtual manufacturing is expert knowledge dependent. Standards based solutions

Manufacturing standards contain structured representation of detailed information about a product and support information exchange framework that when implemented in costing can enable the use of actual cost elements parameters in costing process. The Standard for the Exchange of Product model data (STEP) provides detailed digital description of product's design and lifecycle but the implementation of the standard in costing process has been ignored, save for Fischer et al (1994) development of a STEP based approach that utilised the standards' product information models to provide automatic cost information feedback across product's lifecycle(Fischer et al., 1994). However, STEP does not adequately support process plan and manufacturing resources digital description. Therefore, while the presented STEP based approach demonstrated the automation of costing process at the product development stage, the approach lacks capability to effectively support decision on process and resources alternatives.

4.6 Critique

The previous sections of this chapter outlines a wide range of methods and systems that have been developed to generate product cost estimate in integrated product creation environment. Reviewed literature also indicated that there are a number of limitations with existing costing methods that prevent the realisation of a fully integrated costing system capable of automatic generation of consistent and reliable product cost estimate. These include:

4.6.1 **Reliance on historical database and expert knowledge**

Detailed and reliable product costing is critical to manufacturer's success but it is often difficult to perform detailed costing at the product development stage due to lack of detailed information. Researchers have developed costing methods that rely on historical database of past cases and expert judgement to address the lack of detailed information. However, recent trends towards increased product, process and manufacturing innovation to reduced product development cycle time can make reliance on both historical database and expert knowledge ineffective as similar past cases and expert experience with the new product may not exist.

Other reported drawbacks of reliance on historical database includes the time consuming data gathering, analysis and storage processes, as well as, the high capital investment require to establish, maintain and operate an effective manufacturing database.

Furthermore, costing process includes systemic analysis of product design, processes and resource requirement to improve estimate reliability but the know-how for this improvement exist mostly as tacit knowledge exclusive only to domain expert. In the event of the expert leaving the company the know-how becomes unavailable to the manufacturer. A costing method that is based on structured digital representation of product creation and costing processes would encourage digital quantification and preservation of the crucial tacit knowledge that can then be used for quick training of new personnel. The reliance of reviewed costing methods on expert knowledge makes manufacturer susceptible to loss of valuable process knowledge and high cost of training new cost estimator.

4.6.2 **Confinement to early design phase**

According to literature, existing estimation methods and system were developed to be applicable at early phases of product development stage such as the conceptual design phase (Esawi and Ashby, 2003) and detailed design phase(Ficko et al., 2005)**.** The majority of reviewed costing methods focused on using product design information, rather than using design, process and manufacturing resources information to support decision on alternatives. A key benefit of developing a costing system that utilises design, process and resources information is its applicability across the entire product creation lifecycle to further reduced product creation cost through consideration for not just design alternatives but also cost effective process plan and resource utilisation (Cooper and Slagmulder, 2004).

The type of production process and the amount of material require to realise a product is determine by the product geometry (shape, dimension, accuracy etc.). Take for example, the production of a product with high level of accuracy will require more resources to be deployed to meet the specification, resulting in increase in the production costs. In modern manufacturing operations the shape has a direct influence on the production costs. The transformations of conceptual design into finished product require consumption of resources such as operators, machine tool, tools sets, fixtures etc., but these resources have limitation in there capability and they are therefore restricted in the execution of certain operations. The capabilities of the available resources determine the type of production method and number of operation, both of which can significantly influence production cost. There may be instances of logistical restriction on manufacturing resources (i.e. a resource will not always be available). Prior knowledge of such restriction can support engineering decision on assignment of require operation to available resources and variable cost associated with the product could be further reduced as a result(Giebels, 2000).

Reviewed costing methods and systems focus on the product development stage meant applicable process and resources cannot be accounted for as a relevant cost driver, which limit the scope of costing systems to adequately support cost reduction decision downstream of the product development stage.

4.6.3 **Lack of Interoperability**

Many of the reported integrated costing methods are developed for specific domain and are rarely applicable in different manufacturing facility/environment, particularly in environment characterised by product and manufacturing processes technological innovation. This is a key limitation in a concurrent engineering practice and agile product creation network, where product realisation processes are carried out across geographically dispersed facilities and may involve collaborating manufacturers, that benefit from the advantage of integrated and interoperable systems to reduce product realisation time and cost. Concurrent engineering and more specifically design for manufacture (DFM) has emerged as a critical task integrating the design function and the manufacturing function during the product realization process. The objective of DFM is that by considering manufacturing early in the design process, the design can be favourably influenced to improve quality, reduce cost and decrease time-to-market. DFM is the process whereby design teams evaluate the manufacturability of the product based on manufacturing process knowledge and information, and then provide feedback so that the product design can be improved with respect to manufacturability. The successful realization of DFM requires the availability of both product and process models. Traditionally only internal manufacturing capabilities were necessary to sup- port DFM, but current virtual enterprises must also consider the capabilities of their collaborators during the product realization process. There are many different software applications in use by each company in the collaborating network. Hence, there exists an industry-wide demand for full integrated product creation and costing solutions capable of sharing design and manufacturing information between applications.

4.6.4 **Lack of transparency**

A major requirement for an effective integrated costing is transparency, that is, the parameters that are used to obtain estimate result are traceability. A transparent costing method enables effective analysis of the impact of a specified parameter change on product cost. Furthermore, the utilisation of actual, rather that deduce, values has the potential to improve product cost estimate accuracy. However, reviewed methods often used rule-based computation to deduce nominal values that are used to generate product cost estimates in the absence of actual product data. While this approach may address the lack of detailed information at the early stage of product development, the deduced values used to generate cost estimate result are neither easily traceable nor sufficiently transparent. As a result design, process and resources parameters that have the most impact on product cost are not accessible for determination of further cost reducing strategy.

4.7 Summary

This chapter has presented review of researches on manufacturing costing methods and state-of-the-art integrated costing research. The reviewed in the previous sections of this chapter presents a body of costing methods and systems that have been conducted to eliminate specific problems within the domain of integrated product development. The major research gap has been identified as a lack of a fully integrated costing methodology that is capable of utilising digital representation of product creation data that exist within manufacturing facility, for automatic generation of reliable cost information feedback across the product creation lifecycle.

Reviewed literature indicated that costing systems are integrated with CAx in three different ways. These are the encapsulation, interface and information models type integrations. Encapsulation type integration system allows the designation of cost consideration boundary around features and parameters that defines a product design. This type of integrated costing systems is designed to recognise CAD files, digital representation of the product, and launch the cost estimation process but there is only limited one-way exchange of information between the systems. In the interface type integration, CAD system and costing system can exchange files and some meta-data automatically, without requiring human intervention. The system functions are provided via the application's menus and vice versa but the flow of data is not two way associative. Information models are digital representation of product creation processes and literature have indicated that information models based integration is an improvement on the encapsulation and interface type because it provides full, automatic exchange of all types of product creation process data and meta-data.

Standardised information models also support bi-directional exchange of information among product creation CAx chains.

It is the author's opinion that the lack of support for bi-directional information flow by the encapsulation and the interface integration methods, which are mostly implemented in existing integrated costing system, prevents the development of fully integrated costing methods. The author also believe that a revolutionary and proactive thinking is required to address the existing costing systems limitations outlined in section 4.6 and to developed integrated costing method that is relevant to today's computer aided and digital oriented product creation environment. A revolutionary cost estimation approach require a shift from current method of integrating costing system with CAx; to the exploration of digital information models as a medium through which full integration of costing system with CAx can be achieved. Full integration of costing system with other product creation CAx chain facilitates the utilisation of detailed and actual product creation data, CAx outputs, for automatic generation of reliable cost information feedback.

A major benefit of implementing information model in costing domain is that it contains actual and detailed cost information from across product creation lifecycle. Therefore, it provides opportunity to minimise the inherent costly and time consuming data gathering exercise in costing process by enabling full integrate of costing system with the information-rich computer aided manufacturing environment. However, the potentials of information models to provides a consistent detailed information environment is currently underutilised in manufacturing costing domain and the opportunity to develop a fully integrated costing system capable of supporting decision on alternatives across product creation lifecycle are been overlooked. The limitations of cost estimation methods applied in manufacturing industry has been reported in literature (Cavalieri et al., 2004, Rush and Roy, 2001) and the cost estimation system requirements matrix shown in table 4.1 compares a standard based costing (SBC) with other cost estimation methods to highlights the potential of costing process that is based on structured information model..

Table 4.1 - Cost estimation system requirements matrix

Cost estimation methods / **User's Requirements**	**CBR**	**PE**	**FBC**	**SBC**
Applicable at early product development stage	√	√	x	x
Applicable for feasibility studies	√	√	x	x
Applicable at detailed product development stage	x	x	√	√
Cost estimate result transparency	x	x	√	√
Adaptability for new technology & process	x	x	√	√
Full integration with computer aided systems (CAx)	x	x	x	√
Mitigate against data uncertainty induced error	x	x	√	√
Supports expert & enterprise knowledge quantification	x	x	√	√
Cost estimation process automation	x	x	√	√
Non-reliance on past cases	x	x	√	√
Based on industrially recognised data structure	x	x	x	√
Support decision on alternative at production phase	x	x	x	√

Abbreviations:

CBR: Case Based Reasoning; **PE**: Parametric Estimation;
FBC: Feature Based Costing; **SBC**: Standards Based Costing

5 Information models in CNC manufacture in relation to costing

5.1 Introduction

Following the identified limitation of existing costing methods in section 4.6 and the highlighted potential of information models to address these limitations as discussed in section 4.7, possible information models that can be used to develop fully integrated costing methods are explored in this chapter. A brief description of a number of information models has been provided and based on the comparison of the alternatives, an appropriate information model has been chosen to realise this research objectives.

5.2 Integrated information modelling in CNC manufacture

A widely accepted method of integrating the various information sources to support product realisation is through information modelling that ensures the effective representation and seamless integration of product and process knowledge in the CNC manufacturing environment(Molina et al., 1995, Borja et al., 2001, Liu and Young, 2004). This author believes that identified limitations of existing costing methods can be address by developing a costing method that is fully integrated with product creation CAx chain and that; this can be realised through information models based solutions.

Information models can be classified as, functional, static behaviour or dynamic behaviour, depending on their perspective. A functional perspective describes the manufacturing process including all the activities to change input to output. The behaviour of the process can be subdivided into static behaviour and dynamic behaviour. The dynamic behaviour is the time-varying aspect whereas the static behaviour is a description of the capabilities without reference to time. These models can contain both declarative and procedural knowledge. Declarative models explicitly represent the process information whereas procedural models implicitly represent the process information through rules, expressions and equations that infer process capabilities from imputed parameters. The following information models were considered for their suitability to achieving the aim of this research:

5.2.1 **Analytical process models**

Analytical process models define mathematical relationships between design features and process parameters. Manufacturing process capabilities, such as tolerances or surface finish, are predicted by mapping machine control set point values through the analytical process model. Analytical models are primarily useful during the product/ process specific evaluation stage because the mathematical expressions require precise design and process parameters. Difficulties encountered with analytical models are: they can be difficult to integrate on a systems wide basis because they are generally narrowly focused on a single process; they are based upon empirical data and thus are inherently imprecise; and they do not employ standard representation structures.

5.2.2 **Process simulation models**

Process simulation models provide a computer representation of the process for predicting relevant process capability information. Process simulation provides useful process capability information tailored to the current part being evaluated. Commercial simulation packages are available for machining and a few other manufacturing processes. Process simulation models require a completed or nearly completed product model and thus are only used in the product/ process specific evaluation stage. Disadvantages are the time requirements to complete a simulation package require specialized expertise and knowledge, and they suffer from lack of integration with existing systems.

5.2.3 **Statistical models**

A statistical perspective on process capabilities refers to the statistical process control of a manufacturing process. Process capability indices measure this ability. Although not routinely performed the statistical process capability data can be organized and presented to the design engineer. This provides a very specific indication of the quality and yield capabilities of a manufacturing process. Potential drawbacks are: organising the information in a useable format for design engineers, only have data for quality measures, and data are based on specific parts and may not be relevant to new design.

5.2.4 **Process information models**

Information models represent the entities, attributes and relationships between the entities. Two methodologies are used, generally based upon the final application platform of either a relational or object-oriented format. The IDEF modelling methodology recognizes three viewpoints, the functional (IDEF0), information (IDEF1x) and the dynamic (IDEF2). The information model component IDEF1x is based on the relational data model. While it has been widely and successfully applied to Computer Integrated Manufacturing

(CIM) systems design it does have several limitations: poor abstraction because only atomic attributes are allowed, difficulty in capturing domain constraints, and instance identification through attribute values (Malhortra and Jayaraman, 1992).

5.2.5 **Standards**

These are standardised process information models that have been developed using object-oriented approaches in order to overcome inherent limitations of non-standardised models. There exist several object oriented model definition languages, one of, which is EXPRESS, used for defining the STEP and STEP-NC standards. The use of the object oriented approach enable structured representation of product design, process planning and resource information from several abstract level, which can be utilised for cost based evaluation of decision on alternatives throughout product creation lifecycle. On this basis manufacturing standards, STEP and STEP-NC, based solution is considered appropriate for the realisation of this research aim. The rest of this chapter provide detailed discussion on the prospective standards, the ISO10303 (STEP) and ISO14649 (STEP-NC), starting with brief background on the foremost product design standards, the IGES.

5.3 Standards in CNC manufacture

In integrated CNC manufacture standards has become a vital technique used to represent product creation processes. Standards supports identification of the common information requirements before product manufacture and its application/processing independence makes it suitable for the design of a fully integrated applications(Toh et al., 1998). Standards have capability to represent the common information that is requires to execute and control product creation processes. These are generally the product information model that defines the design specification, the process information model that define the process planning requirement and the manufacturing information model which relates to the process capabilities. However, there is interrelation between the product, process and resource models components of standards. The product information supports the identification of design requirements, while the determination of the required process plan is supported by the process model; subsequently the manufacturing information facilitates the optimisation of the design specifications and other applicable processes. The integration of these interrelated models into a unified information model has been facilitated by modelling tool such as the EXPRESS language (ISO 1992 – part 11) which supports structured object-oriented representation of interrelated product creation processes information and data.

5.3.1 **The need for standard compliant product creation approach**

Standards in integrated product creation have become increasingly important in manufacturing industry as complex information are digitally communicated within manufacturing facilities and between collaborating manufacturers (NIST, **2002**).

Implementation of manufacturing standards to support seamless exchange of information across the product creation network has enables manufacturers' to increase interoperability and integration of product creation processes for agile response to market(Newman et al., 2007). Modern manufacturers need standards mainly because with digitised information being continually exchange across the CAx chains during product creation processes, a common communication format for the various CAx is vital for efficient exchange of information.

The term Standards in this thesis is a reference to a group of standards, as a single technology, that enables product design, process planning and manufacturing resource representation. For instance, the Standard for the Exchange of Product model data (STEP) supports the information exchange of product design in the form of solids model and a variety of other technical information among computer aided systems (CAx) software (ISO 1994). Process improvement role of standards in facilitating adequate integration and interoperability for product creation processes improvement in CNC manufacture have been reported by researchers (Hardwick, 2002b, Hardwick, 2002a, Venkatesh et al., 2005, Suh et al., 2002b, Suh et al., 2003, Newman et al., 2003, Allen et al., 2005, Nassehi et al., 2006b, Newman and Nassehi, 2007). The economic argument for implementation of manufacturing standards were also made in a 2001 report on US manufacturing industry. The report indicated that while $928 (£596) million per year could potentially be save through reduction in interoperability and integration problems, only about 17% ($156 million) of the quantified potential benefit of STEP were being realised (NIST, **2002**). Previous report that focus on the US automotive sector shows that manufacturers spent considerable amount every year to resolve integration and interoperability problems, around 50% of which was linked to addressing file and information exchange issues (NIST, 1999).

This research aims to improve cost information feedback process across product creation lifecycle by implementing standards to enable full integration of costing system with other manufacturer's CAx chain. The reported ability of the Initial Graphics Exchange Specification (IGES), ISO 10303 (STEP) and ISO 14649 (STP-NC) to facilitate system integration and interoperability in CNC manufacture provide helpful basis for current research.

5.3.2 **IGES**

As manufacturing practices continue to increase in complexity and scope, the need for more and various computer aided systems that utilised proprietary data models to support complex representations of real world objects also increases. In the late 1970's the need to exchange digital information representing design objects between proprietary Computer Aided Design (CAD) systems led to the first efforts to standardised product creation that resulted in the development of the Initial Graphics Exchange Specification (IGES) (Parks, 1984). In 1988, the US department of defence requirement that all collaborating manufacture must deliver electronic drawings of their designed systems in IGES format increases the standards adoption (DOD, 1992). While IGES has proved successful as standards for information exchange, being designed mainly for sharing design information meant its application is limited to the early stage of product creation lifecycle (PCL). As the limitation of IGES became apparent, the lesson learnt from the implementation were leveraged to formalise, the ISO10303 standards (STEP), a more robust product information model (ISO (1994)). The influential U.S. Product Data Association (US Pro) indicated that the IGES 6.0 release will probably be the last IGES upgrade after which focus will shift to improving the STEP standards (US Pro, 2002).

5.3.3 **ISO 10303 (STEP) standards**

The ISO10303, informally known as the Standard for the Exchange of Product model data (STEP), is an evolving international standard that has been developed to provide detailed, digital specification and functional characteristics of a product throughout its life cycle (Eastman, 1999). Literature shows that STEP has strongly contributed to research in the specification of product information. The standards object-oriented EXPRESS format supports complete and unambiguous representation of product geometrical information, such as constructive solid geometry (CSG), boundary representation (B-Rep), or feature-based representation. STEP also provides a clear distinction between the information model and the implementation method; this allows the organisation of product data into a unique set of entities for a specific product, process, or operation. As a result, richer product information can be exchanged consistently across the product creation lifecycle. The capability of STEP information models to support the design for manufacturing in a virtual enterprise have been demonstrated by researchers (Giachetti, 2004).

Although the specification of STEP is in the form of a standardised information model designed to be independent of proprietary computer languages or applications, the standard require the implementation of distinct file exchange format derived from an information model formally specified in EXPRESS computing language (ISO 1994). As a result the standards comprised of various parts with designated part number in the form "ISO10303-partnumber". For instance, ISO10303-203 and ISO10303-204 are CAD information exchange standards that were the first parts in STEP to be completed, followed by the development of manufacturing information exchange protocols. Table 5.1 list the STEP’s parts that are of interest to this research objectives.

Table 5.1 - A list of STEP parts within the scope of research

Description methods	
Part 11	EXPRESS language reference manual
Implementation methods	
Part 21	Clear text encoding of the exchange structure
Part 22	Standard data access interface specification
Part 23	C++ language binding of the standard data access interface
Part 24	C language binding of the standard data access interface
Part 27	Java TM programming language binding to the standard data access interface with Internet/Intranet extensions
Part 28	XML representation for EXPRESS-driven data
Application protocols (APs)	
Part 203	Configuration controlled design.
Part 204	Mechanical design using boundary representation
Part 214	Core data for automotive mechanical design processes
Part 224	Mechanical product definition for process plans using machining features
Part 238	Application interpreted model for computer numeric controllers

(i) ISO10303-11: EXPRESS language

The EXPRESS language (ISO (1994))(part 11) is used as the main description method for the data models within the STEP framework. EXPRESS is a data modelling language that utilises Object Oriented like concepts to allow modelling of domains within the field of product data.

Thesystemprotocols or APs models‟ are defined using EXPRESS schemas. The fundamental constructs in EXPRESS are entities and types. Table 5.2 shows the definition of an entity with EXPRESS. Entities are useful for complex representation of data as their instances have identifiers and they allow depiction of subtype/supertype objects relations.

Table 5.2 - Entity definition in EXPRESS

```
ENTITY drilling_type_operation (* m0 *)
ABSTRACT SUPERTYPE OF (ONEOF(drilling_operation, boring_operation,
back_boring, tapping, thread_drilling))
SUBTYPE OF (milling_machining_operation);
cutting_depth: OPTIONAL length_measure;
previous_diameter: OPTIONAL length_measure;
dwell_time_bottom: OPTIONAL time_measure;
feed_on_retract: OPTIONAL positive_ratio_measure;
its_machining_strategy: OPTIONAL drilling_type_strategy;
END_ENTITY;
```

(ii) ISO10303-21: Clear Text Encoding of the Exchange Structure

Part 21 (ISO 1994b) of STEP is the implementation method that describes how a valid population of a specific domain within the standard can be presented using an ASCII file. The file starts with a header section followed by a data section. The header contains information about the creation of the file: names of the creators and dates of modifications. The data section contains the instances of the entities representing the population. Each entity instance is preceded by a hash number that is used to refer to that instance where needed. Table 3.3 shows an excerpt of a part 21 file.

Table 5.3 - ISO10303-21 Excerpt

```
DATA;
#1=PROJECT('SAMPLE PROJECT',#2,(#3),$,$,$);
#2=WORKPLAN('MAIN WORKPLAN',(#6,#7,#8,#9,#10,#11,#12,#13,#14,#15),$,$,$);
#3=WORKPIECE('SIMPLE WORKPIECE',#4,0.010,$,$,#52,());
#4=MATERIAL('ST-50','STEEL',(#5));
#5=PROPERTY_PARAMETER('E=200000N/M2');
#6=MACHINING_WORKINGSTEP('WS ROUGH POCKET 1',#53,#16,#21,$);
#7=MACHINING_WORKINGSTEP('WS FINISH POCKET 1',#53,#16,#22,$);
#8=MACHINING_WORKINGSTEP('WS ROUGH POCKET 2',#53,#17,#23,$);
#9=MACHINING_WORKINGSTEP('WS FINISH POCKET 2',#53,#17,#24,$);
#10=MACHINING_WORKINGSTEP('WS DRILL HOLE 1',#53,#18,#25,$);
#11=MACHINING_WORKINGSTEP('WS REAM HOLE 1',#53,#18,#26,$);
#12=MACHINING_WORKINGSTEP('WS DRILL HOLE 2',#53,#19,#27,$);
#13=MACHINING_WORKINGSTEP('WS REAM HOLE 2',#53,#19,#28,$);
#14=MACHINING_WORKINGSTEP('WS DRILL HOLE 3',#53,#20,#29,$);
#15=MACHINING_WORKINGSTEP('WS REAM HOLE 3',#53,#20,#30,$);
#16=CLOSED_POCKET('POCKET 1',#3,(#21,#22),#60,#54,(),$,#36,$,$,#37);
#17=CLOSED_POCKET('POCKET 2',#3,(#23,#24),#62,#55,(),$,#36,$,$,#38);
#18=ROUND_HOLE('HOLE 1',#3,(#25,#26),#64,#56,#31,$,#35);
#19=ROUND_HOLE('HOLE 2',#3,(#27,#28),#66,#57,#32,$,#35);
#20=ROUND_HOLE('HOLE 3',#3,(#29,#30),#68,#58,#33,$,#35);
```

(iv)systemprotocols in STEP

STEP conceptual information model is primarily a logical combination of defined Aplication Protocol (AP) that specifies: (1) a portion of the data in STEP which describes the information structures and their relationships in the context of a particular type of system(Palmer and Gilbert, 1993) and, (2) the constraints on how the information is to be used based on the product data requirements for the application area. These specifications are intended to permit product information to be seamlessly exchanged or shared between proprietary systems. An Applicationprotocol (AP) consists of two types of information models:

- The Aplication Reference Model (ARM) that specifies the information requirements of the AP in terms familiar to domain practitioners.

- Application Integrated Model (AIM) that specifies the requirements of the application but is integrated with other APs in STEP

Each AP is referenced in relation to the corresponding part number in STEP. For instance, AP238 refers to ISO10303-238 (STEP's part 238) that was designed as the applicationprotocol for using STEP in exchanging information in the CNC domain (ISO (2007)). Other protocols mainly used to described part design but referenced within the other protocols of STEP such as AP238 are: AP203 (ISO 2005), AP204 (ISO 2002), AP214(ISO 2003) and AP224 (ISO 2006). Together, this APs are the basis for various representation of product creation (PCP) information that ranges from vertices and lines in AP203 to manufacturing features in AP224. STEP also includes another general information models known as Integrated Resources (ISO (1992)) that is AIM specification libraries for supporting various application.

5.3.4 **ISO 14649 (STEP-NC)**

ISO14649 (STEP-NC) was developed as a neutral language, based on the STEP standard, to extend support for seamless information exchange to the process planning and manufacturing stages of product creation lifecycle (ISO (2000)). STEP-NC standardizes the information describing the various product creation processes in integrated CNC manufacture. The standards came out of a project developed under the International Standards (ISO) technical committee TC184 in the sub-committee SC1 and SC4. The STEP-NC as it is known in Europe and Asia, Super Model in the USA, has a data structure that is developed by extending the STEP product data model to include representation of process planning and manufacturing processes (Allen et al., 2005), thereby improving the integration of the various CAx systems employed in CNC based product creation environment. In a STEP-NC compliant product creation environment the various CAx applications are fully integrated and interoperable via the unified (product, process and manufacturing) data model. This enables support for information and knowledge sharing across the product development stage through to manufacture (Newman, 2004). A comprehensive review on the STEP-NC standard and its development has been provided in literature (Xu and He, 2004) and review of researches that implemented the standard for process improvement in CNC manufacture is provided in this section after discursion on the standards constituent parts that are within the scope of this research.

a) A list of STEP-NC parts in CNC research

The ISO14649 EXPRESS schema definition contains entities and types but the relationship definitions are covered in the AIM and are part of STEP's AP238. A valid representation in STEP-NC standard contains design geometry, process plans and manufacturing resources information packaged in "workingsteps". STEP-NC is comprised of the following various parts that individually deals with a specific CNC technology:

(i) ISO14649-1: Overview and fundamentals

ISO14649-1 contains the overview and fundamental principles for the standard. This part of the standard serves as an introduction and establishes the context and the domain of the standard. It does not contain any formal EXPRESS definitions and therefore does not include a machine readable component.

(ii) ISO14649-10: Generic process data (ISO2004)

Part 10 of the standard contains representation models for generic process data. The entities in this part of the standard are process and technology independent. Entities like manufacturing features, general program structure definitions and workinsteps are defined within the EXPRESS schema for this part of the standard.

(iii) ISO14649-parts 11 (ISO2004a), 12 (ISO2005), 13 & 14 : Process specific data

ISO14649-parts 11, 12, 13 and 14 contain constructs for representation of process specific data related to milling, turning, wire-EDM and sink-EDM respectively. These parts of the standard contain entities describing the manufacturing process. They can thus be utilised to represent generic process plans for a product given that the process used to manufacture the part is known. Parts 13 and 14 are still in draft stages.

(iv) ISO14649-parts 111 and 121 (ISO2004b, ISO2005a): Tools

ISO14649-parts 111 and 121 contain entities to describe manufacturing tools for milling and turning respectively. Currently part 121 has been released as an international standard and part 111 is a final draft.

(v) ISO14649 part 16: Inspection

ISO14649-part 16 embodies the process specific data for measurement operations and is currently under development.

In chapter 6, a detail explanation of the ISO 14649 (STEP-NC) standard and its enabling entities in relation to costing process within the scope of this research has been presented. Researchers have proposed the use of STEP and STEP-NC standards to improve CAx integration and interoperability for efficient product creation (Xu and He, 2004, Xu et al., 2005, Nassehi et al., 2006b) and the costing (Fischer et al., 1994) processes in CNC manufacture

b) Review of STEP-NC based solutions in CNC manufacture

The STEP-NC comprehensive information contents and its facilitation of bi-directional information flow between CAx systems has been the basis of researches to improve CNC manufacturing process (Suh et al., 2002b, Suh et al., 2002c, Newman et al., 2003, Rosso et al., 2004, Nassehi et al., 2006c, Heusinger et al., 2006, Kumar, 2008, Vichare et al., 2009, Zhang, 2012). STEP-NC compliant manufacturing improves manufacturing systems integration/interoperability and modelling of product creation information to support flexible, agile and global manufacturing paradigms that reduce product creation cost and lead time to market (Xu and He, 2002, Xu and He, 2004, Xu et al., 2005, Xu and Newman, 2006, Newman et al., 2007, Newman et al., 2003).

Weck *et al.* (2001) provided an overview of ISO 14649 (STEP-NC) standard in relation to milling technology and CNC machine programming alternatives(Weck et al., 2001). This research identified bi-directional information transfer, easier object-oriented programming of manufacturing resources and feature-based processes as the key advantages of STEP-NC.

Hardwick (2004) conducted a review of data exchange standards for computer aided systems (CAx) that place STEP-NC within its context to facilitate exchange of manufacturing information between systems in a manner similar to transfer of CAD information with IGES and STEP (Hardwick, 2004). A practical implementation that investigate potential improvement to a shipyard's manufacturing processes shows that utilisation of STEP-NC brings about significant reduction in production time (Hardwick et al., 2005).

Ali *et al.* (2005) implemented STEP-NC (ISO 14649) in conjunction with AP219 to provide a milled component inspection framework the capability for close loop exchange of bi-directional standardised measuring and inspection information across the product creation chain (Ali et al., 2005) .

Nassehi *et al.* (2006a) explored a novel concept based on STEP-NC standard that incorporate mobile agents to realise the interoperability in a global manufacturing environment and the system's functionality was demonstrated using mobile agents based multi-agent system prototype(Nassehi et al., 2006a).

Wang and Xu (2004) investigated thesystemof STEP-NC and AP238 as medium for linking CAPP with CNC (Wang and Xu, 2004). AP238 was used as the information model for a generic STEP-NC information that is hardware-independent. The STEP-NC file was then employed to convey "machine specific" manufacturing information. The implementation of the research on enabling high-level integration and interoperability was later considered in the expanded work (Wang et al., 2006).

Brecher *et al.* (2006) presented a software prototype for the integration of measuring technology into STEP-NC compliant product creation environment to preserve the manufacturing process as a set of data the can be fed back to the job planning stage (Brecher et al., 2006).

Wosnik *et al.* (2006) presented a generic method for bi-directional transfer of process data from servo drives to CNCs and CAPP systems by using application-dependent algorithms to drive signals for both, online and offline optimization of machining processes (Wosnik et al., 2006).

Zhang *et al.* (2006) proposed a promising view for an autonomous STEP-NCsystemin product development process. The proposed framework present autonomous manufacturing decision making based on system configuration (Zhang et al., 2006). The framework was reported for its potential to enhance system integration and interoperability due to its capability to use similar input for alternative manufacturing resources.

Gang *et al.* (2006) presented XML as a suitable file format for online communication of STEP-NC information to enhance digital manufacturing(Gang et al., 2006). Digital manufacturing afford manufacturers the benefit of globally distributed product creation process and successful implementation of a seamless data transfer format that is necessary to realise the full potential of collaborative product creation process was presented.

Xu (2006a) implemented a web-enabled STEP-NC compliant manufacturing framework to demonstrate the role of STEP-NC in product creation process and its applicability for communicating generic and interoperable manufacturing information along the entire stages of PCP (Xu, 2006a). In this research, STEP Tools were used to read and process STEP-NC information. The research concluded with the generation of resource specific low-level information based on the manufacturing information contained in STEP-NC.

Nassehi et al.(2007) developed a novel software platform called Integrated Platform for Process Planning and Control (IP$_3$AC) to support STEP-NC compliant process planning (Nassehi et al., 2007). IP$_3$AC provides a fully object-oriented encapsulation of ISO 14649 information that facilitate the expansion of the upper process planning system to handle more complex product with little or no change to the platform itself. The research was later extended to develop a universal manufacturing platform (Newman and Nassehi, 2007).

Newman and Nassehi (2007) proposed a Universal Manufacturing Platform (UMP) using STEP-NC as the enabler to realise a standardised information communication platform for various computer aided systems (Newman and Nassehi, 2007). The UMP function as a manufacturing knowledge and information support system that enables bi-directional information exchange among product creation CAx chain and other business application, such as costing systems, employed in CNC manufacture. Figure 5.6 show the following functional components of the UMP: 'manufacturing data warehouse' for storing standardised (STEP-NC) manufacturing information; 'manufacturing knowledge base' for housing the necessary conceptual transformation that enabled information exchange among employed computer aided systems (CAx); the 'intercommunication bus' that provides mobile agent based messaging system to facilitate inter-CAx communication and CAx-manufacturing data warehouse-manufacturing knowledgebase communication and; the 'manufacturing Systems interfaces' that utilised a subset of knowledge representation in the platform knowledgebase to interpret messages coming from different manufacturing systems. A systematic roadmap, based on Axiomatic Design methodology, for implementation of UMP has been proposed by other researchers (Mokhtar and Houshmand, 2010).

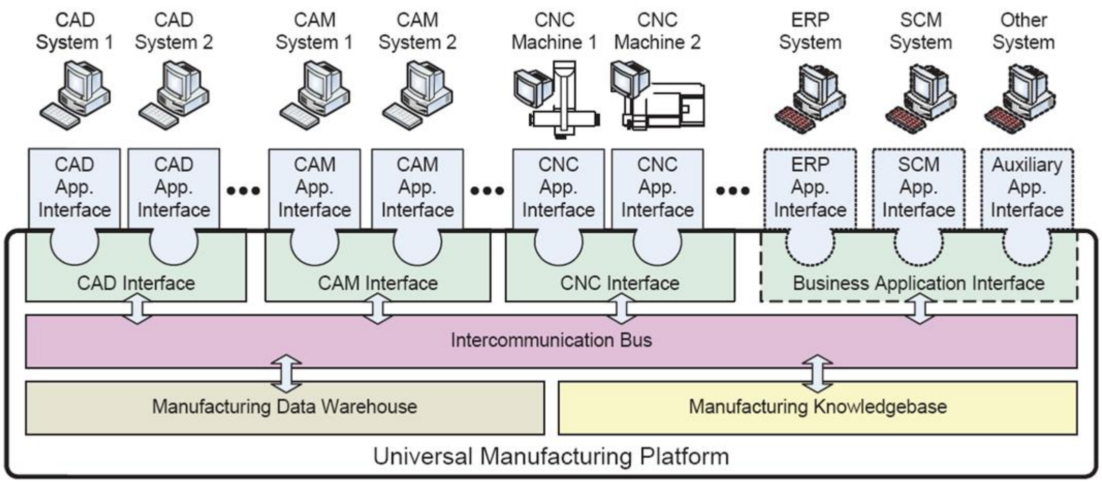


Figure 5.1 - The Universal Manufacturing Platform

(Newman and Nassehi, 2007)

This thesis section has identified various research that have implemented the ISO14649 (STEP-NC) standards to improve product creation process in CNC manufacture. Table 5.2 presents these papers and categorises them based on the manufacturing technology in the paper and the focus of CNC manufacture process improvement. The reviewed literature reported the viability and benefits of utilising STEP-NC for process improvement in integrated manufacturing environment. However, researchers have not implement STEP-NC for process improvement in the manufacturing costing (product cost estimation) domain.

Table 5.4 - STEP-NC based researchs in CNC manufacture

Paper reference	Technology			Process improvement focus		
	Mill	Turn	Other	CAx Chain integration	Information modelling	Data exchange platform
(Weck et al., 2001)	☑			☑	☑	
(Wang and Xu, 2004)	☑			☑		
(Nassehi, 2007)	☑			☑		☑
(Wang et al., 2006)	☑			☑		
(Vichare, 2009)					☑	
(Zhang et al., 2006)				☑		
(Zhang, 2012)	☑			☑		☑
(Kramer et al., 2006)				☑	☑	
(Gang et al., 2006)				☑		
(Xu, 2006a)	☑			☑	☑	
(Suh et al., 2002b)	☑			☑		
(Suh and Cheon, 2002)	☑			☑	☑	
(Suh et al., 2003)	☑				☑	
(Lee and Bang, 2003)	☑				☑	
(Lee et al., 2006)	☑				☑	
(Amaitik and Kilic, 2007)	☑			☑	☑	
(Rosso et al., 2004)		☑			☑	
(Xu and He, 2004)		☑		☑		
(Xu, 2006b)		☑		☑		
(Suh et al., 2006)		☑			☑	
(Choi et al., 2006)		☑				☑
(Heusinger et al., 2006)		☑		☑		☑
(Shin et al., 2007)		☑			☑	☑
(Suh et al., 2002c)			Insp		☑	

(Ali et al., 2005)			Insp		☑	
(Brecher et al., 2006)			Insp	☑	☑	
(Wosnik et al., 2006)			Insp	☑	☑	
(Zhao et al., 2008)			Insp		☑	
(Kumar, 2008)			Insp	☑	☑	
(Sokolov et al., 2006)			WEDM		☑	
(Ho et al., 2005)			WEDM		☑	
(Ryou et al., 2006)			RP	☑		
(Bi et al., 2006)			Grdn			
(Stroud and Xirouchakis, 2006)			AShp		☑	

Technology abbreviation:

Insp = Inspection; WEDM = Wire Electro Discharge Machining; RP = Rapid prototyping; Grdn = Roll Grinding; Ashp = Aestetic shape

6 A framework for information rich costing

6.1 Introduction

A framework for the realisation of manufacturing standards based costing methods has been presented in this chapter. The limitations identified in section 4.6 have been used to develop a set of requirements for the standard compliant costing framework and the framework functionalities have been designed based on the identified requirements.

6.2 Vision for a unified costing system in CNC manufacture

The author defines standards compliant costing in CNC manufacturing as: *the 'implementation of information rich unified model to provide detailed and actual data for generation of cost information feedback across the product creation lifecycle.*

As discussed in chapter 5 effective and accurate product cost estimation (costing) is critical to the profitability of a new product and the success of manufacturing company. However, the inability of existing costing system to access actual product, process and resource information for detailed costing often makes consistent and reliable estimate a difficult task. The author's vision for achieving effective and reliable costing is to utilise internationally recognised manufacturing standards, which provides unified representation of actual product design, process planning and resources information, as the source of detailed information for cost estimation generation. The proposed method aims to address the inherent challenge of lack of actual detailed information for reliable product and process costing in integrated product development environment. Also, it aims to enables the automation of costing process, as actual cost driving parameters output of various CAx are seamless accessible for cost analysis without the need for manual inputs or expert knowledge.

In CNC manufacture, a manufacturing platform is any computational application that provides a communication mechanism to enable exchange of standardised information among different computer aided systems (Newman and Nassehi, 2007). The architecture of manufacturing platforms has the potential to make detailed PCL information accessible for cost analysis because it facilitates effective linking of product creation and company specific information with applicable manufacturing resources. To make effective use of manufacturing platform's standardised information model for cost analysis, it is necessary to develop a standard compliant costing methodology for identification and retrieval of the actual cost parameters that are contained within a standard information model.

In this regard, a framework for a standard compliant costing system that is fully integrated with other manufacturers CAx has been developed. Figure 6.1 illustrates the full integration of a costing system with manufacturers CAx chain based on a STEP-NC compliant manufacturing platform. This framework bridges the gap between lack of access to detailed information and generation of reliable cost estimate by using a manufacturing platform's standardised representation of the integrated CAx information outputs for cost analysis.

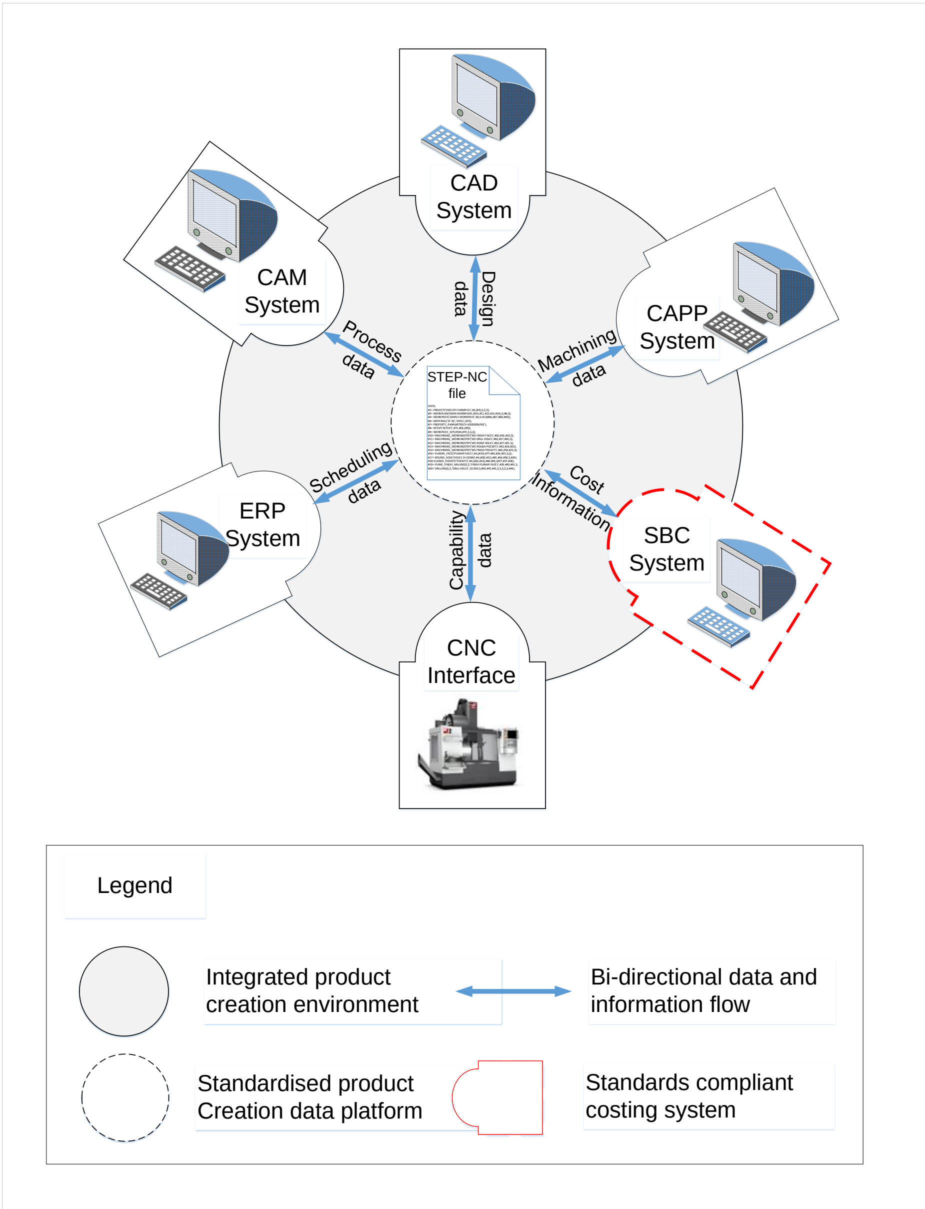


Figure 6.1 – High level integration of costing system with product creation CAx chain (Newman and Nassehi, 2007)

6.3 Information requirement for cost estimation in CNC manufacture

It is generally accepted that a major cause of inaccuracies in cost estimation is lack of detailed information. In other words, in the context of CNC manufacture, the availability of product, process and resources information is a requisite for generation of reliable and consistent cost estimate. Figure 6.2 shows the category of indentified information that exists in integrated product creation environment, which can be utilised to generate detailed cost estimation in CNC manufacture.

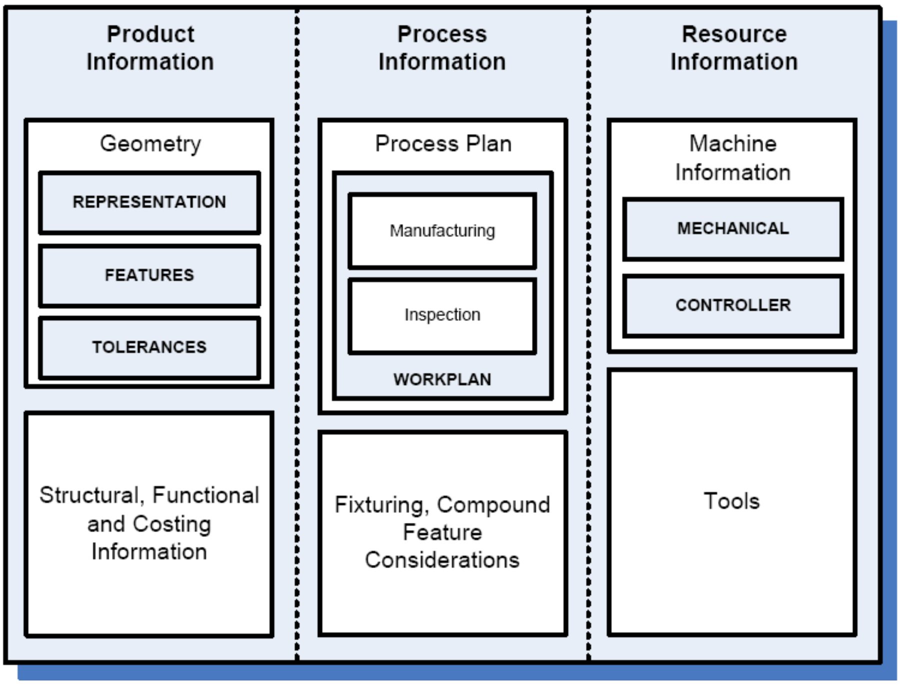


Figure 6.2 - Information category for a milled component in CNC manufacture (Nassehi, 2007)

By utilising detailed information that exist within integrated manufacturing environment, this research has the potential to minimise the extensive data gathering and analysis exercises and, reduce the time and cost investment associated with detailed cost estimation. According to reviewed literature manufacturing standards contains the category of product creation information applicable in cost estimation process. This makes manufacturing standards compliant costing method a viable choice for this research.

6.4 Requirements for standards complinat costing Framework

The identified research gaps in section 4.6 together with the scope and the hypotheses of the research lead to the development of a set of requirements for a novel costing framework capable of utilising the categorised detailed information, that exist within an integrated product creation environment, for cost estimate generation. The requirements that have been determined for the development of an effective framework are as follows:

6.4.1 **Standardisation of product creation information**

Effective cost analysis and generation of reliable cost information feedback across product creation lifecycle requires a costing system capable of accessing and utilising information from CAD, CAM, CAPP systems and digital representation of manufacturing resources. A major hindrance to high level integration of costing system with other product creation CAx chains is the proprietary communication language of individual CAx. This prevents bi-directional exchange of information along product creation CAx chain and restricts access to requisite detailed data, contained in the various CAx vendor specific file format, for reliable cost estimate. Manufacturing standards provides digital representation of product creation process as a neutral file format to support bi-directional exchange of information across integrated CAx chain. The realisation of standard compliant costing framework requires the implementation of manufacturing standards capable of representing the various CAx's information output in a structured and accessible format. This enables full integration of costing system with other product creation CAx chain and provides opportunity to access actual cost information from the product development phase through to manufacture.

The category of product creation information for a milled component that exists in various formats within a CNC manufacturing facility is shown in figure 6.3, to indicate the need for a unified information model that represent product design, process and resource information to support decision making relating to integrated product creation in CNC manufacture. Manufacturing standards has a common source of well defined and structured information capable of satisfying the information requirements needed to carry out detailed costing processes in CNC manufacture. The standards is divided into a number of major parts, for example part 11 of the ISO/DIS 14649 standard (ISO 2004a), that are dedicated to the milling process. Figure 6.3 shows information modelling requirements in CNC manufacture based on unified information models in which the manufacturing intent is located in the product models (PM) to describe the relevant instances of the manufacturing models (MM). This allows the capture of information for an entire product creation processes in such a model, thus promoting the development of a fully integrated and automatic costing system. This is consistent with other researchers' views that the information held in unified models must be made available during product development in order to facilitate integration and interoperable manufacturing in design for manufacture environment (Suh et al., 2002a).

EMBED Visio

.Drawing.15

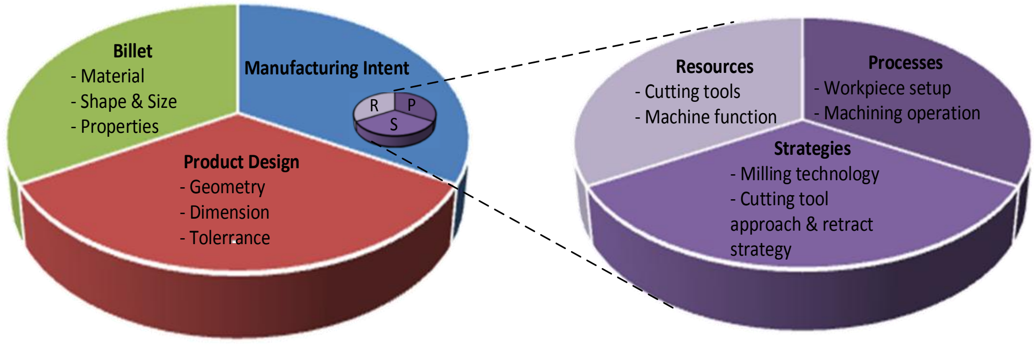


Figure 6.3 – The require information category for detailed costing in CNC manufacture

6.4.2 **The ability to generate cost information from standardised information**

To ensure functionality of the standard compliant costing framework within the manufacturing environment it is imperative that it generates cost information from categorised information that exists across the product creation lifecycle with little or no additional data acquisition. Manufacturing standards represent the categorised information as a single neutral file format, therefore, the framework should be able to utilise a standard file as the source of detailed information for the generation of cost information feedback.

6.4.3 **Object-Orientation**

Object-oriented programming is currently widely adopted for software development as it provides a reusable and consistent model for cognitive real world application(Booch, 1994). An object oriented approach is required to design the standard compliant framework to benefit from the advantages offer by this programming environment. Java is one of the most popular object oriented programming (OOP) languages today as it provides cross-platform portability, that is, the ability to run the same code on different hardware and software platforms. This feature is particularly useful for implementing the framework on commercial operating systems that are widely used in manufacturing industry. This makes Java, the programming language of choice for realisation of this research proposed framework.

6.4.4 **Integration platform**

In order to ensure the availability of high quality product creation data in the unified framework the computer aided systems should be integrated in a way that preserve information integrity across the CAx chain. That is, to make sure that the there is a medium to support by bi-directional exchanges of data among CAx. The framework requires the implementation of a manufacturing platform capable of providing standard compliant information exchange environment.

6.5 STEP-NC as enabler of standard compliant costing framework

As discussed in the preceding section, the development of a standard compliant costing framework requires the implementation of manufacturing standards that is capable of providing product creation information in neutral file format that facilitate bi-directional information exchange. The ISO10303

(STEP) standards are an object oriented information models that has been developed to enable bi-directional exchange of information among CAx and to improve systems integration and interoperability in CNC manufacture. While STEP provides standardised representation of product design information, process and manufacturing resources representation are not adequately supported. The ISO14649 (STEP-NC) standard that built on STEP's functionalities, was later developed to extend the natural format structured representation of product creation information from the early design stage through to manufacture. Its potential to provide detailed structured representation of CNC milled component actual information makes STEP-NC the main focus of this research; as it contains revenant information require to generate detailed cost estimate.

6.5.1 The STEP-NC structure representaion of product creation information

Accessible detailed product creation processes' information is necessary for the development of a costing methodology that is capable of supporting decision alternatives across the lifecycle phases (Blanch et al., 2011, Maropoulos et al., 1999, Garcia-Crespo et al., 2011, Jin et al., 2012, Xu et al., 2012). Manufacturing standards (Cheung et al., 2009, Geiger and Dilts, 1996, Fischer et al., 1994) and STEP-NC in particular (Xu and Newman, 2006, Suh et al., 2002b, Newman and Nassehi, 2007) represent sufficient information that are require to perform detailed costing process. STEP-NC contains structured information contents and semantics (ICS) for a milled part manufacture as shown in Figure 6.4.

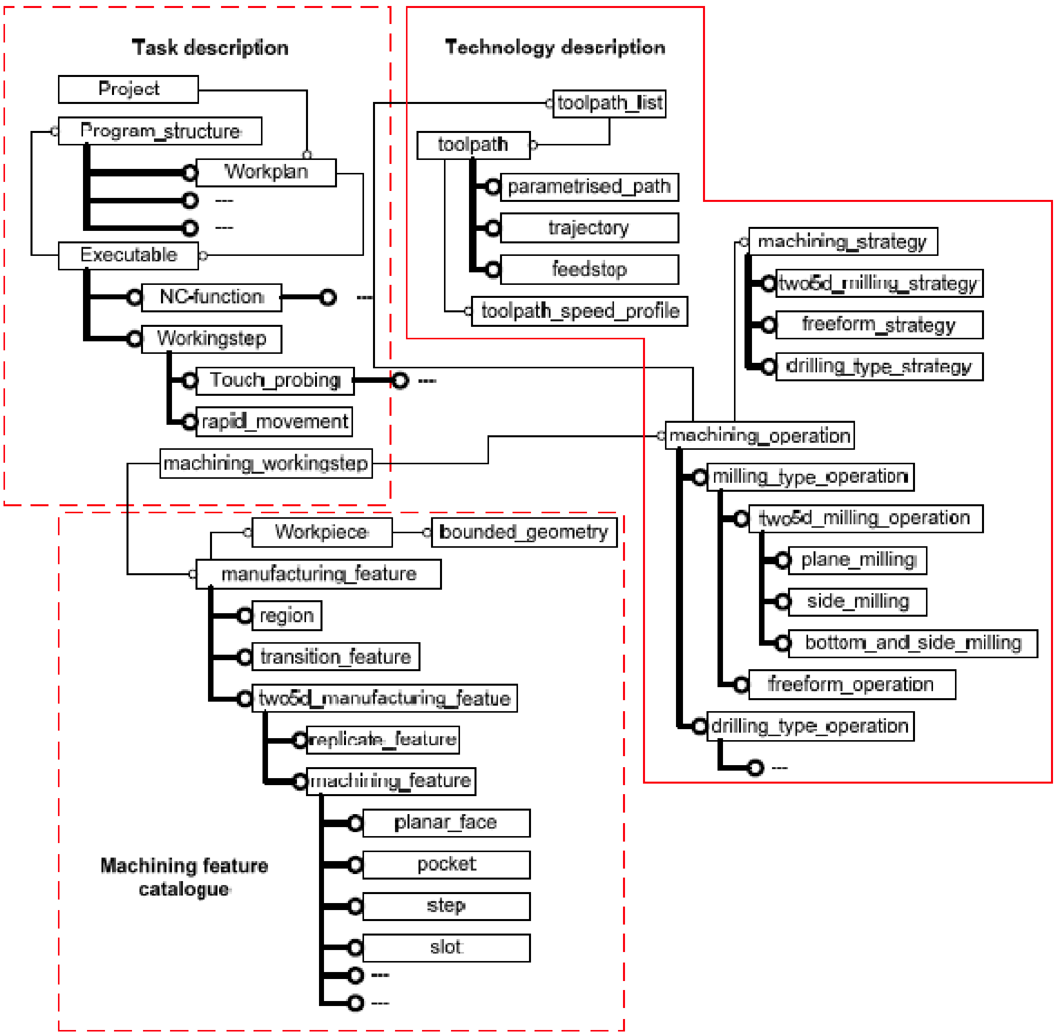


Figure 6.4 - Data structure of ISO14649 (STEP-NC) standard (Suh and Cheon, 2002)

The STEP-NC information contents and semantics provides a unified representation of design, process and manufacturing data models, as neutral file format, that is applicable in standards compliant costing process (Suh et al., 2002a).

(i) STEP-NC representation of product design information

The STEP-NC comprises of a product models that represents the essential properties and characteristics of a part designed for CNC manufacture. These include the representation of the billet, in terms of the material, nominal shape and size, together with the product design in relation to the geometries, dimensions, and tolerances (G, D, and T) of the part to be machined. In addition, a manufacturing view of the part is offered to the PM in order to serve as a means of unifying the PM and the manufacturing model. Since the product model is ultimately used to satisfy the information requirement of the manufacturing process at the later stage of the process chain, it is vital to set it in the context of the selected process to manufacture the part. By doing so, the manufacturing view supports the preliminary and interoperable process planning in the early product development stage in an integrated manufacturing environment. Figure 6.5 shows the data structure of the STEP-NC's product model that offers a manufacturing view of a part. The manufacturing models residing in the product model shares the same data structure, which holds the manufacturing information of the actual system domain. These entities are briefly described as follows:

- **Billet parameters** – the characteristics of the raw material, which have an adverse effect on the selection of cutting parameters (milling technology). Examples include the material and the nominal shape and size.
- **Product design parameters** – the G, D, and T of the part, which have direct influence on the determination of the machining operation and the selection of the cutting parameters. Examples include surface finishing and dimensional accuracy.
- **Manufacturing intent** – the relevant instances of the manufacturing view, which give an early assessment of the manufacturability of the

part and the interoperability of the machining workplan. Examples include interoperable workplan, production history, and manufacturing features.

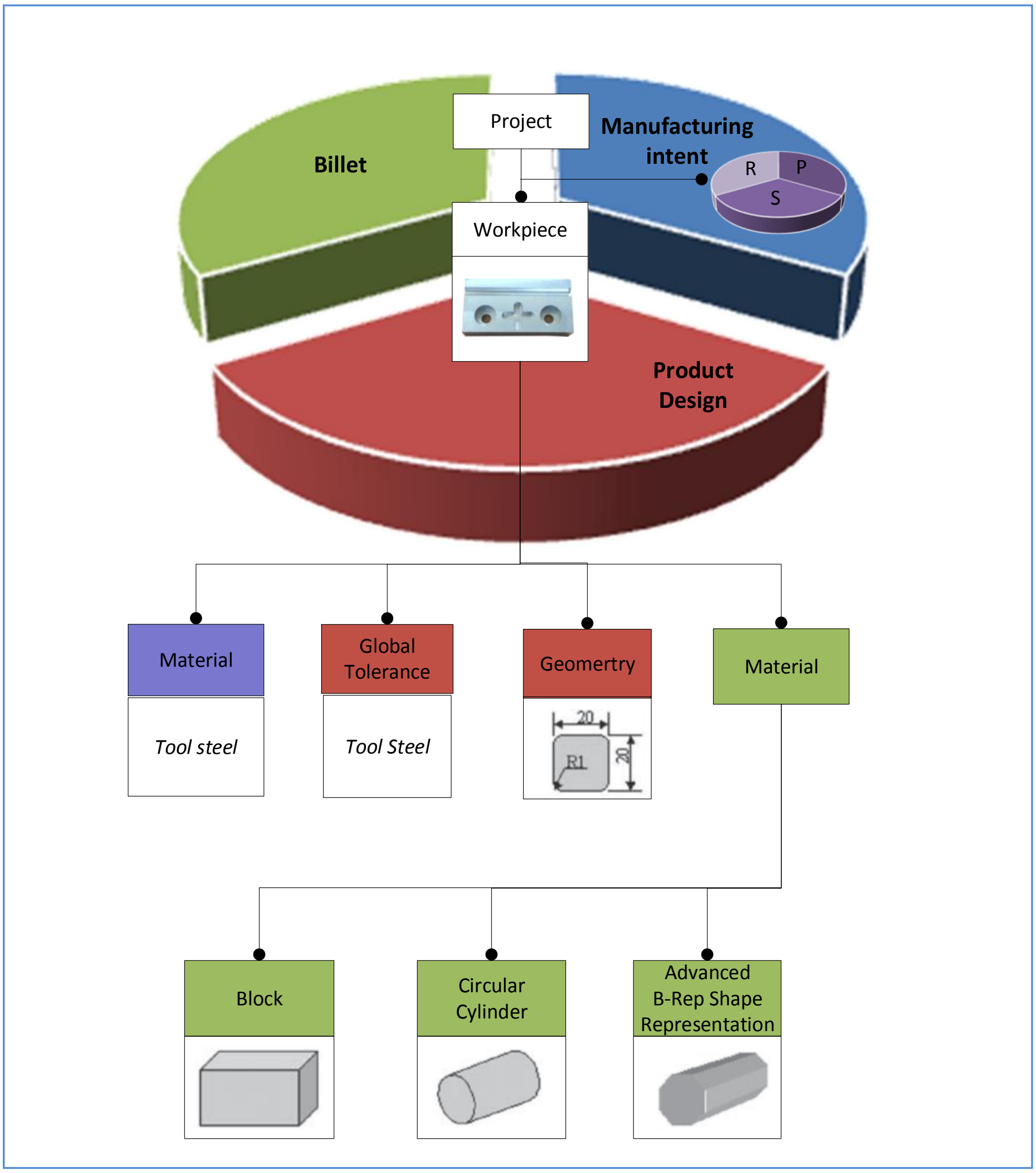


Figure 6.5 - STEP-NC product data representation

(ii) **STEP-NC representation of manufacturing information**

STEP-NC supports digital description of processes, strategies and manufacturing resources that allow economic evaluation of product creation activities by taking a physical (resource) and functional (process) properties perspective of the machining process. It also takes into account the representation of the feasible machining schemes (strategies) based on the composition of the milling resources and processes. This is attributed to differences in milling resources and processes that can directly affects specified milling operation such as the number of cuts required to obtain a desired surface finish. The object oriented organisation of the product creation data in enables selection of appropriate strategies to machine a part based on processes feasible and available resources. Figure 6.6 depicts STEP-NC object-oriented data structure characteristics of processes and manufacturing resources and the entities shown are

- **Resources parameters** – the physical constraints imposed on the milling process to machine a raw material to the required part. Examples include cutting tool and milling machine functions.
- **Processes parameters** – the functional capabilities of the milling process to perform the machining operations. Examples include workpiece set-up and milling machining operations.
- **Strategies parameters** – the machining schemes of the milling process based on the given milling resources and processes. Examples include milling approach/retract strategy and milling technology.

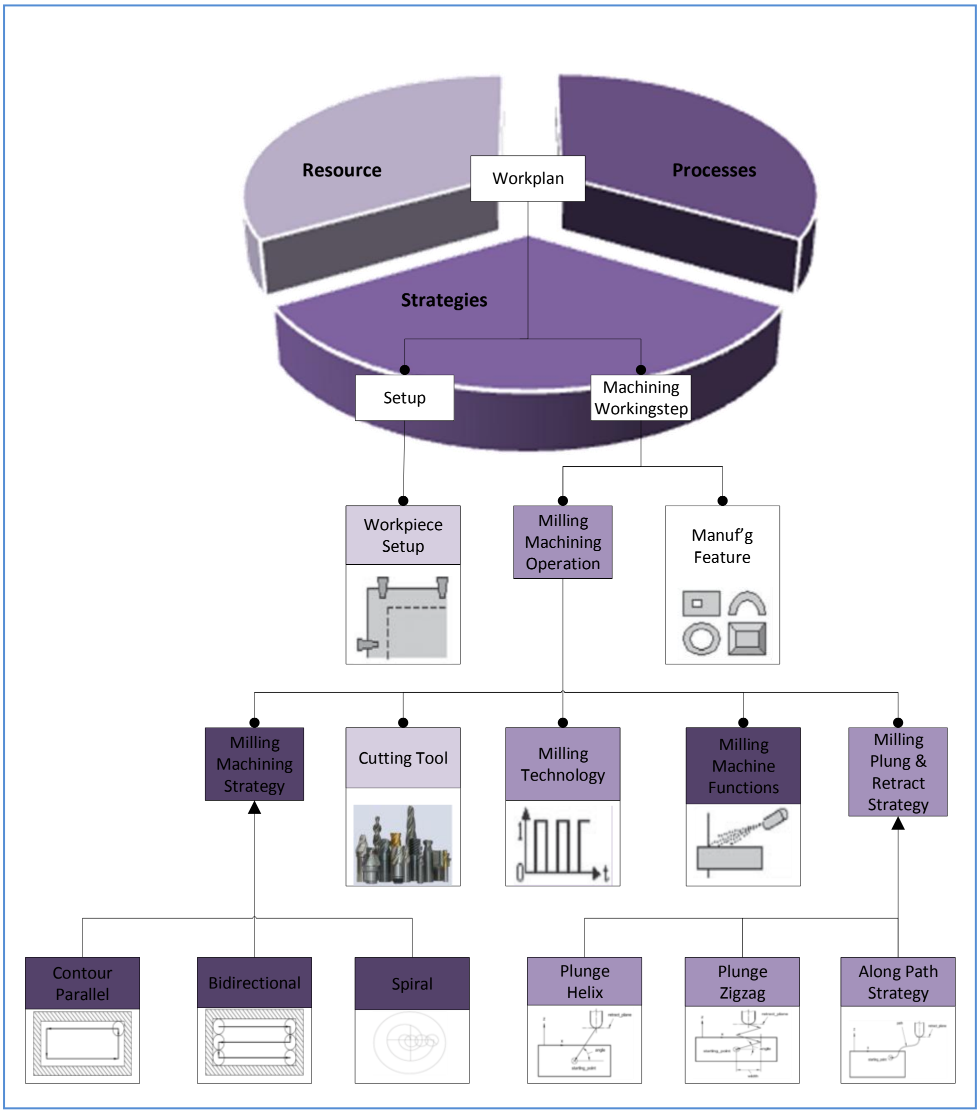


Figure 6.6 - STEP-NC representation of manufacturing information

6.5.2 The STEP-NC facilitation of bi-dircetional information exchange

STEP-NC's neutral file format facilitates bi-directional exchange of information between CAx during product creation process. A key advantage of a bi-directional information flow over the traditional uni-directional flow of information is that the integrity of information is maintained across the product creation lifecycle. From the cost estimation process viewpoint, this ensures that detailed and quality information is available for generation of a reliable cost estimate. Figure 5.4 illustrate increased information availability when the traditional uni-directional information flow is replaced with bi-directional information links across the product creation CAx chain.

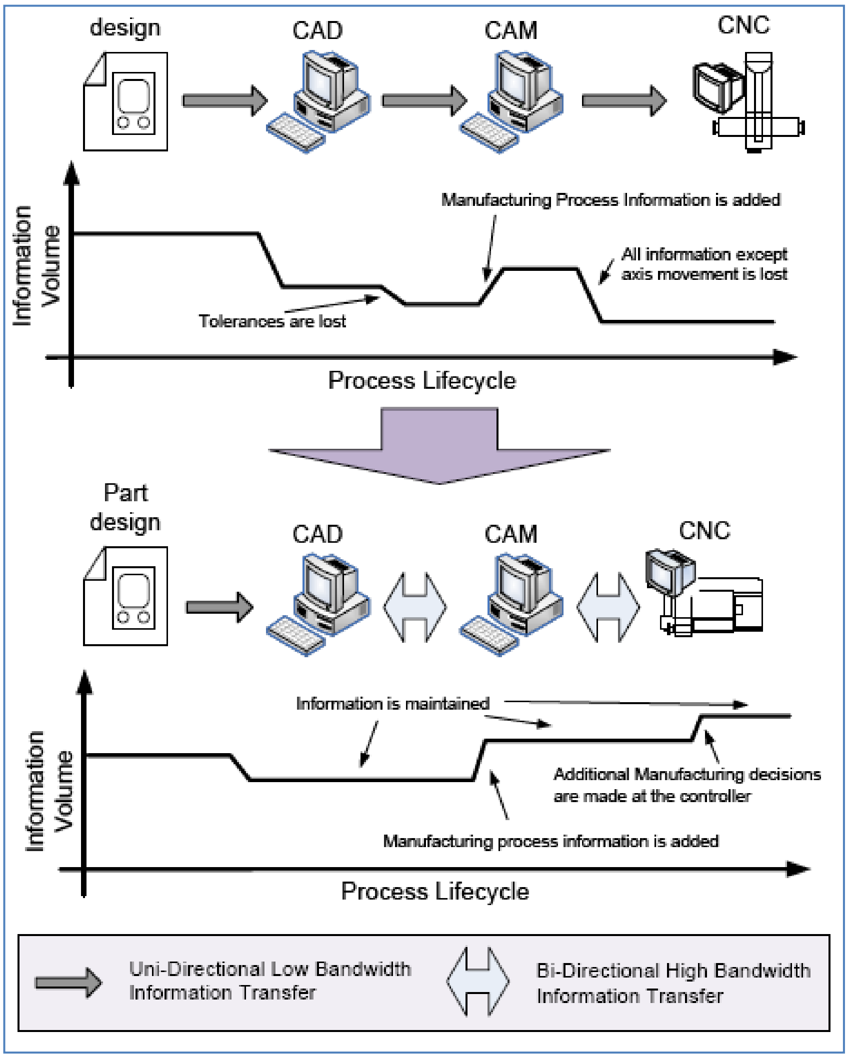


Figure 6.7 – Increasing information in STEP-NC compliant CNC manufacture (Nassehi 2007)

6.5.3 **STEP-NC object oriented schemas**

STEP-NC standard adopt a modelling approach that captures PCP data using domain terminology to maps this data onto a common set of EXPRESS schema. The ISO14949 EXPRESS schema is an Object-Oriented data modelling language (formally defined in ISO10303-11) that contains entities for structured representation of PCP data. The EXPRESS language supports single and multiple inheritances such that a child entity inherits all of its parents' attributes and constraints. Entities are useful for complex representation of data as their instances have identifiers and they allow depiction of subtype/supertype objects relations.

(i) Example entity definition

An entity may provide attributes to another entity thereby extending the "type" construct in EXPRESS. The type construct in provides a means to add semantic meaning to attributes within EXPRESS. The entities definition in a STEP-NC file that consist of three entities: "ENTITY_1", "ENTITY_2", and "ENTITY_3" is illustrated in Table 6.1.

ENTITY_1 has three attributes, one of which is another entity. ENTITY_3 is a subtype of ENTITY_1. This means that an instance of ENTITY_3 will also have three attributes defined because ENTITY_3 inherits all of ENTITY_1's attributes.

Table 6.1 - Example of STEP-NC entity definition

```
ENTITY ENTITY_1;
      ATTRIBUTE_1 : INTEGER;
      ATTRIBUTE_2 : STRING;
      ATTRIBUTE_3 : ENTITY_2;
END_ENTITY;

ENTITY ENTITY_2;
END_ENTITY;

ENTITY ENTITY_3
      SUBTYPE OF(ENTITY_1);
END_ENTITY;
```

(ii) EXPRESS-G representation

The two most common representations of EXPRESS data schemas, that use entities as key construct, are lexical and a graphical. The lexical form presents the physical (ASCII) file format and the graphical form, called EXPRESS-G, consists of semantically defined symbols. Figure 6.8 shows the EXPRESS-G representation of the entity definition illustrated in Table 6.1. Each entity is represented as a texted box with solid borders. The text is the entity's name. The thin lines with circles show entity_1's attribution. These thin lines represent the 'has' a relationship. The thick line between entity_1 and entity_3 shows inheritance. This thick line represents the relationship link between two entities, ENTITY_1 and ENTITY_3 in this case.

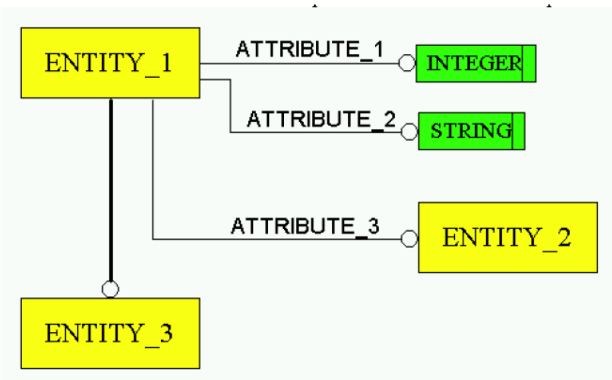


Figure 6.8 - Example EXPRESS-G representation of entity definition

The mapping of data from instances of an EXPRESS into a physical (ASCII) file format for clear text encoding of the exchange structure is the final stage of the ISO 14649 object oriented implementation. The ISO10303-21 (part 21) provides the implementation method that describes how a valid population of a specific domain within the manufacturing standards can be presented using an ASCII file. Detailed explanation on how the STEP-NC object oriented construct support the utilisation of its rich information content for cost estimation process has been provided in chapter 6.

6.6 Standards based costing framework for a CNC milled part

In this section, a framework for a unified cost estimation based on the ISO14649 (STEP-NC) standards and an implementation strategy to develop a costing system capable of utilising the information rich STEP-NC file as sole data source for automatic generation of cost information feedback has been proposed. The term ‘Unified’ in this thesis refers to ability of costing system to integrate with and access information from various CAx in an integrated PCP environment to generate cost estimate. It is thus distinguished from reviewed integrated cost estimation methods and systems that are only capable of partial integration with manufacturer’s CAx chain is possible.

The standard based costing method presented in this thesis is based on the analysis of information contents of the STEP-NC, and cost estimation system role in supporting decision on alternatives during integrated product creation process. It is a method for the next generation manufacturing cost estimation application, which can be implemented in standard compliant enterprise and global manufacturing network.

6.6.1 **Framework overview**

The goal of the STEP-NC standard based costing (SBC) framework is to realise product cost estimation for a prismatic component. It should therefore be able to generate cost information feedback from standardised information model that has been specifically developed for CNC manufacturing process. An overview of the STEP-NC compliant cost estimation framework is shown in Figure 6.9.

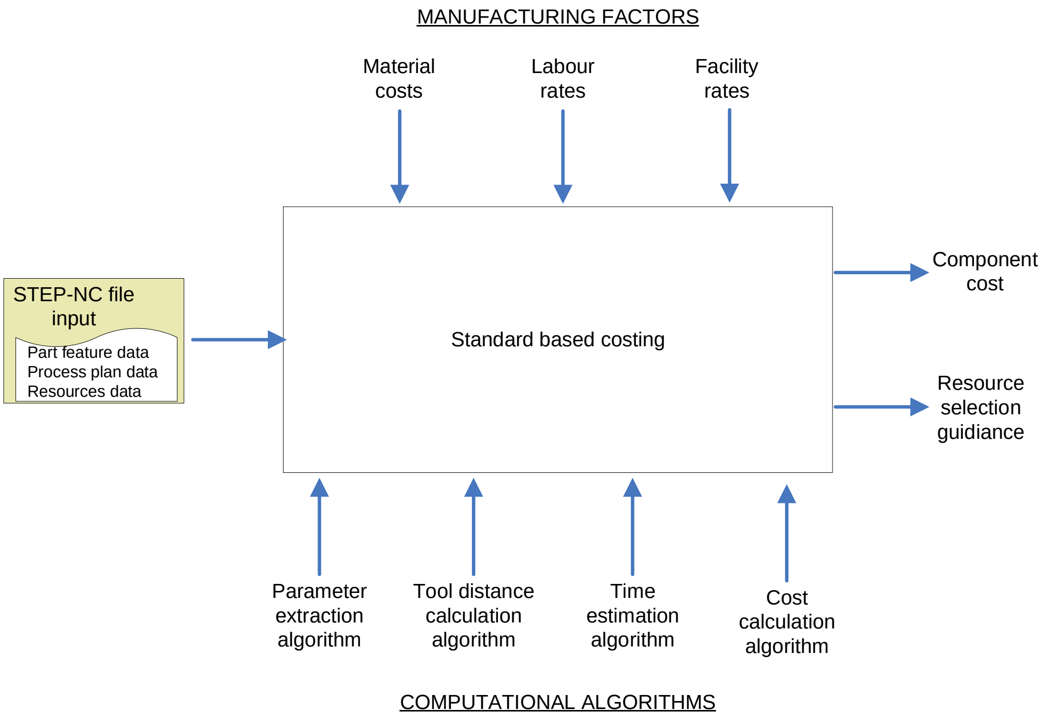


Figure 6.9 - IDEF0 diagram of STEP-NC compliant costing framework

6.6.2 **Framework implementation strategy**

The framework implementation requires three stage sequential transformation of standardise information into cost value. The transformation sequence has been defined into information recognition; parameters acquisition and the estimation stages. Figure 6.10 illustrates the sequence of information transformation to provide cost estimation feedback through the use of the standard compliant framework. The standard compliant costing starts with the information recognition process after a STEP-NC file is presented to the system. This involves the parsing of the neutral file to identify the manufacturing features, process plan and resource information represented in the standard file. This is followed by the parameter acquisition stage where cost relevant parameters are retrieved, from the identified process creation information, and stored for use at the final estimation stage. The stored cost relevant parameters are used to estimate a given component's machining time that is applied to manufacturer's specific labour and manufacturing resources rates to generate cost estimate.

To realise the standard compliant framework, an object oriented program for feature, process and resource information recognition from a standard information model, as well as, algorithms for logical extraction of parameters that are necessary to estimate machining time has to be developed. Finally, methods for calculating the aggregated product cost have to be identified.

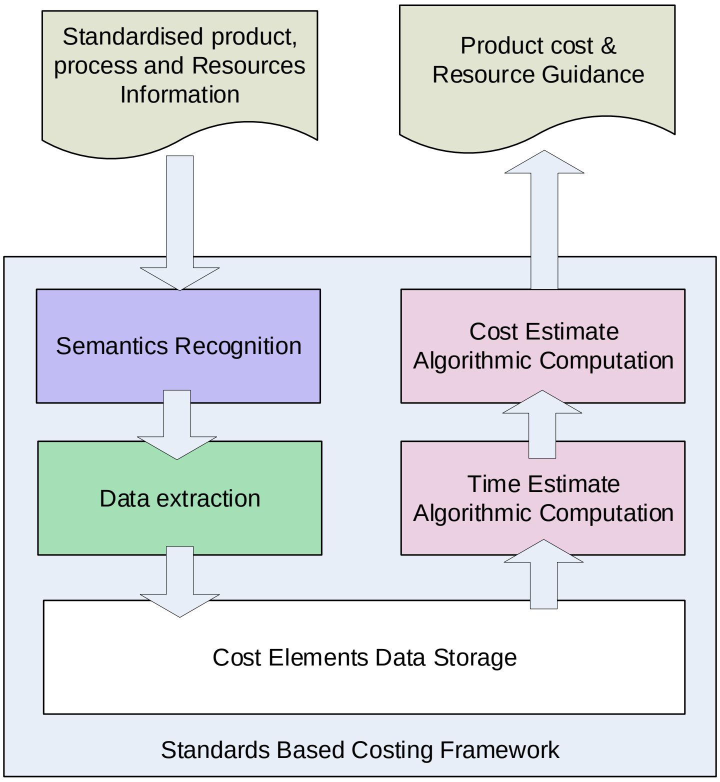


Figure 6.10 - Framework information transformation

6.6.3 **Object oriented platform for STEP-NC compliant costing**

The EXPRESS entities in STEP-NC are defined in object oriented form. To benefit from the advantages provided by the standard's object-oriented structure, it is necessary for an object oriented software platform that facilitates the STEP-NC' entities transformation into applicable cost data is implemented in the framework.

An Integrated Platform for Process Planning and Control (IP3AC) that is capable of encapsulating STEP-NC entities into objects that allows a JAVA program manipulation of standardised information has been developed at the University of Bath(Nassehi, 2007). The data object encapsulation and neutral file structured representation within IP3AC is presented in Figure 6.11. The capability of IP3AC to present STEP-NC data schema as Java classes, its support for object oriented translation of STEP-NC entities and its Java-friendly characteristics makes it a suitable platform for the standards based costing framework.

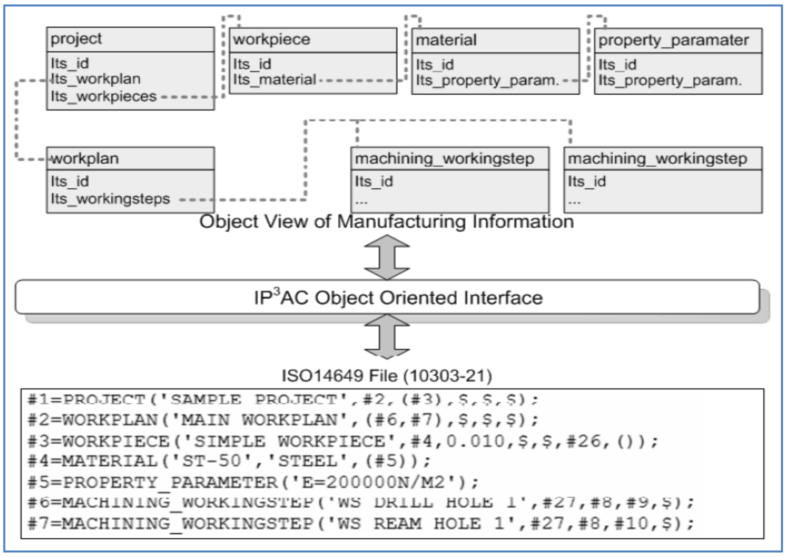


Figure 6.11 - Objects encapsulation of product creation information in IP$_3$AC (Nassehi, 2007)

6.7 Functional overview of the SBC framework

The functional view of the SBC framework is depicted, using an IDEF0 diagram, in Figure 6.12. This figure shows how the computational mechanisms within the framework provide the necessary tools for STEP-NC file transformation and generation of cost information.

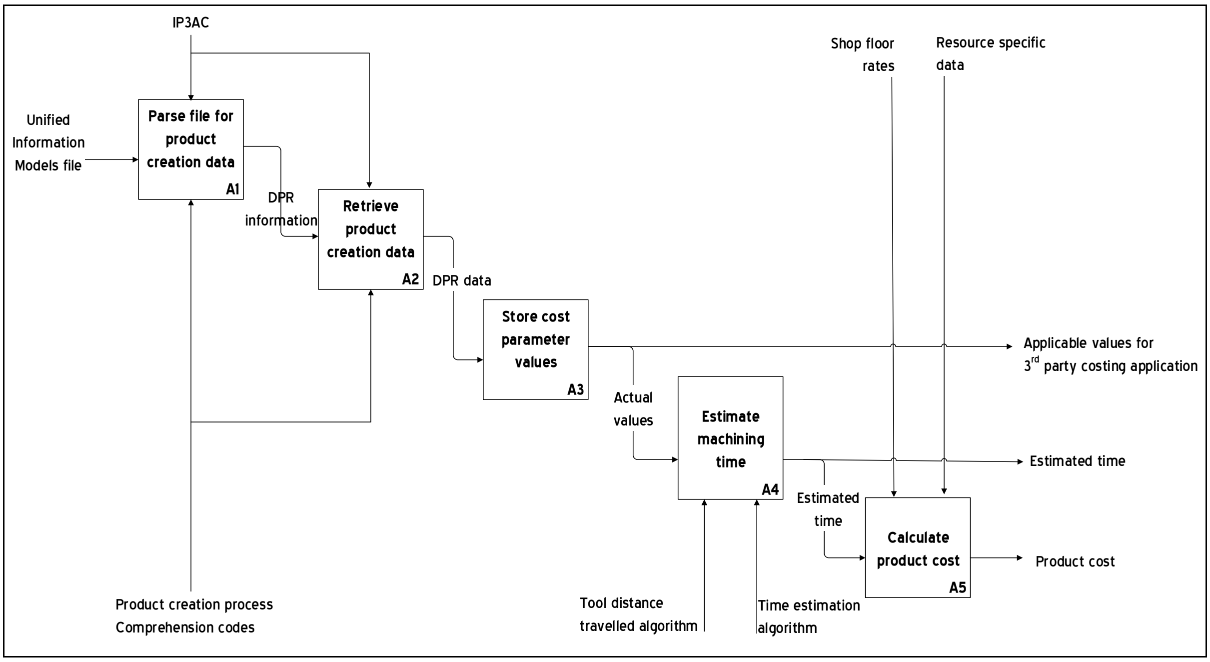


Figure 6.12 – Functional overview of a information model based
Unified costing framework

The product creation process information stored in a STEP-NC file is read and interpreted using an object-oriented programming language. The detailed information is then parsed using standard compliant feature recognition programming to identified product (milled component) features and process plan. An object-oriented programming mechanism is utilised to extract the cost-driver parameter from the identified process plan. Then an algorithm uses the extracted parameters to estimate machining time. Finally, the estimated machining time in conjunction with manufacturer's labour rates and facility rates are used to generate product cost for design, process and resources comparison to support alternative decision.

6.8 Summary

The research needs for the development of a standard compliant costing system for CNC manufacture have been outlined in this chapter. The chapter introduced the authors' vision towards achieving integrated costing in standard compliant product creation environment. The attributes of the STEP-NC standards in terms of its rich information model for product design, machining process and manufacturing resources have been discussed. These characteristics of the STEP-NC standards that form the basis for the development of a standard based costing method (SBC) and a functional overview showing computational mechanisms requirement for the development of the SBC have been presented.

7 Computational platform of SBC

As mentioned in chapters 5, an essential requirement for enabling standard compliant integrated costing is transformation of the standardised information. This transformation will allow object oriented entities conversion into objects data from which parameters that can be utilised for machining time estimation and cost estimate generation are extracted. In order to use the detailed PCP information represented in manufacturing standards to generate reliable cost information, a computational implementation is required. As mentioned in chapter 5, STEP-NC provides detailed and structured PCP information and an object-oriented methodology capable of utilising a STEP-NC file can facilitate the standard compliant costing system. This chapter identifies STEP-NC's entity representation of manufacturing feature, process plan and resource cost relevant parameters that need to be extracted and explained the acquisition process for extraction and utilising the parameters for detailed costing.

This chapter starts with the design specification for an integrated costing system that is based on the internationally recognised ISO14649 (STEP-NC) standards and referred to as SBC Then the STEP-NC's entity representation of manufacturing feature, process plan and resource cost relevant parameters that need to be extracted are identified. In the final part, the SBC system parameters extraction, time estimation and cost calculation process are explained.

7.1 STEP-NC file analysis and SBC conceptual prototype design

The SBC prototype has been designed to makes use of the standards that represent the data model for product design, process planning and manufacturing resources for detailed cost estimation. This prototype is based on the set of requirements and the futuristic view of integrated costing as outlined in chapter 4.

7.1.1 STEP-NC file structure for an example milled part

As mentioned in chapter 5, ISO14649 (STEP-NC) is basically a structured object oriented representation of detailed processes information for CNC manufactured components. This section of the thesis further illustrates the structure of a STEP-NC file to explain the standards' entities representation of product, process and manufacturing resource information. The example milled component provided in the ISO14640 part 11 documentation, Figure 6.1, has been used in this section to illustrate STEP-NC information content that are applicable in detailed cost estimation process. An excerpt of the STEP-NC file for the example component is shown Figure 6.2. The complete STEP-NC file for the example milled component is provided in appendix B.

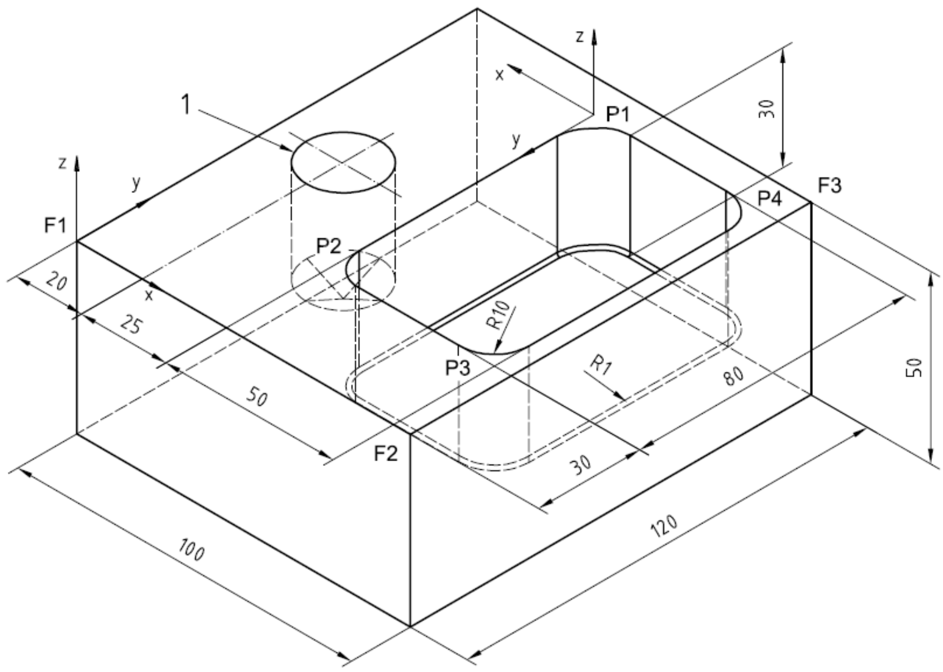


Figure 7.1 - Example milled part provided in ISO14649-11 document

The example component shown in figure 7.1 consists of three manufacturing features, facing, round hole and rectangular pocket. The five milling operations that were conducted to machine the components are: plane milling, drill hole, ream hole, rough pocket and finish pocket. Figure 7.2 shows the STEP-NC file excerpt for the example milled part provided in ISO14649-11 document in which the process plan for the part is represented by a workplan (line number: #2) that consists of a sequence of workingsteps (#10 to #14) representing the manufacturing features and machining operations.

```
DATA;
```

Project entity

```
#1= PROJECT('EXECUTE EXAMPLE1',#2,(#4),$,$,$);
#2= WORKPLAN('MAIN WORKPLAN',(#10,#11,#12,#13,#14),$,#8,$);
#4= WORKPIECE('SIMPLE WORKPIECE',#6,0.010,$,$,$,(#66,#67,#68,#69));
#6= MATERIAL('ST-50','STEEL',(#7));
#7= PROPERTY_PARAMETER('E=200000N/M2');
…
```

Executable process plan representation

```
#10= MACHINING_WORKINGSTEP('WS FINISH PLANAR FACE1',#62,#16,#19,$);
#11= MACHINING_WORKINGSTEP('WS DRILL HOLE1',#62,#17,#20,$);
#12= MACHINING_WORKINGSTEP('WS REAM HOLE1',#62,#17,#21,$);
#13= MACHINING_WORKINGSTEP('WS ROUGH POCKET1',#62,#18,#22,$);
#14= MACHINING_WORKINGSTEP('WS FINISH POCKET1',#62,#18,#23,$);
...
```

Machining parameters representation

```
#39= MILLING_CUTTING_TOOL('MILL 20MM',#29,(#125),80.000,$,$);
#40= MILLING_TECHNOLOGY(0.040,.TCP.,$,12.000,$,.F.,.F.,.F.,$);
…
#44= MILLING_CUTTING_TOOL('SPIRAL_DRILL_20MM',#31,(#126),90.000,$,$);
#45= MILLING_TECHNOLOGY(0.030,.TCP.,$,16.000,$,.F.,.F.,.F.,$);
…
#48= MILLING_TECHNOLOGY(0.030,.TCP.,$,18.000,$,.F.,.F.,.F.,$);
…
#50= MILLING_TECHNOLOGY($,.TCP.,$,20.000,$,.F.,.F.,.F.,$);
#51= CONTOUR_BIDIRECTIONAL($,$,$,$,$,$);
#52= MILLING_TECHNOLOGY($,.TCP.,$,20.000,$,.F.,.F.,.F.,$);
#53= CONTOUR_PARALLEL(5.000,.T.,.CW.,.CONVENTIONAL.);
…
```

Feature geometry representation

```
#121= CARTESIAN_POINT('P1',(0.000,0.000,0.000));
#122= CARTESIAN_POINT('P2',(0.000,80.000,0.000));
#123= CARTESIAN_POINT('P3',(-50.000,80.000,0.000));
#124= CARTESIAN_POINT('P4',(-50.000,0.000,0.000));
…
```

Figure 7.2 - A STEP-NC file excerpt for the example milled component

The information structure of the STEP-NC file comprised of: (1) project entities, (2) process plan entities, (3) machining entities, and (4) geometry entities. The project entities describe the logical sequence of executable tasks (e.g. *machining_workingstep*, *NC_function*) and data types. Details of each *workingstep* are covered in the *process plan entities* with reference to the machining_*entities* and the manufacturing features' *geometry entities* for 2.5D (*two5D_manufacturing_feature*) and 3D milling operations (*region*). It is important to note that each *workingstep* has its subordinate sub-features (such as *planar_face*, *pocket*, *step*, *slot*, *round_hole*, and *general_outside_profile*) together with cutting condition information. This STEP-NC file structure allows detailed representation of product, process and resource information category. Figure 6.3 shows PCP information category represented in the STEP-NC file for the example milled component. From the costing process viewpoint, this makes the STEP-NC file a viable source of detailed PCP information that is required to generate reliable cost estimates. The STEP-NC file can be prepared either through a computational standard (STEP-NC) compliant platform implemented in an integrated environment, or the off-line programming (OLP) system. In either case, development of a neutral file format is required to make it possible to retrieve PCP information from the computer aided systems.

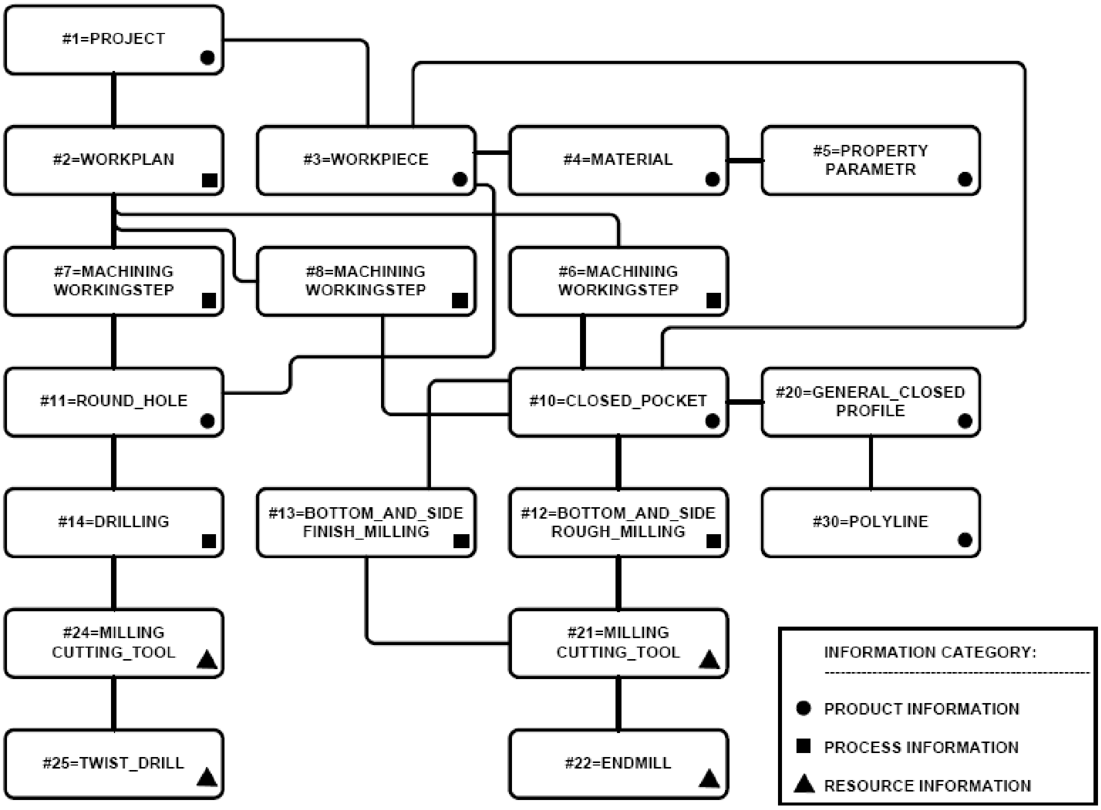


Figure 7.3 - Information category in the STEP-NC file for figure 7.1 part(Nassehi, 2007)

7.1.2 **Standards based costing (SBC) prototype design**

The conceptual design for the SBC prototype is shown in Figure 6.4. The prototype consists of four main functional modules: the process comprehension module, the data extraction module, the time estimation module and the cost calculation module. When a STEP-NC file containing standardised product creation processes information is input into the system, first the process compression module parses the file line by line to identify and transformed machining features, process plan and manufacturing resource entities into corresponding process data that is presented to the extraction module for identification and capture of cost relevant parameters. The time estimation module then utilises the extracted parameters to estimate the machining time. The last component in the system is the costing module that uses the estimated machining time result with labour and resource rates to generate product and production cost information. The major supporting components of the SBC system as shown in figure 7.4 are:

- Manufacturing knowledgebase that provides process and resource data to the estimation module and;
- Accounting database that contains manufacture's specific rates that are utilised by the costing module to calculate cost estimate.

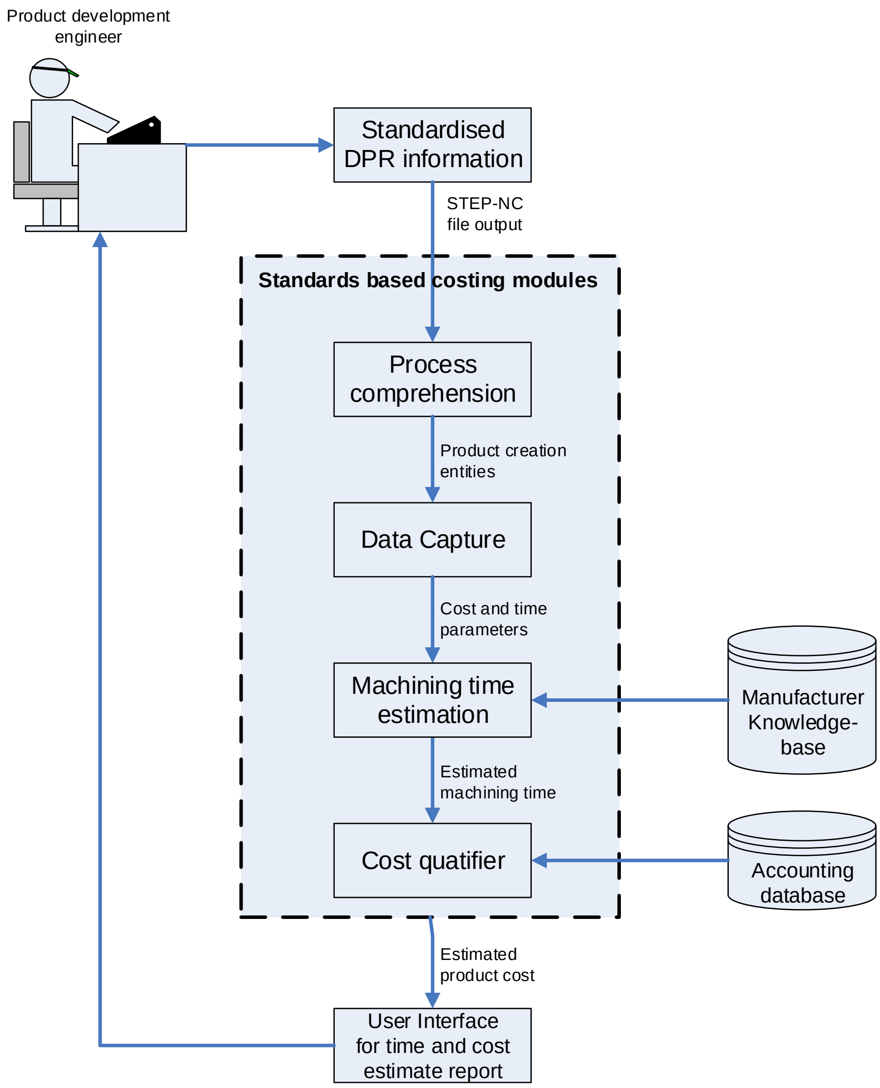


Figure 7.4 - Conceptual model of unified cost estimation

7.2 SBC functional processes

The basic function of SBC is to utilised the detailed process creation information contained in the object oriented data structure of ISO 14649 (STEP-NC) to generate reliable cost information and provide cost based resource guidance. The various functional processes of the SBC and the relevant data items provided by the databases are shown in figure 7.5. The prototype calculates the cost of the new part from a STEP-NC file. The first step in the cost estimation process is the parsing of the STEP-NC file input and capturing of process creation parameters form the file by the Data capture module. Next, the machining time estimation module uses the extracted parameters to calculate cutting tool travel distance which it then utilised in conjunction with other data from the manufacturer's database to generate machining time estimate. Finally, the costing module apply labour and resource utilisation rates to the estimated machining time to provide product unit cost estimate and extends the unit costs to compute total part cost. The input to these modules is STEP-NC file, resource specific set-up time and manufacturer's rates. The output of these modules is the cost estimate for a part and the production cost comparison for alternative resources. The detailed explanation of the costing modules activities is provided in next the section. The four major activities that comprise the SBC process have been identified as:

i). Transformation of standardised information
ii). Recognition and extraction of cost relevant parameters
iii). Estimation of machining time
iv). Calculation of product and production cost estimate

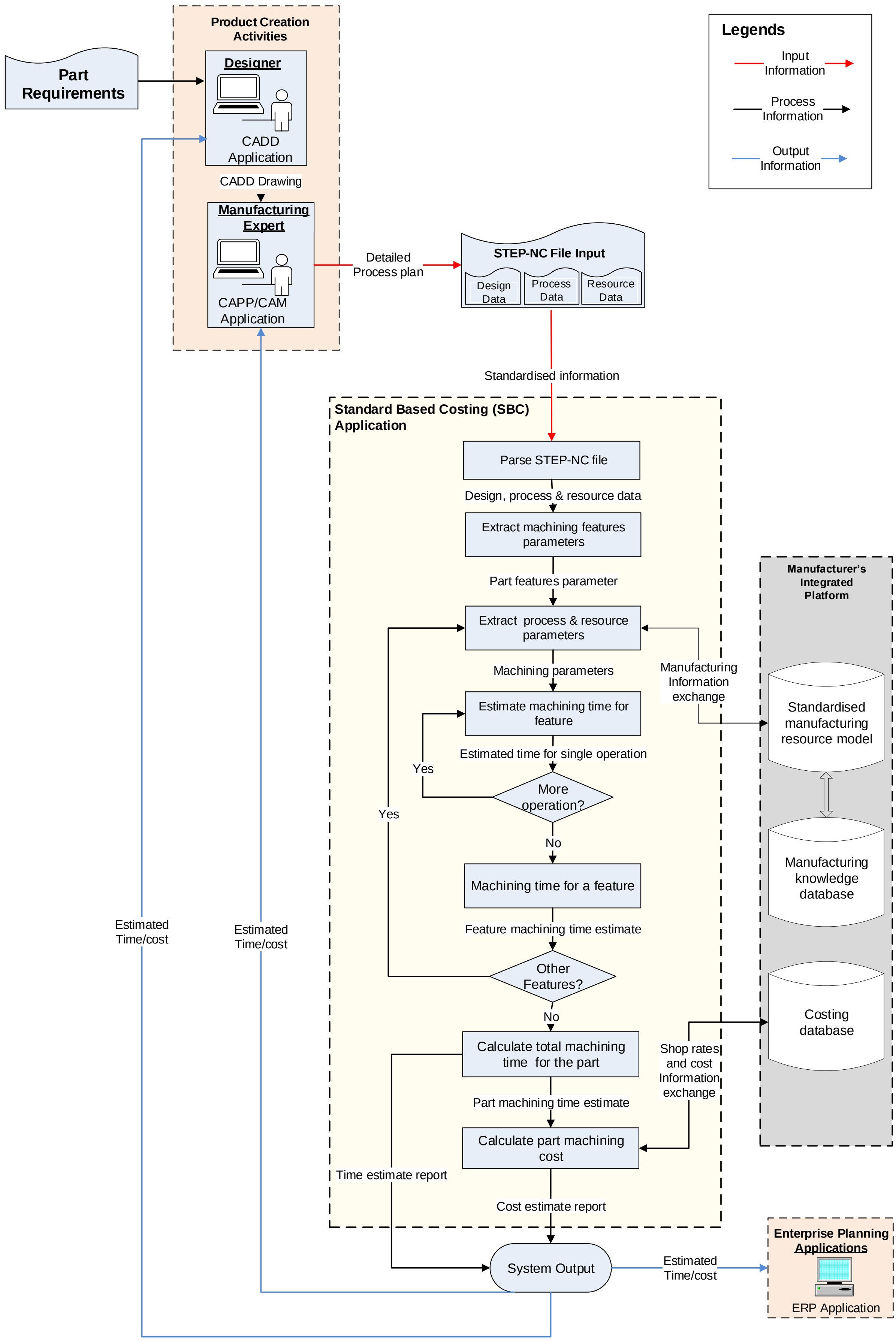


Figure 7.5 - Process flow for the SBC prototype

7.2.1 **Transformation of standardised information**

The process of transforming STEP-NC standardise PCP information into data objects applicable in the Java programming environment starts with the identification of various product creation process entities by the SBC transformation module. Based on the identified entities the translation module implement a previously developed object-oriented library called IP_3AC (Nassehi *et al.* 2007) to manipulate the STEP-NC information structure and generate java friendly product creation processes object parameters, as shown in Figure 7.6. The generated parameters becomes directly accessible in the object space provided by SBC Java environment and can be organised to provide associated actual values with ease in the Java runtime environment.

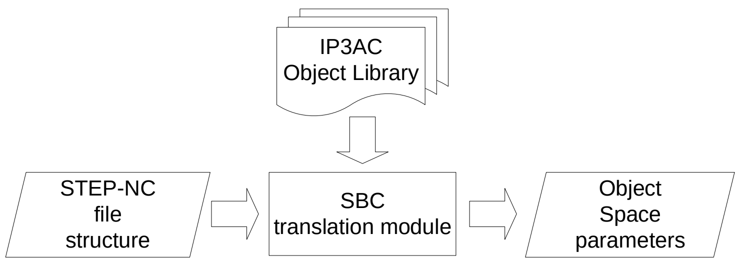


Figure 7.6 - Information translation by standard compliant costing framework

7.2.2 **Recognition and extraction of cost relevant parameters**

In this section the cost relevant parameter contained within STEP-NC file that are to be extracted and used for detailed cost estimation will briefly described. Recognition is the process whereby workingsteps entities containing specified cost relevant parameters are identified by the SBC translation module. Extraction is the process of retrieving actual design, process and resource data/values from identified cost relevant parameters.

This is the function of the extraction module and the extracted data are later use for machining time estimation and subsequent cost calculation. Figure 7.7 illustrate the standard based costing framework data recognition and extraction structure.

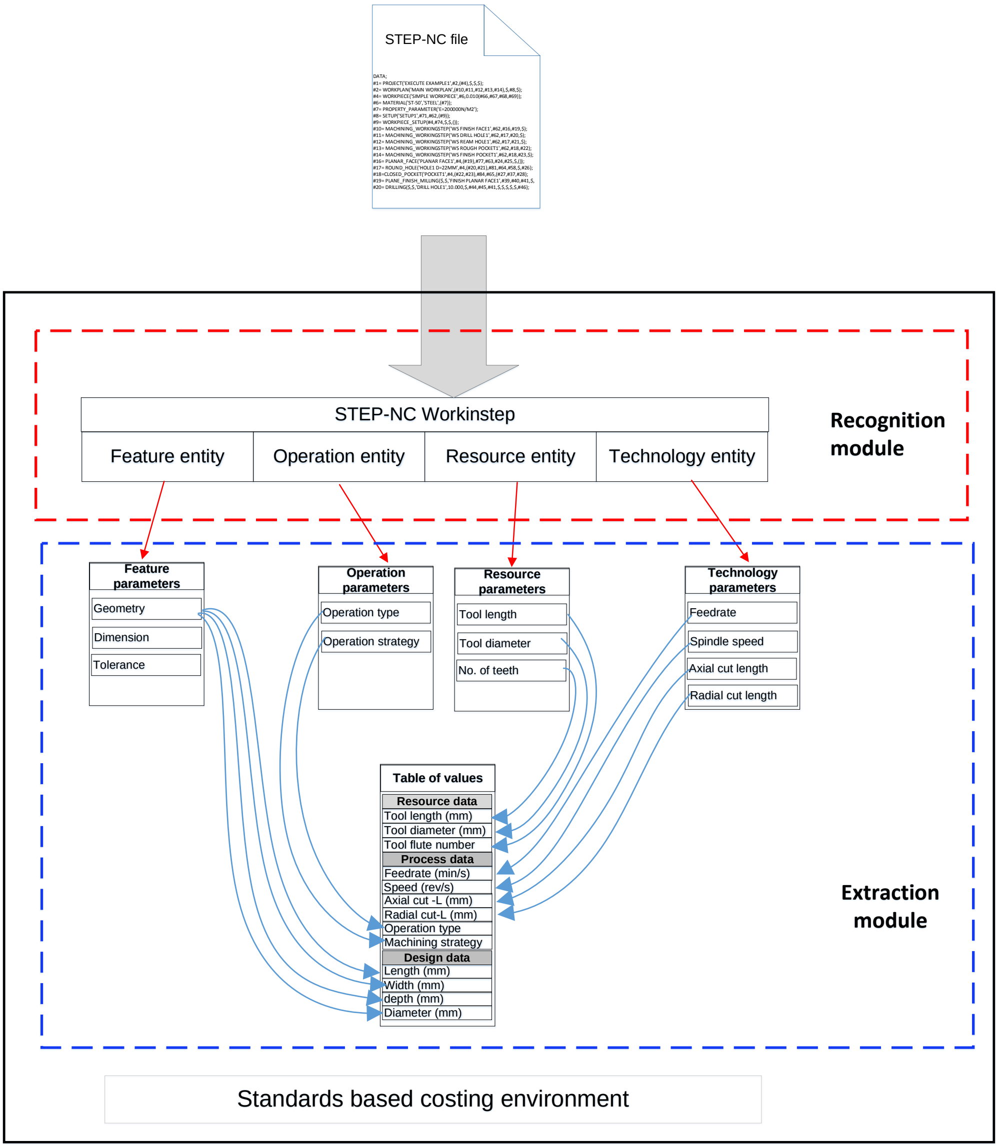


Figure 7.7 - Data recognition and extraction by standard based costing framework

7.3 Machining time estimation and cost calculation

This research utilises an improved time estimation methodology that is consistent with those developed by other researchers (OuYang and Lin, 1997, Maropoulos et al., 1999) that based machining time estimation on the type of machined feature and its surface finish requirement. The OuYang and Lin (1997) estimation method relied on assumed feedrate value extracted from cutting tool material literature that may not be adequate if the resulting time estimation result is require to generate reliable cost estimate. This is because the machining condition determines the choice of aplicable resources, therefore, there may be a significant disparity between the assumed value and the actual feedrate used to machined a part. The time estimation methodology in Maropoulos *et al.* (1999) extends the OuYang and Lin (1997) but utilises a feeds and speeds values that are determined on the assumption that tools having the same tooltype share similar characteristics. Being an assumed value based, the Maropoulos *et al.* (1999) methodology is also likely to result in time estimates of questionable accuracy. Hence, this standard compliant framework allows the application of the actual cutting parameters to improve time, thus cost, estimation accuracy.

7.3.1 **Time estimation Equations Cutting conditions parameters**

In CNC manufacture a wide range of cutting tools are used but in this case a face mill, slot mill and twist drill are defined in the STEP-NC file. In a standard compliant machining environment, the STEP-NC file contains the actual feed and speed values which are directly extracted by the SBC and utilised for machining time estimation as shown in the next section. In instances where the STEP-NC file does not contain a feedrate value but contains spindle speed, cutting speed and the feed per tooth values, then Equation 7.1 and Equation 7.2 (OuYang and Lin, 1997) are used to generate the required feedrate values.

$$\boldsymbol{n = \frac{v_c \times 1000}{\pi D}} \quad \text{.......... Equation 7.1}$$

$$\boldsymbol{v_f = nzf_z} \quad \text{.......... Equation 7.2}$$

Where:

n is the spindle speed (rpm), v_c is the cutting speed (m/min), D is the diameter of the cutting tool (mm), v_f is the feedrate (mm/min), z the number of teeth and f_z is the feed per tooth (mm/tooth).

a) Calculation of aggregate machining times

The STEP-NC entities provide data representation for the main operations that are performed to realise the finished milled part. These operations are rough milling (roughing), finish milling (finishing) and drilling. Estimating the machining time to for drilling operation is straight forward and it is calculated using equation 7.3 below:

$$\boldsymbol{T_d = \frac{d_c}{v_f}} \quad \text{.......... Equation 7.3}$$

Where:

T_d is the machining time for a drilling operation (min) and
d_c the required depth of cut (mm).

This equation is based on the assumption that the drilling operation is continuous and does not account for non-continuous operation such as pecking. For a hole to have reduced surface finish, a reaming operation is performed and the time estimation for this operation can be calculated using equation 7.3 in much the same way as for drilling.

The machining time estimation for other manufacturing features requires the calculation of the machining time for removing the material volume (roughing operation time) and the machining time to achieve the desired surface finish (finishing operation time). The roughing time is calculated using equation 7.4 to equation 7.7 (Maropoulos et al., 1999) below:

$$\boldsymbol{T_r = t_{lr}\, n_{pdr} + t_{lr}\, r_b;\ \ T_r = t_{lr}\,(n_{pdr} + r_b)}$$ ....Equation 7.4

$$n_{pdr} = \left|\frac{d_c}{3}\right|^+$$ ....Equation 7.5

$$r_b = 0 \ \ \forall R_{ab} \geq 0.8, \ \ r_b = \frac{0.8}{R_{ab}} \ \ \forall R_{ab} < 0.8$$ ....Equation 7.6

$$\boldsymbol{t_{lr} = \frac{l_r}{v_f}}$$ ....Equation 7.7

Where:

T_r is the machining time for a roughing operation (min), t_{lr} the time taken to machine roughing tool path per depth pass for a default surface finish of 0.8 mm (min), n_{pdr} the number of depth passes for roughing operations, r_b the ratio of default surface finish to required surface finish for the base of the feature, $|X|^+$is the round up to the next integer number, R_{ab} the required surface finish for the base of the feature (mm) and, l_r the length of tool path per depth pass for the roughing operation.

In this case the manufacturers preferred depth of cut for the roughing operation is 3mm, hence this research uses this consideration to calculate the number of depth passes as shown in equation 7.5. In machining time estimation the, roughing feedrate value is directly proportional to the required surface finish (OuYang and Lin, 1997), on this basis this research used the r_b value in equation 7.4 to adjust cutting time according to the required surface finish.

This research assumed the default surface finish of 0.8mm. In equation 7.6, if the required surface finish is greater than or equal to 0.8 mm, then the r_b value used to adjust machining times is zero. On the other hand, if the required surface finish is less than 0.8 mm, then a finishing operation is required and the time taken for the additional operation is taking into account. To obtain a value for the T_r in equation 7.4, it is necessary to calculate the machining time per pass (t_{lr}) using equation 7.7 similar to machining time calculation for drilled holes. The calculation of the cutting tool travel distance (l_r) uses feature and cutting tool parameters.

The aggregate machining time for a feature with a surface finish of less than 0.8 mm (min) consist of: the time taken for the roughing operation, the time taken for an additional finishing operation to achieve the feature's wall surface finish requirement and the time taken for an additional operation to achieve the feature's floor surface finish requirement. For such a feature the machining time is calculated using equation 7.8 to equation 7.11 (Maropoulos et al., 1999):

$$\boldsymbol{T_p = t_{lp}\left(n_{pdp}\,(1 + r_w) + r_b\right)} \text{ .... Equation 7.8}$$

$$\boldsymbol{n_{pdp}} = \left|\frac{\boldsymbol{d_c}}{\boldsymbol{a_p}}\right|^{+} \text{ .... Equation 7.9}$$

$$\boldsymbol{r_w = 0} \ \ \forall \boldsymbol{R_{aw}} \geq \boldsymbol{0.8},\ \boldsymbol{r_w} = \frac{\boldsymbol{0.8}}{\boldsymbol{R_{aw}}} \quad \forall \boldsymbol{R_{aw}} < 0.8 \text{ .... Equation 7.10}$$

$$\boldsymbol{t_{lp}} = \frac{\boldsymbol{l_p}}{\boldsymbol{v_f}} \text{ .... Equation 7.11}$$

Where:

T_p is the machining time for a profiling operation (min), t_{lp} the time taken to machine profiling tool path per depth pass for a default surface finish of 0.8 mm (min), n_{pdp} the number of depth passes for profiling operations, r_w the ratio of default surface finish to the required surface finish for the wall of the feature, a_p the maximum depth of cut of selected tool, R_{aw} the required surface finish for the wall of the feature (mm) and l_p the length of tool path per depth pass for the profiling operation.

In the finishing operation tool engagement is minimised, hence adherence to 3mm depth of cut as in equation 7.5 is not necessary. Therefore, a tool allowable maximum depth of cut (a_p) is assumed during calculation of the number of depth passes for a roughing operation (n_{pdp}).

For a surface finish lower than the default value (0.8mm) the finishing operation is performed using a proportionally smaller feed rate defined by the r_w value.

Obtaining a value of t_{lp} in equation 6.11 requires the calculation of the finishing tool travelled distance (l_r).

(i) Calculation of tool travel distance based on machining operation

This research considers the major component of the cutting tool travel distance, that is, the length of the tool path in the local XY plane (the plane perpendicular to the approach direction). The travel distance for the plunge, retract and rapid tool movements are not considered in this research because modern CNC machines are capable of automatic fast plunge, retract and rapid tool movements such that these aspects of machining time are considered negligible. The tool travel distance for drilling is easily determined as the cutting distance is equal to the depth of the drilled hole. The rest of this section focuses on determining the tool travel distance for other manufacturing features based on the machining strategy used to perform the operation. The tool travel distance is required for the (l_r) and (l_p) values in equations 7.7 and equation 7.11 respectively.

The parameters required to determine l_r and l_p are the length (L), width,(W) and the corner radius (r) of the feature, as well as the cutting tool diameter (D). The STEP-NC file provides information, in the form of the entity machine_strategy, on how the material is removed to create a feature. Figure 7.8, 7.9 and 7.10 respectively illustrates the contour, bidirectional and a combination of both (contour-bidirectional) strategies that are regularly used for milling operations. In this section, the equation that defines the cutting tool travel distance (l_r) and (l_p) has been developed for the following machining strategy:

- **Bidirectional milling**

  Milling in a zigzag fashion, i.e. going from one side to the other and back as shown in figure 7.8. The first and second directions for zigzagging may be specified to further describe the milling strategy. The cutting mode (conventional or climb cutting) is alternated.

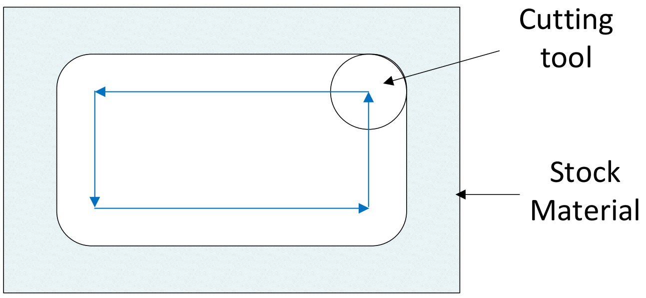


Figure 7.8 - Contour parallel milling strategy

- **Contour parallel milling**

  Milling in several paths following the contour of the feature as shown in figure 7.9. A typical strategy for pocket milling. The step over direction (outside_in or inside_out) is automatically derived from rotation_direction and cutmode.

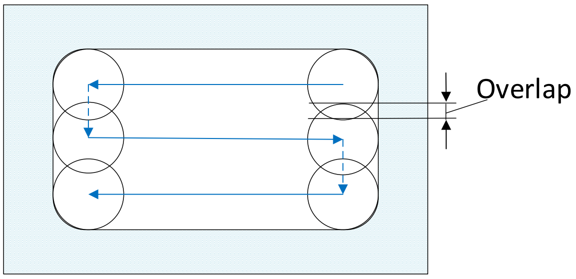


Figure 7.9 - Bidirectional milling strategy

- **Bidirectional and contour milling**

  Milling of the contour in bidirectional fashion first, then one final contour-parallel path on the very outside of the feature as indicated in figure 7.10.

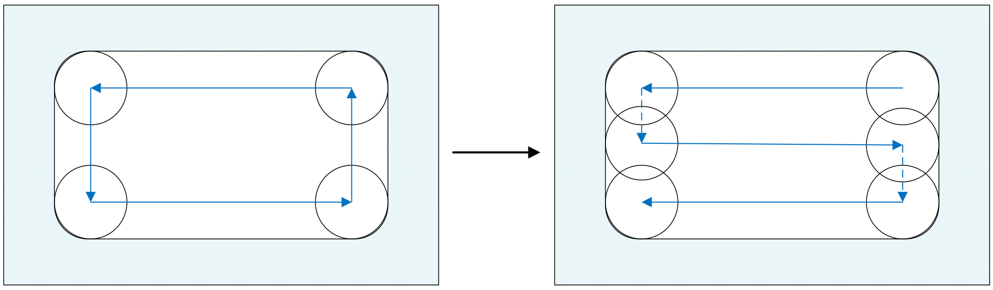
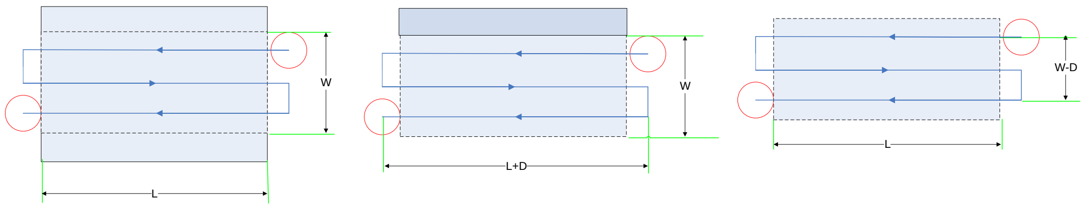


Figure 7.10 - Contour and bidirectional milling

- **Contour and bidirectional milling**

  Is typically the reverse of the bidirectional milling in that a contour parallel path on the very outside of the contour is performed first, then bidirectional milling of the remaining centre.

The operation for roughing full slots, full shoulders and faces are performed using a bidirectional strategy as shown in figure 7.9. The operation starts with the cutting too starting from outside the feature and maintaining its travel direction until exiting the feature. If the feature width is the same as the cutting tool diameter a linear movement is all that is performed. However, if the cutting tool diameter is proportionally smaller than the feature's width, a bidirectional machining strategy is performed to cut the feature. If the feature depth is larger than the depth of cut, the tool plunges into the material from its current position to perform the next depth of cut. The bidirectional cutting tool travelled distance (l_r) for Facing, full slot and step features machining is calculated using equation 6.12 and equation 6.13 below:



(a) Full slot (a) Full step (c) Face plane

Figure 7.11 - Bi-directional machining strategy for roughing full dlots, step and facing

$$\boldsymbol{n_{pw}} = \left|\frac{\boldsymbol{W}}{\boldsymbol{D}}\right|^{+} \text{.......... Equation 7.12}$$

$$\boldsymbol{l_r} = \boldsymbol{n_{pw}}\,(\boldsymbol{L}+\boldsymbol{D})+\boldsymbol{W}-\boldsymbol{D} \text{.......... Equation 7.13}$$

Where:

n_{pw} is the number of passes required to cut the width of the feature and L, W, D the dimensions shown in Fig. 7.9a.

The estimation of closed type feature machining time is done by calculating the cutting tool travelled distance in the XY plane for a closed feature having length (L) and width (W) as shown in figure 7.12.

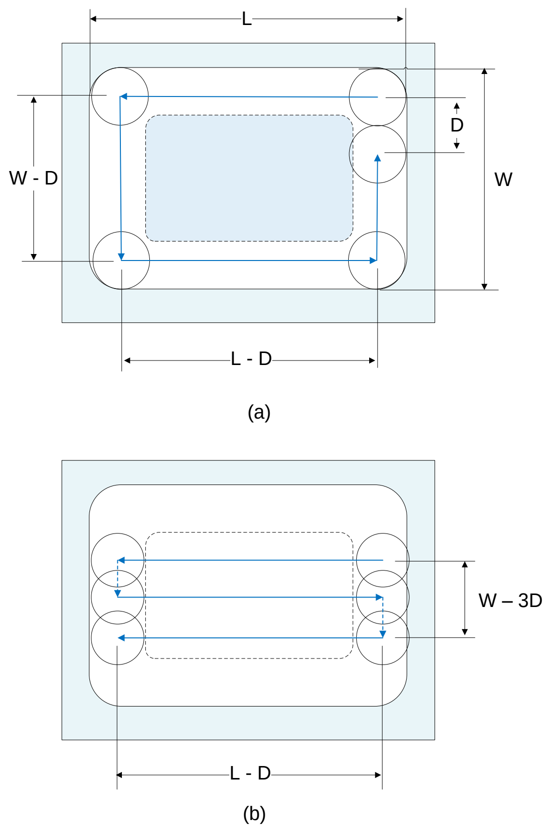


Figure 7.12 - Cutting tool paths during machining of a closed pocket

The roughing out of a closed type rectangular feature is started with the cutting tool drilling an access hole a tool diameter from a corner in the feature width (W) direction. From this position the cutting tool starts the bidirectional cutting operation and ended up in the position shown in figure 7.12(b) where it plunges down for the next depth of cut. The cutting tool travelled distance in the XY plane is calculated using the following equations:

$$l_{rp} = 2(L - D) + 2(W - D) \text{ .... Equation 7.14}$$

$$n_{pw} = \left|\frac{W}{D}\right|^{+even} \text{ .... Equation 7.15}$$

$$l_{rz} = n_{pw}(L - D) + W - 3D \text{ .... Equation 7.16}$$

$$l_{rt} = W - 3D \text{ .... Equation 7.17}$$

$$l_r = L(2 + n_{pw}) + 4W - D(10 + n_{pw}) \text{ .... Equation 7.18}$$

Where:

l_{rp} is the profiling path length shown in Fig. 3a, l_{rz} the zigzagging path length shown in Fig. 3b and, l_{rt} the return-tostart path length shown in Fig.7.12b.

(ii) Cutting tool distance for cylindrical pocket

The machining of a circular pocket requires a circular operation and for the purpose of calculating the cutting tool travelled distance it is considered that the milling of a circular feature starts with the tool cutting 3mm into the material and moves in a circular path at that cutting depth. This movement is repeated consecutively with decreasing the cutting tool path diameter until all material is removed. Figure 7.13 illustrates the cutting tool path for a cylindrical feature and the total cutting tool travelled distance is calculated using equation 7.19 to equation 7.20 below:

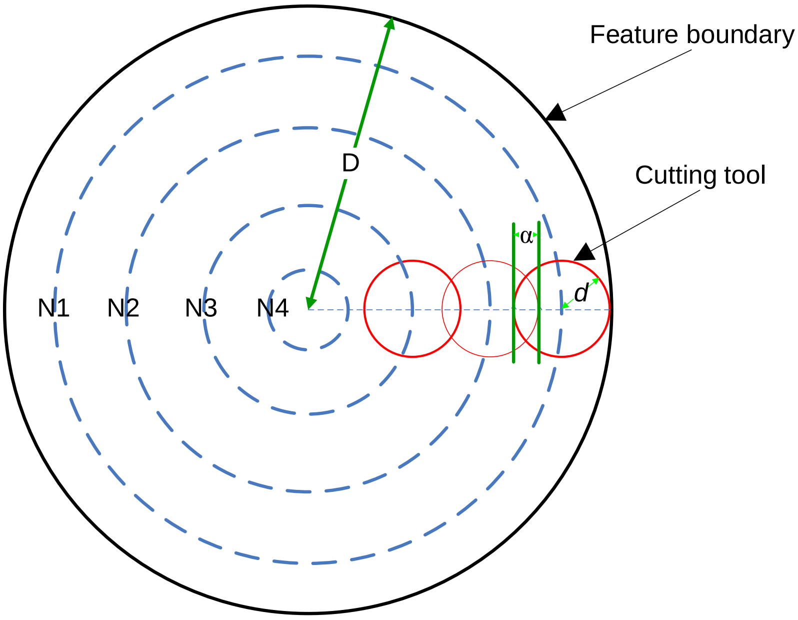


Figure 7.13 - Cutting tool path for machining of a cylindrical pocket

$$l_r = \pi N \left(D + d(2 \propto -1) + d\,(1-\propto)(N-1)\right) \text{...............Equation 7.19}$$

$$N = \left|\frac{D}{(d-\propto)}\right|^{+} \text{...Equation 7.20}$$

Where:

N is the number of circular passes per depth of cut, D is the feature diameter, d is the cutting tool diameter and, $\propto$ is the cutting tool overlap distance.

7.3.2 **Cost calculation module**

This module calculates the cost of manufacturing a part. In addition to machining time, it uses the set-up plan of the part to determine the cost of manufacturing a part. The total cost of a machining operation depends on the time required to carry it out (Boothroyd and Knight, 1989). This system's cost estimation module used equation 7.21 below and the estimated machining time results to calculate the machining cost.

(i) Computation of the required machining cost for each operation:

$$C_{ij} = M_h \, T_{ij} + S_h \quad \text{..........Equation 7.21}$$

Where:

C_{ij} is the estimated machining cost for the operation *j* of feature *i* , M_h the unit time cost for machining *h* (machine *h* is selected to perform operation *j*), T_{ij} is the time require to accomplish the operation j of feature i and S_h the set-up cost for machine *h .*

(ii) Estimation of the required machining cost for each feature

$$FC_i = \sum_j C_{ij} \quad \text{..........Equation 7.22}$$

Where:

$\boldsymbol{FC_i}$ is the estimated machining cost for each feature *i .*

(iii) Computation of the required manufacturing cost for each product

$$TC = \sum_i FC + \sum_{m=1}^{i-1} NP_{m.m+1} \quad \text{..........Equation 7.23}$$

Where:

TC is the estimated manufacturing cost for a product. In which $\sum_{m=1}^{i-1} NP_{m.m+1}$ is the non-productive cost namely the cost incurred by cutter rapid movement from one machining feature to another machining feature. Its calculation process is similar to T_{ij}.

It can be seen that the SBC prototype has been designed to generate total manufacturing cost by estimating the cutting (machining) time that is used to calculate the machining cost which is summed up with the set up and non-productive costs.

7.3.3 **Set-up costs**

Set up time is the time required to establish and adjust the tooling, and to set speeds and feeds on the metal removal machine. Set-up times for various machine tools were obtained from machining handbooks and were used to estimate set-up costs.

7.3.4 **Non-productive costs**

Non-productive costs are incurred every time when the cutter moves from one machining feature to another machining feature. Usually, the non-productive costs would be quite small. However, when a series of machining operations are used, the non-productive costs accumulate and become a highly significant factor in the machining cost. The non-productive cost is a complicated issue. It involves in many other factors such as the workpiece is loaded into or unloaded from a machine tool, and when the operation is completed, the tool must be withdrawn. Therefore, the content of non-productive cost can be decided according to different research goals or different system requirements.

7.4 Summary

In this chapter a computational platform has been specified and designed to enable the use of rich product creation information contents of manufacturing standards for cost estimate generation. The system entitled SBC utilises design and process data provided by ISO14649 to generate time and cost estimate. It also allows actual process creation information to be used for automatic product costing in standards compliant integrated product creation environment.

8 Implementation of a software prototype for SBC

8.1 Introduction

A software prototype has been developed for standard based costing. The author described unified costing as an estimation process that make use of actual data from CAD, CAM, CNC and other CAx to generate cost information feedback across that product creation lifecycle.

To demonstrate the feasibility of SBC a prototype system has been implemented. The development of the prototype accomplishes a number of objectives:

(i) It demonstrate availability of detailed product information in STEP-NC file
(ii) It evaluates if SBC model perform as expected and,
(iii) It evaluates the developed model viability for industrial requirement on a small scale.

The prototype uses commercially available computer and the choice of Java as the programming language provides a robust and powerful object oriented environment for the transformation of PCP data contained in STEP-NC file, using a Graphical User Interface (GUI). Another consideration was the scope of the prototype. The prototype focuses only on CNC milling operations and is limited to prismatic components whose geometry can be described in 2.5D. These restricted focuses are necessary to given the research time constraint but they are sufficiently broad to allow for an adequate evaluation of the standard compliant model.

8.2 Specification of the SBC platform

The SBC prototype comprises of four modules: An EXPRESS language translation module to read and translate STEP-NC entities into data objects, a retrieval module to extract cost parameters from the data objects, a repository object that contains the actual design, process and resources parameters for costing, an estimation module to use the parameters and specified algorithms for machining (cycle) time estimate and finally, a cost module to use the time estimate result and manufacturers rates to generate cost feedback. The structure of the SBC system is shown in Figure 8.1 and has the primary functions specified in Chapter 5. This prototype generates product cost information from standardised product creation data contained in a STEP-NC file as shown in Figure 7.1. It realises the use of detailed information that exist within integrated environment for cost based guidance on alternative design, process and manufacturing resources.

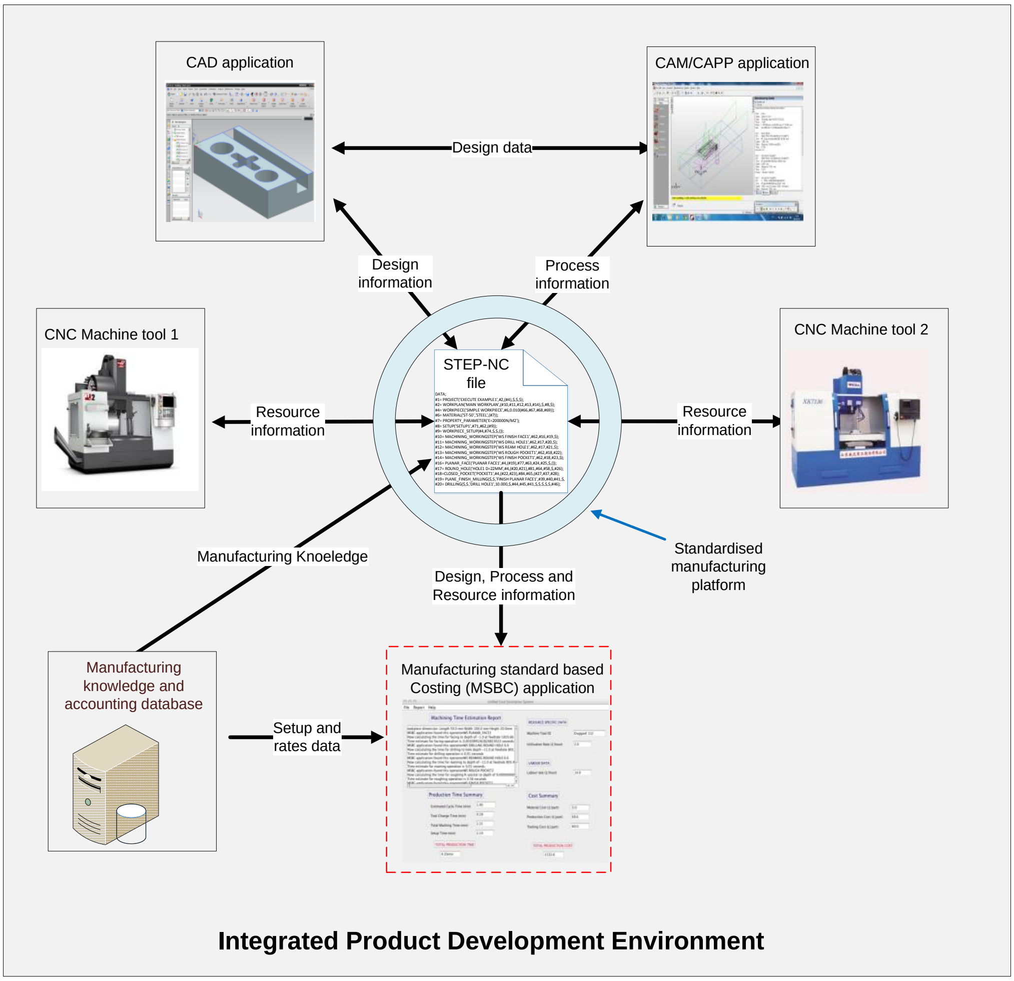


Figure 8.1 – SBC enables use of existing information for cost estimation across stages on integrated product creation

The implementation of SBC prototype is documented using five CAx resources: CAD/CAM system, STEP-NC compliant integrated platforms, STEP-NC compliant cost estimation system and two modern commercial CNC machine tools. CAD/CAM systems provide part design and NC codes that are transformed into the STEP-NC file by the STEP-NC compliant computational interface. TheSBCprototype system has been developed with the object-oriented computer programming language Java, in an integrated development environment NetBeans (Version 6.8) (Oracle Corporation 2011). This is a user toolkit to develop desktop and internet based applications from the Oracle Corporation.

An overview of the prototype system is shown in Figure 8.2 in which the main menus and reported data headings are shown. All that is required of the user in the cost estimation process is the loading of the correct standardised file into the system. The prototype uses its graphical user interface (GUI) to allow the user to load a STEP-NC file as input via the 'Open' sub-menu under the 'File' tab. Once the file is loaded the system automatically runs the cost estimation process and present the production cost estimate, via the GUI, in seconds. For cost based guidance on alternatives, the user only has to modify the STEP-NC file with proposed changes to design, process or resource utilization and reload the updated STEP-NC file into the system for instant cost information that can be compared with previous cost estimate.

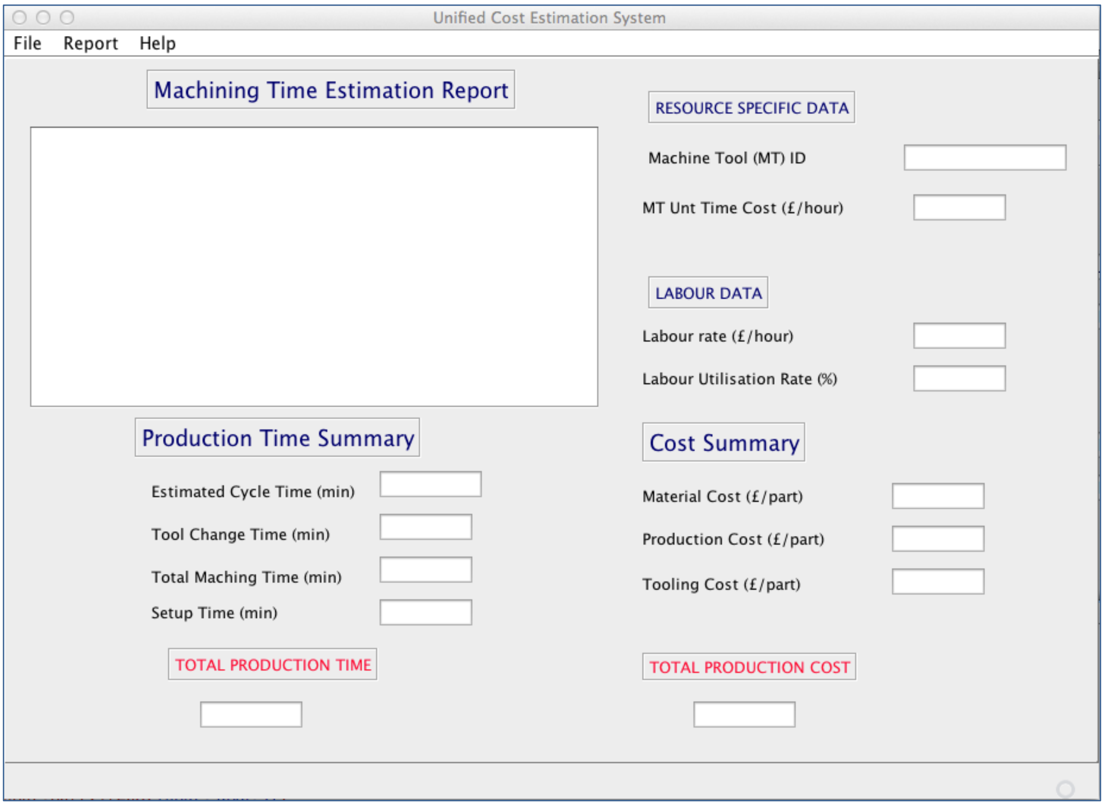


Figure 8.2 - Overview of SBCsystemprototype

8.3 SBC estimation process

As mentioned in section 6, ISO14649 provides the necessary information that represents product creation process (PCP) information for prismatic components. Figure 8.3 shows the category of information that is available in a STEP-NC file for the example milled part in figure 7.1. The first step for SBC is the interpretation of the STEP-NC file to retrieve the cost element data it contains for use as cost estimation module input.

Using the sample STEP-NC file in figure 7.2 as example, to retrieve cost element parameters from the file, the SBC system reads the STEP-NC file line by line to identify the Workplan and workingsteps entities for the part. The identified entities are then organized into product, process and resource entities before being stored in the system for later recognition and retrieval of parameters that are relevant to generate cost estimate.

8.3.1 **The extraction of cost parameters from STEP-NC file**

To retrieve cost element data, SBC reads the STEP-NC file line by to identify the Workplan and workingsteps entities for the part. This *express_entity* includes manufacturing features, machining operation and strategy that are the basis for all SBC generated cost estimates. The SBC system employs an object-oriented programming language to retrieve cost parameters from the information contained in the *express_entity.*

The rest of this section reports on how the data represented in standardised format (STEP-NC file) would be used in the proposed SBC system. The relevant operation attributes lines (#), for an example milled part in figure 7.1, would be described and the retrievable instruction they contain used to estimate the machining time for the part. The machining time result is multiplied by manufacturer's rate to obtain product /part machining cost.

An abridged version of the STEP-NC file which encapsulate the machining parameters is shown in table 8.1. The relevant STEP-NC lines are describe in this section to emphasise the potential use of standardised data representation to support manufacturing cost estimation methodology.
In table 8.1 the line #19 (plane finish entity) bracketed attributes consist facing process information such as the "cutting tool" line #39, the "milling technology" line #40; the" machining functions", line #41 and; the 'machining

strategy’ line 42. Figure 6.9 and the Table 6.1, below respectively indicates and describes the operation strategise for the plane-face milling operation. The operation strategies attribute contains machining parameters values which can be used to calculate the time taken for the plane-face milling operation (i.e machining time for plane-facing). The “drilling entity” line #20, the “reaming entity” line #21, the “rough pocket entity” line #22 and the “finish pocket entity” line #23 consist of operation strategies attributes for the drilling, reaming, roughing and finishing operation respectively. The time taken to realise the part would be the sum of the machining time for each of the operations that has to be performed on the raw material.

Table 8.1 - STEP-NC Part 11 file for the example milled part

```
#1= PROJECT('EXECUTE EXAMPLE1',#2,(#4),$,$,$);
#2= WORKPLAN('MAIN WORKPLAN',(#10,#11,#12,#13,#14),$/#8,$);
. . . . . .
#9= WORKPIECESETUP(#4,#74,$,$,());
#10= MACHINING_WORKINGSTEP('WS FINISH PLANAR FACE1',#62,#16,#19,$);
#11= MACHINING_WORKINGSTEP('WS DRILL HOLE1',#62,#17,#20,$);
#12= MACHINING_WORKINGSTEP('WS REAM HOLE1',#62,#17,#21,$);
#13= MACHINING_WORKINGSTEP('WS ROUGH POCKET1',#62,#18,#22,$);
#14= MACHINING_WORKINGSTEP('WS FINISH POCKET1',#62,#18,#23,$);
#16= PLANAR_FACE('PLANAR FACE1',#4,(#19),#77,#63,#24,#25,$,());
#17= ROUND_HOLE('HOLEI D=22MM',#4,(#20,#21),#81,#64,#58,$,#26);
#18= CLOSED_POCKET('POCKET1',#4,(#22,#23),#84,#65,(),$,#27,#35,#37,#28);
#19= PLANE_FINISH_MILLING($,$,'FINISH PLANAR FACE1',10.000,$,#39,#40,#41,$,
#60,#61,#42,2.500,$);
#20= DRILLING($,$,'DRILL HOLF1',10.000,$/#44,#45,#41,$,$,$,$,$/#46);
#21= REAMING($,$,'REAM HOLE1',10.000,$,#47,#48,#41,$,$,$,$,$,#49,.T.,$,$);
#22= BOTTOM_AND_SIDE_ROUGH_MILLING($,$,'ROUGH
POCKET1',15.000,$/#39,#50,#41 ,$,$,$,#51,2.500,5.000,1.000,0.500);
#23= BOTTOM_AND_SIDE_FINI_SHMILLING($,$,'FINISH POCKET1',15.000,$,#39,#52,
#41,$,$,$,#53,2.000,10.000,$,$);
. . . . . . . . .
#29= TAPERED_ENDMILL(#30,4,$,.F.,$,$);
#30= MILLING_TOOL_DIMENSION(20.000,$,$,S,1.500,$,$);
#31= TWIST_DRILL(#32,2,.RIGHT.,.F.,0.840);
#32= MILLING_TOOL_DIMENSION(20.000,31.000,0.100,45.000,2.000,5.000,8.000;
#33= TAPERED_REAMER(#34,6,$,.F.,$,$);
#34= MILLING_TOOL_DIMENSION(22.000,$,$,$,$,$,$);
#35= TOLERANCED_LENGTH_MEASURE(1.000,#36);
#36= PLUS_MINUS_VALUE(0.100,0.100,3);
#37= TOLERANCED_LENGTH_MEASURE(10.000,#38);
#38= PLUSMINUSVALUE (0.100,0.100,3);
#39= MILLING_CUTTING_TOOL('MILL 20MM',#29,(#125),80.000,$,$);
#40= MILLING_TECHNOLOGY(0.040,.TCP.,$,12.000,$,.F.,.F.,.F.,$);
#41= MILLING_MACHINE_FUNCTIONS(.T.,$,$,.F.,$,(),.T.,$,$,());
#42= BIDIRECTIONAL_MILLING(5.000,.T.,#43,.LFFT.,$);
#43= DIRECTION('STRATEGY PLANAR FACE1:1.DTRECTIONT,(0.000,1.000,0.000));
#44= MILLING_CUTTING_TOOLS (SPIRAL_DRILL_20MM’,#31,(#126),90.000,$,$);
#45= MILLING_TECHNOLOGY(0.030,.TCP.,S,16.000,$,.F.,.F.,.F.,$);
#46= DRILLING_TYPE_STRATEGY(75.000,50.000,2.000,50.000,75.000,8.000);
```

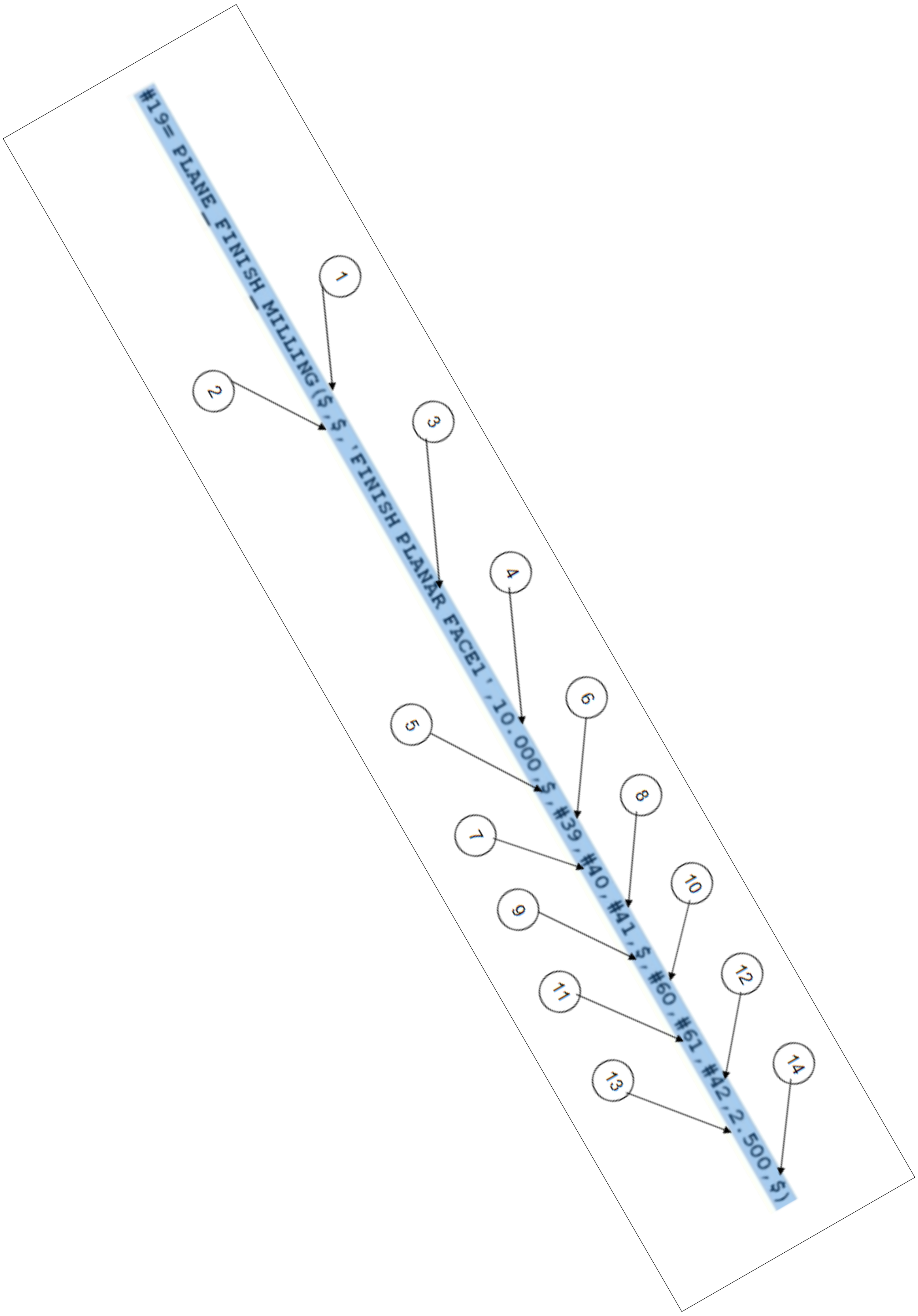


Figure 8.3 - Indicating STEP-NC operational strategies (line #19) instruction for example part

Table 8.2 - Operational strategy descriptions

No:	STEP-NC Line (#)	Operation strategies	Description
1	$	its_toolpath	Its_toolpath defines a list of all toolpaths in this operation
2	$	its_tool_direction:	Specification of the type of tool orientation used
3	Finish planar face	its_id	A unique identifier of the operation.
4	10 (10.000)	retract_plane	The height of a retract plane associated with this operation
5	$	start_point	Optional starting point of the cutting process specified as tool centre point in the local xy plane. The z co-ordinate of start_point is determined depending on the type of operation
6	#39	its_tool	The tool which has to be used for this workingstep.
7	#40	its_technology	The technological parameters of the machining operation, like spindle speed and feed of the tool.
8	#41	its_machine_functions	Indicates the state of various machine functions, like coolant, chip removal, etc. to be applied during the time span of this operation.
9	$	overcut_length	The overcut on the open side(s) of the feature
10	#60	approach	Optional information about approach (plunge) strategy to reach the first cut
11	#61	retract	Optional information about retract strategy after finishing the last cut
12	#42	its_machining_strategy	Description of the strategy to be used when executing the operation
13	2.5 (2.500)	axial_cutting_depth	The cutting depth in the direction of the tool axis
14	$	allowance_bottom	The allowance is a layer of material which will be left on top of the plane surface defined by the associated manufacturing feature

8.4 Summary

In this chapter a prototype implementation of the Standard Based Costing Framework has been realised. The prototype utilises STEP-NC structured product creation information to demonstration availability of detailed information for integrated product costing in CNC manufacture. The development of the prototype has also address the issues of full integration of costing system with other computer aided systems to improve the process of product costing. The prototype can be used in STEP-NC compliant manufacturing facility to test the feasibility of the standard based costing framework CNC manufacture.

9 Evaluation of the standard based costing prototype

9.1 Introduction

It is necessary to show that, in practical terms, a standard compliant cost estimation method can utilise available detailed product creation processes information to generate reliable cost estimate in order to gain manufacturers confidence in the approach. A practical implementation provides the foundation to prove the viability of standards based costing. Therefore, appropriate testing based on costing of milled parts, which comprise of representative manufacturing features found in industry, has been conducted to ensure this research proposed method indeed meets the functional requirement of product costing in integrated product creation environment.

A framework to generate product cost estimation based on the information contained in STEP-NC standards data structure was proposed in chapter 8. In this chapter the SBC prototype has been implemented to evaluate the viability of the standard based costing method. The evaluation was achieved by comparing the SBC prototype machining time estimate with those calculated by Featurecam, a commercial CAM system (Delcam 2012), and the time results obtained for the actual machining operations for a given part. FeatureCam simulates designed part's operation to generate the NC codes that controls machine tool's movement and manufacturing sheet that includes that machining time estimate result.

This chapter starts with the description of the experimental setup used to develop the comparison, followed by the comparison of the machining time results obtained from the SBC prototype, FeatureCam system and the actual machining. Finally, the conclusions drawn from the conducted analysis are presented.

9.2 Experimental setup

The steps taken for the evaluation of the developed SBC are explained in this section. First industrially inspired parts that contain representative features were chosen and a CAD system (Unigraphics) was used to generate detailed part design. The designed parts are prismatic components and consist of manufacturing features that are machined by milling operations.

In the second step, the CAD designs were transferred, in the standard IGES file format, to a CAM software application. Information about available manufacturing resources such as cutting tools was manually imputed into the CAM software, which uses it to perform process plan simulation and generate NC code for the part manufacture. Based on the feature and process parameters the CAM software also generated manufacturing sheet that contain estimated machining time for each component. The NC codes generated by the CAM system were transferred into standard compliant computational platform that uses it to provide standardised product creation process information in the form of STEP-NC file, which is applicable as the main input for the standards based costing method.

The actual machining of the designed parts was later carried out during which three digital timers were used to simultaneously time each operation performed, to realise the finished part, by the CNC machine tool. An average of the three timers was then recorded as the actual machining time results. The machining time estimates results obtained from the commercial CAM application, SBC prototype and the actual operation were compared and analysed. The machining time estimate evaluation process is illustrated in Figure 9.1

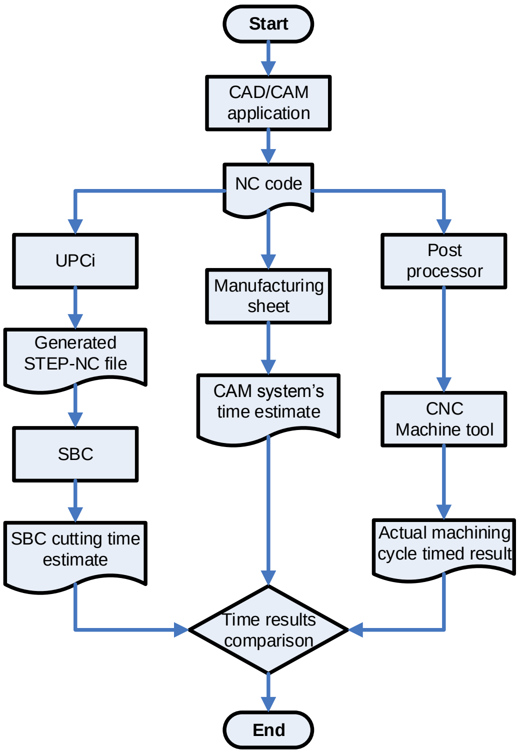
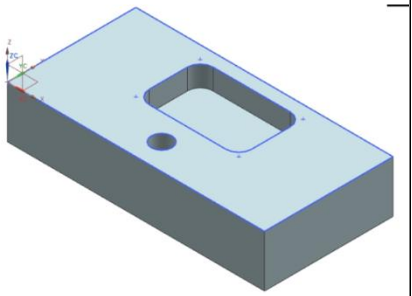
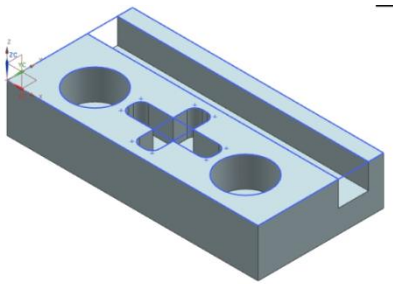


Figure 9.1 - Evaluation method for SBC machining time estimate result

9.3 Case study (I) – prismatic part time and cost estimation

Part designs were machined on a Duggard vertical 3-axis CNC machining centre, with FANUC 180i post processor. Appropriate cutting tools were selected to perform different operations that are required to manufacture the part design. Parts used to evaluate the estimated machining time by SBC prototype are presented in this section. In order to validate the developed prototype a number of studied industrial operations informs on the design of parts with a reasonable number of milling operations. Two prismatic components were designed to consist of autonomous and interacting features most common to milled parts. The parts used in this case study comprise of the following manufacturing features: planar face, rectangular pocket, cylindrical pocket, slot and drilled hole. Table 9.1 presents the case study parts and the evaluation criteria of interest in this research.

Table 9.1 - Test parts used in evaluation case study

Component	CAD image	Evaluation criteria
Part 1		• Autonomous features recognition • Manufacturing parameters capture • Rectangular pocket and drilled hole time estimation • Part cost estimation
Part 2		• Interacting features recognition • Manufacturing parameters capture • Cylindrical pocket, closed slot and open slot time estimation • Part cost estimation

9.3.1 **Test part 1**

This first part is an adaptation of the example part in ISO14649-11 documentation and it has been designed in a CAD system with three features: a planar face, a pocket and a round hole. This part is selected in order to compare the STEP-NC file provided in the ISO 14649-11 documentation with the STEP-NC file generated for similar part by the standard compliant platform implemented in this research. This provides a means to check that the structure of the generated file is in compliance with established manufacturing standards.

This section of the thesis demonstrates the use of data contained in STEP-NC entities representation for a milled part to generate machining time estimate and cost information feedback. The detailed dimension for this part is shown in figure 7.2.

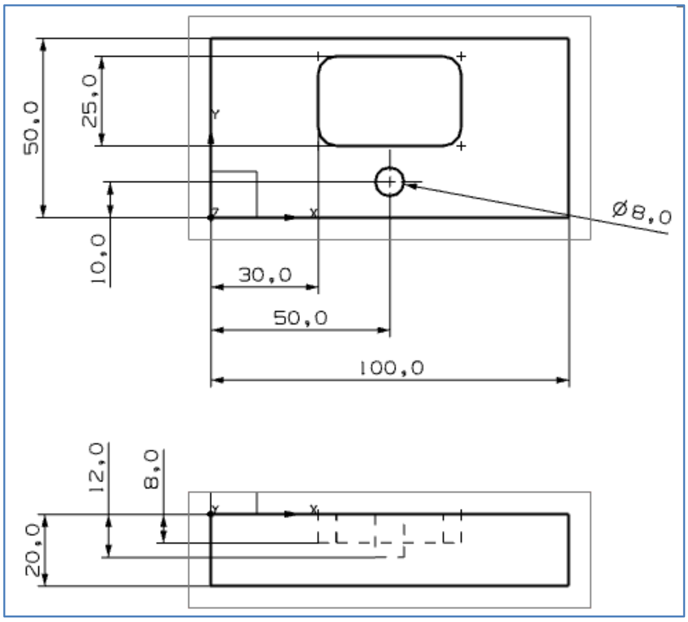


Figure 9.2 – Case study Part I design

The stock material for the machined part is a 50mm x 100mm x 20mm block. The STEP-NC entity representation for the features and operations that make up the standard compliant process plan are as follows in Table 7.2:

Table 9.2 - STEP-NC process plan representation for Part 1 manufacture

Workingstep	**Operation sequence**	**Operation entity**	**Feature**
WS1	OP1	Plane_milling	Planar face
WS2	OP2	Bottom_and_side_milling (Rough)	Pocket
WS3	OP3	Bottom_and_side_milling (Finish)	Pocket
WS4	OP4	Drilling	Round hole

Each operation has its machining parameters such as cutting speed, feed rate and depth of cut. The standard compliant platform generated STEP-NC file for the same part manufacture has been used as the SBC input. The SBC prototype parsed the standardised information and retrieved the cost elements data values as described in chapter 8**,** and utilised them to generate machining time and cost estimate. The retrieved cost element parameters for the case study part 1 are displayed in the SBC system graphical user interface (GUI) under the 'Time estimation report' heading. The category of product creation processes data and their actual values that were retrieved from the STEP-NC file, for part 1, by the SBC system and utilised for machining time estimation are shown in table 9.3.

Table 9.3 - SBC retrieved cost elements parameters values for part 1

Data category	Cost element Parameters	Actual cost element value			
		Facing	Rectangular pocket		Drilled Hole
			Rough	Finish	
Design Data	Length (mm)	100	40	40	*NA*
	Width (mm)	50	25	25	*NA*
	Depth (mm)	1	12	12	14
	Diameter (mm)	*NA*	*NA*	*NA*	8
Process plan data	Feedrate (mm/min)	2972	1261	374	*NA*
	Spindle Speeds (rev/min)	800	4504	8000	3031
	Feed per tooth (mm/tooth)	*NA*	*NA*	*NA*	0.16
	Machining strategy	Bidirec-tional	Bidirec-tional	Contour	Drilling
	Axial cut depth (mm)	3	3	3	*NA*
Resource data	Tool diameter (mm)	40	14	14	8
	Tool teeth no.	4	2	2	2

The SBC system substituted the retrieved values into equations (7.3), (7.13), (7.14), (7.18) and (7.9) to calculate the cutting tool travel distance (lr) for drilling, contour and bi-direction machining strategies used to realised part 1's autonomous features. The obtained values for cutting tool travel distance (lr) were then used in conjunction with retrieved actual feedrates values to estimate machining time for each feature through substitution into equation (7.3), (7.7) and (7.11). As can be seen in table 9.3 there is no feedrate value reported for the drilling operation but the spindle speed, number of teeth and feed per tooth values were retrieved. These values are substituted into equation (7.2) by the SBC system to calculate the feedrate which is then used to estimate time taken for the drilling operation.

The system combined the estimated machining time for individual features to obtained the aggregated machining time for part 1; the part machining time estimate is then used in conjunction with manufacturer's specific labour and resource rates to calculate likely cost for part 1 production. The SBC application's GUI caption reporting the generated machining time and cost estimate results for the case study part (part 1) is shown in figure 9.3. Labour utilisation rate has been built into the system to enhance its flexibility by making it possible to specify the proportion (in percentages) of actual labour time spent at the machine tool. The utilisation rate of 100% has been entered for the case study part (I) suggesting that machinist stayed with the machine tool throughout. In circumstances where it can be established that the machinist only spent a portion of his time, say 50%, at the machine tool, then a value of '50' can be entered for the labour utilisation rate.

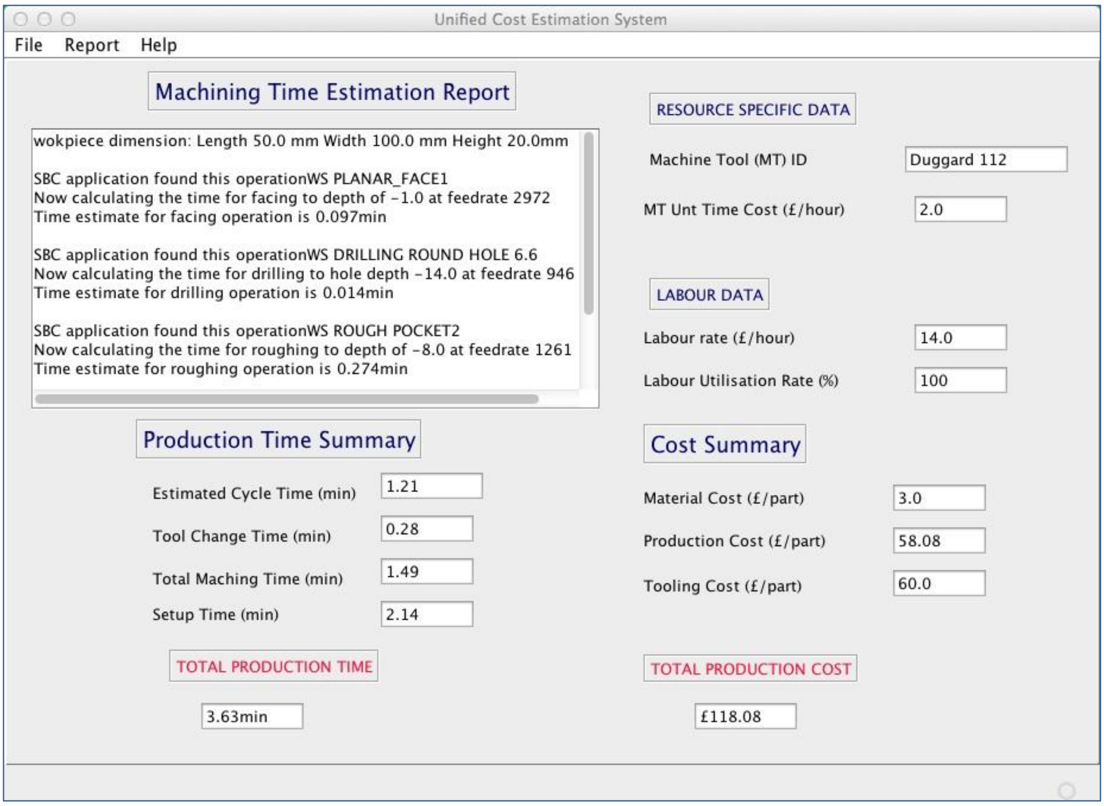


Figure 9.3 – SBC system time and cost estimation result display for part 1

9.3.2 **Test part 2**

The second case study milled component (Part II) has been designed with the intention to prove the ability of SBC to generate machining time and cost estimation for non-rectangular and slot features. In this part, there are two circular pockets with central round hole, an open slot and two interacting closed slots. These features are to be cut from a 50mm x 100mm x 20mm block. The drawing of the part is provided in Figure 9.4.

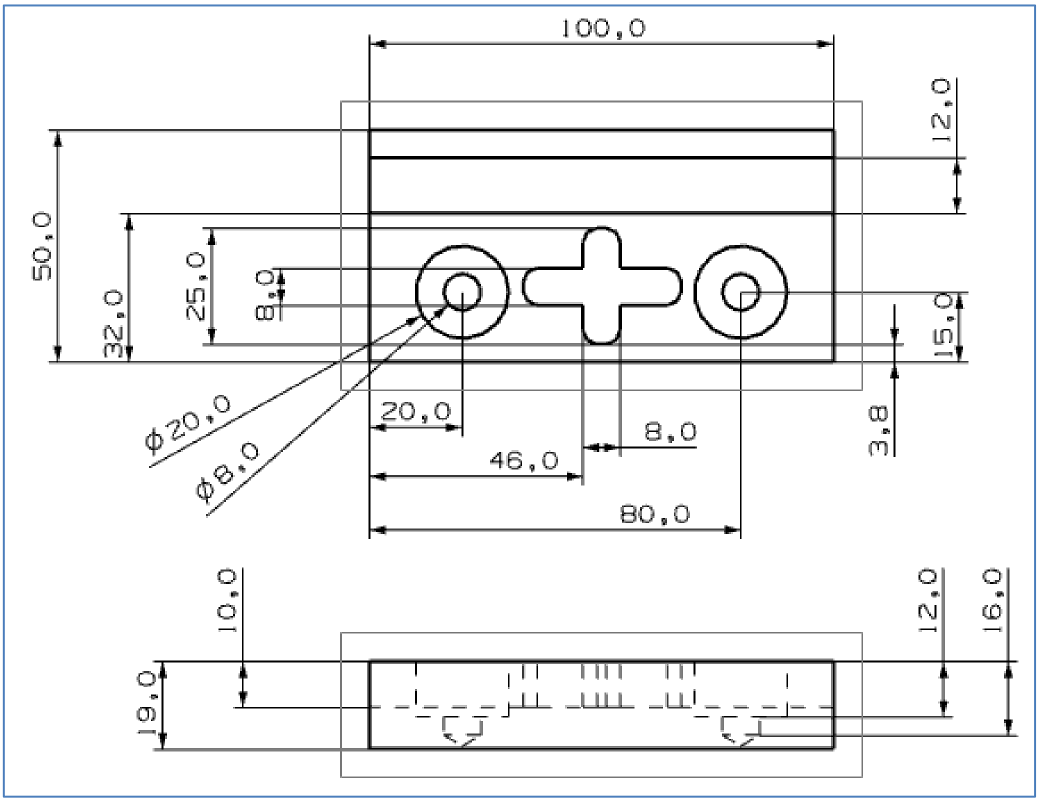


Figure 9.4 - Case study Part II design

The features and the operation that makes up the process plan are as follows in Table 9.4. The CAM system generated manufacturing sheet with time estimate for this part design can be found in the Appendix A.3. The generated STEP-NC file for this case study part is provided in Appendix A.4.

Table 9.4 - STEP-NC process plan representation for Part II manufacture

Workingstep	Operation sequence	Operation entity	Feature
WS1	OP1	Plane_milling	Planar face
WS2	OP2	Bottom_and_side_milling (Rough)	Cylindrical pocket
WS3	OP3	Bottom_and_side_milling (Finish)	Cylindrical pocket
WS4	OP4	Bottom_and_side_milling (Rough)	Cylindrical pocket
WS5	OP5	Bottom_and_side_milling (Finish)	Cylindrical pocket
WS6	OP6	Bottom_and_side_milling (Rough)	Closed slot
WS7	OP7	Bottom_and_side_milling (Rough)	Closed slot
WS8	OP8	Bottom_and_side_milling (Rough)	Open slot
WS9	OP9	Drilling	Round hole
WS10	OP10	Drilling	Round hole

The SBC system follows the same process as described for the previous case study component (part1) to perform standard compliant machining time estimation and cost calculations for current component (part II). The category of product creation process data and STEP-NC based actual values retrieved by SBC for time and cost estimates generation for this case study part are shown in table 9.5.

Table 9.5 - SBC retrieved cost elements parameters values for part II

Data category	**Cost element Parameters**	**Actual cost element value**							
		Facing	Cylindrical pockets		Closed slots		Open slot	Drilled holes	
			PI	PII	SI	S2		H1	H2
Design Data	Length (mm)	100	*NA*	40	25	25	100	*NA*	*NA*
	Width (mm)	50	*NA*	25	8	8	12	*NA*	*NA*
	Depth (mm)	1	12	12	12	12	10	16	16
	Diameter (mm)	*NA*	20	20	*NA*	*NA*	*NA*	8	8
Process plan data	Feedrate (MMPM)	4572	946	1261	1261	1261	1261	*NA*	*NA*
	Spindle Speeds (RPM)	800	5912	3941	7882	7882	5255	3031	3031
	Feed per tooth (MMPT)	0.191	0.08	0.160	0.080	0.08	0.120	0.16	0.16
	Machining strategy	Bidirec	Circ	Circ	Uni	Uni	Uni	Drill	Drill
	Axial cut depth (mm)	8	1.6	2.4	1.6	1.6	2.4	*NA*	*NA*
Resource data	Tool diameter (mm)	40	14	6	8	8	12	8	8
	Tool teeth no.	4	2	2	2	2	2	2	2

In a similar way for part I, the SBC system calculates the cutting tool travel distance (lr) for the cylindrical pocket machining by substituting the corresponding retrieved actual values shown in table 9.5 into equation (7.19) and (7.20). The SBC system also substituted retrieved corresponding values into equations ((7.3), (7.13), (7.14), (7.18) and (7.9) to calculate the cutting tool travel distance (lr) for the facing, slots and drilling operations. The calculated cutting tool travel distance (lr) values for individual features were used by the SBC system to generate individual feature's machining time estimates that were aggregated to obtain the total machining time estimate utilised with labour and facility rates to generate cost estimate for the current case study component (part II). The SBC machining time estimate result for this case study part (II) is compare with the featureCAM and the actual machining time estimate as shown in figure 9.5. The bar chart for the compared results indicates that the SBC time estimate result (4 minutes, 10 seconds) is marginally lower than the actual recorded machining time (4 minutes, 52 seconds) while on the other hand the commercial CAM (FeatureCAM) generated a comparatively higher machining time estimate (5 minutes, 12 seconds) than the actual recorded machining time. It is worth noting that the commercial CAM system have been program to account for both cutting and non-cutting tool movement for machining time estimate generation but only the time for cutting tool movements were recorded during actual machining of parts and by . This is a possible reason why the FeatureCAM time estimate result is higher than the actual results. The fact that the aggregated time estimate generated by the SBC system is also lower than the actual recorded machining time indicates the developed SBC's time estimation algorithms may require improvements. Therefore it is important to evaluate the estimated time for individual operation in order to identify the relevant time estimation algorithms for improvement.

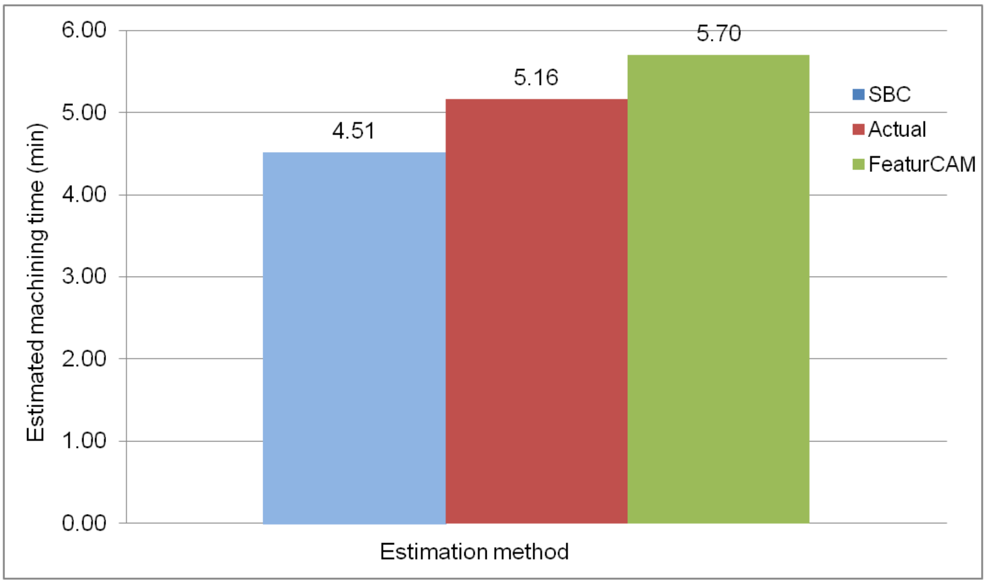


Figure 9.5 – Comparison of SBC machining time estimate result for case study part (II)

9.3.3 **Evaluation of operations time estimate result**

The two designed prismatic components were machined using a Duggard 3 axis CNC vertical machine tool and each timed machining durations for the two components were compared to the FeatureCAM generated machining time results and the develop prototype (SBC) machining time estimate results. The manufactured case study milled parts are shown in Figure 7.6.

(a) Manufactured case study part I

(b) Manufactured case study part II

Figure 7.6 – Manufacture milled parts

The difference in machining time estimate for the three estimation methods were compare in relative term to provide an objective analysis. Given that the developed SBC has been designed to be applicable within small and medium manufacturing enterprises, as well as in large facility the accuracy of developed system has to be within a range that is acceptable in the industry. Researchers have proposed 10% has a reasonable error for prismatic parts which this research aim to establish.

The analysis of the deviation among the machining times has been presented in figure 9.6 and Figure 9.7 where the actual machining time has been represented as 100%.

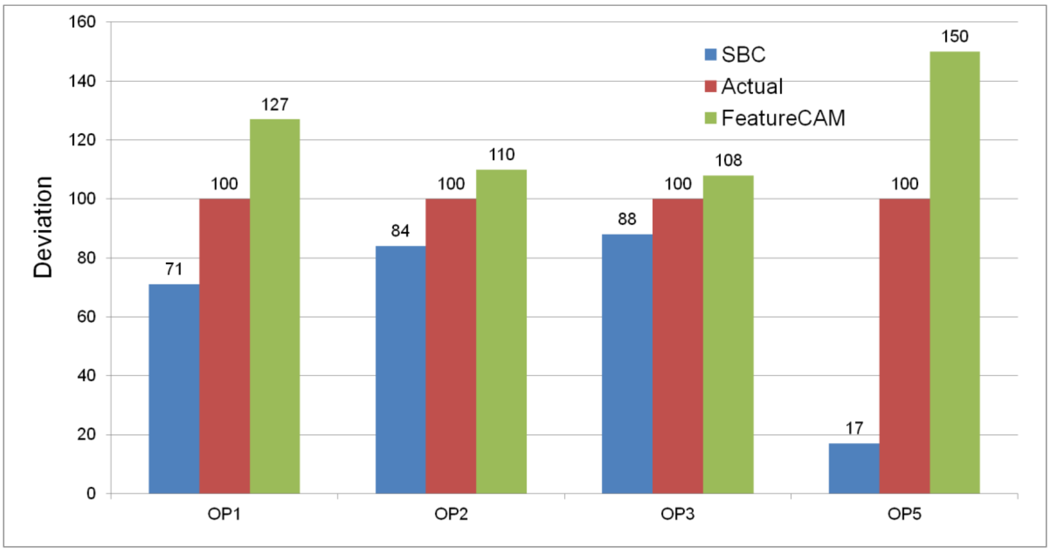


Figure 9.6 - Chart showing estimated machining time comparison for part I

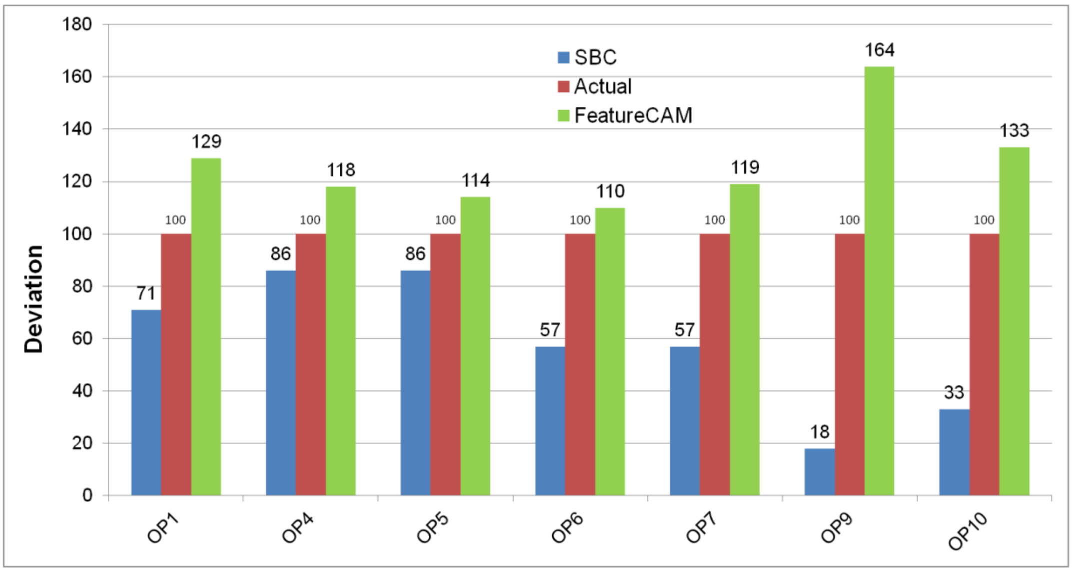


Figure 9.7 - Chart showing estimated machining time comparison for part II

According to figure 9.7 SBC generates lower estimates for the facing, drilling and the rectangular pocket machining operation. This provides a reasonable indication that the algorithms for these operation need further improvement. While FeatureCAM accounts for both the cutting and the non-cutting tool paths, its overcompensation for tool path between operation may be a reason for the higher time estimate results. Also, the SBC system generated machining time estimate for drilling operations were markedly lower compare to the actual recorded times for this type of operation. One explanation for this is that the SBC tool path calculation algorithm does not sufficiently account for the movement involved in a particular type of drilling operation. Another explanation is that the system also does not consider the cutting tool retract movements that is performed during the actual drilling operation.

Other factors that may have caused the observed disparities between SBC machining time estimates and the actual result is the SBC system lack of capability to account for the inherent machine tool's spindle acceleration and deceleration during cutting operation movements and the XYZ movement accuracy of the machine tool during machining operation.

Considering that modern CNC machine tools, like the ones utilized in the research, are capable of very fast rapid movement, the non cutting time is significantly reduce. For this reason the non-productive time has not been evaluated in this research. Whereas the cutting distance travelled during rapid and retract movement are components of the FeatureCAM time estimate results for each operation, hence a possible reason why the featureCAM estimated results are higher than the actual recorded time for most operations. While this comparative analysis of the machining time results generated by SBC and the commercial CAM system (FeatureCAM) indicates differences between the two, it none the less showed that the obtained results in most part followed similar pattern.

9.4 Advantages of the standarad based costing framework

Researchers have contended that a multi-faceted costing method is the ideal approach to obtain reliable estimate results and for satisfactory support for decision on alternatives during product creation(Lan and Ding, 2007, Xu et al., 2012, Elgh, 2008). This SBC framework provides a paradigm shift from partial integration of costing systems with CAx, CAD/CAM interfaces, to a multi-faceted integration with product development CAx chain. In a standard compliant based costing, instead of a single chain of CAD, CAM, unidirectional transfer of limited information, a detailed product creation information can be seamless exchange between the costing system and the various product creation CAx .

Other advantages of using the standard compliant costing framework, during integrated product creation, for automatic generation of reliable cost information feedback are:

(i) **Improves product development's information sharing** – researchers have reported the need for information models based costing methods to improve the sharing of product and manufacturing information (Xu et al., 2012). A standard based methodology, with its neutral format for data exchange, facilitates a unified information infrastructure to support the sharing of models and information relevant for product creation and costing process.

(ii) **Supports process planning at detailed design stage** – the need for costing research based on models representation of pre-defined product creation process has also been reported (Xu et al., 2012). STEP-NC's 'Workingstep entity' is a digitalised representation of actual processes performed to realise a given product. Therefore, a STEP-NC based method has the potential to support process planning from the detailed design stage through to the manufacture stage.

(iii) **Support for process planning during the bidding process –** Recognition of manufacturing features and associated manufacturing resource is important for generating highly accurate quotations to support a bidding process (Elgh, 2008). A STEP-NC based method provides a structured representation of manufacturing features, process and resource parameters that are applicable to support the company's activities toward efficiency increases, lead-time reduction and process-planning improvement.

(iv) **Support for automatic costing based on CAPP information** – STEP-NC provides the structured object-oriented linking of product design, process and manufacturing resources information. Hence a method based on STEP-NC, is important for automatic computer aided process-planning (CAPP) based costing because the required standardised parameters are specified and the sources of cost-drivers are traceable.

(v) **Uncertainty reduction in the costing process** – Literature indicates that the accuracy of cost estimates at the conceptual design stage are low but increases when the detailed information becomes available (Creese and Moore, 1990a, Corbett, 1986a). Reducing uncertainty caused by lack of detailed information during product development is an integral component of improving estimate accuracy. Another advantage of this research is that it implements a recognised international standard that preserves the integrity of information across the product creation process. This ensures the availability of quality and detailed information for costing, reducing data oriented uncertainty in the process and improve accuracy of cost estimates.

(vi) **Addresses lack of a standard based approach** – While a manufacturing standard based methodology has the potential to improve manufacturing costing process, only rare attempts have been made to harness its benefits. Researchers in the field of cost estimation agreed on the need for a method based on structured information medium linking product design to process-plan and manufacturing resources (Corbett, 1986a, Roy, 2003) but attempts are seldom made to develop such a system. The standard compliant framework bridges this research gap and contributes to knowledge in the researched area.

(vii) **Reduce time and cost associated with data gathering** – in addition to the significance of improving the cost estimation process in an integrated CNC manufacturing environment, this research also support the use of product creation information that exists within manufacturing facilities to reduce both the implementation cost and time taken for cost estimation activities. The high cost of establishing a database system and the comparatively long duration requires to perform a detailed product cost estimation are the reasons why feature based cost estimation are not widely adopted by small and medium size manufacturers. This research is intended to mitigate against these barriers for small and medium enterprises (SMEs) and make a significant contribution toward extending the applicability of ISO 14649 (STEP-NC) in CNC manufacture.

(viii) **Implementation of IM based solution** – a costing method based on formal model would benefit from the following advantages of information modelling:

- Formalisation often leads to the discovery of inconsistencies, omissions, ambiguities and contradictions;

- Formalisation guide systems development methodologies; and
- Detailed representation of product, process and resources processes enables seamless exchange of information across product creation chain.
- Formal models can be used to develop systems to realize the benefits brought about by the increased speed, efficiency and effectiveness of collaborative work.

The above outlined shows that the adoption of standard compliant costing method is therefore advantageous to manufacturers and can proactively provide the foundation for the next generation of costing research in a fully integrated environment.

9.5 Summary

This chapter demonstrates the viability of developed standard based costing system to determine cutting time for different machining operations. The results obtained from comparing the SBC system cutting time estimates with those taken from FeatureCAM software and from the actual machining of the part prove they are reliable within reasonable error margin and the established difference is predictable.

10 Discussions, Conclusions and future work

This chapters provides discussion on issues that were considered in relation to this research scope and context.

10.1 Discussion

10.1.1 **Integrated Product creation process**

The literature review on integrated product creation process in CNC manufacture in chapter 3, has shown that, while product design, process and manufacturing resources data are available within the integrated environment, each computer aided system uses proprietary format for uni-directional exchange of information with other computer aided system (CAx) in the product creation chain. This prevents high-level integration of the CAx and reduces the quality of information that is available for generation of reliable cost information feedback downstream of the product creation lifecycle.

A number of manufacturing standards have been developed to facilitate high-level integration and bi-directional exchange of information among product creation systems in CNC manufacture, which makes it possible to represent the entire product creation information in a neutral file format. The author believes this provides the opportunity to access available detailed product creation process information for product cost estimation. As a result a re-imagination of the costing researches based on new paradigms and emerging international standards is necessary. Visionary research into standards based costing can not only solve today's challenge of a lack of detailed information about a product to generate cost estimates but also provides the necessary tools to support digital manufacturing of the future.

10.1.2 A novel framework for realisation of standard compliant cost estimation

The framework envisioned in chapter 6, provides a novel and extensible foundation for enabling standards based costing in CNC manufacturing. The philosophy behind the framework is the utilisation of existing processes data to provide cost information feedback across the entire product creation lifecycle. By implementing manufacturing standards for cost estimation, detailed knowledge generated during the product creation process is accessible. The standards neutral file format ensures that the integrity of the captured processes information is maintained to provide high quality data for reliable and consistent product cost estimate. This is an exceptional improvement over the quantity and quality of information used by current integrated costing system to generate cost estimate, where detailed process and resource information are not available and bits of information are lost along the process chain.

Through the use of actual process data retrieved from manufacturing standards, the framework enables generation of a reliable cost estimate to support decision on alternative design, process and resources. The approach is also fundamentally different to conventional integrated costing systems that adopt non-transparent rules to compute nominal data used in product cost estimation.

10.1.3 **Computational platform for SBC**

To demonstrate SBC potential in an integrated manufacturing environment a computational software for translating machining and information objects in a Java based object oriented platform was implemented. This neutral file format is represented as an encoded text file according to the ISO 14649 standards. The text encoded file has been shown to contain the design, process and manufacturing information at different stages in the CAx chain. The developed SBC system provides an integrated costing interface that can utilise information derived from different stages of the product creation life cycle. This information, contained in a STEP-NC file, is presented in a unified manner to provide object oriented data that can be used by standard compliant applications for product manufacture and cost estimation processes improvement.

It has been shown that SBC system uses the STEP-NC standards high-level integration capability and the neutral file format for product cost estimation and to guide decision on alternative manufacturing resources.

10.1.4 **Prototype implementation**

In other to demonstrate the standards based costing methodology, a prototype has been implemented. As described in chapter 8, this prototype has been realised using three integrated resources; A standard compliant platform, a STEP-NC file and an estimation system fully developed in Java to demonstrate product cost estimation..

The prototype allows PCP data contained in a STEP-NC file to be retrieved and used to generate cost estimates for prismatic components. The accuracy of the cost estimate is reasonable. The prototype is also capable of supporting cost based guidance for selection of available CNC machine tools.

While the product creation process data retrieval and costing elements of the framework have been fully implemented in the prototype, a scaled down version of the manufacturing resource model has been implemented. This has been due to the fact that a system to fully incorporate a detailed resource model into a STEP-NC file was not available at the time of this research. The same object oriented logic for resource specific data retrieval, applicable to a detailed manufacturing resource model, has been maintained during the development of the prototype.

The prototype provides an actual interface to demonstrate the viability of standards based costing. Automatic transformation of STEP-NC file input into cost to support guidance on design, process and resource alternatives highlights the brilliance of using manufacturing standards' structured representation of detailed PCP information to get around the usual lack of access to detailed product creation information in costing.

10.1.5 Evaluation of the prototype

To evaluate the prototype implementation of the standards based costing system, an industrially inspired prismatic component has been utilised in a typical manufacturing condition. The condition involves the design of the component in CAD/CAM system, the translating of the NC codes to a STEP-NC file in a standard compliant platform and generating the cost estimate for the component. Comparison of the prototype time estimate with actual machining time and commercial CAM system shows the prototype perfoms satisfactorily. Furthermore, reviewed integrated cost estimation systems lack total transparency on how cost elements are used to generate cost estimates. Using the developed SBC prototype the cost elements of the estimate results can be traced back to their origin and changed to review their cost impact on product realisation.

10.1.6 **Limitation of the SBC**

Outlined below are some of the limitations of the developed SBC:

(i) A major limitation of the proposed SBC costing framework is that the ISO14649 (STEP-NC) standards is not yet widely adopted by manufacturers.

10.2 Conclusions

The conclusions that have been derived as the result of this research are provided as follows:

- In order to generate cost estimates across the product creation lifecycle, information from all applied computer aided systems must be accessible. Structured representation of information from all stages of product creation lifecycle is required to make the actual cost elements data available for product cost estimates. As the information throughout the product creation lifecycle are not presented in a unified manner, this is sometimes difficult to achieve.

- The current methods for integrated product cost estimation are unable to make use of detailed product creation information that exists within manufacturing environment as they are inadequately integrated with other CAx system. Thus high level integration that allow bi-directional exchange of information with other CAx is required to improve the cost estimation process, as current low-level integration creates information bottlenecks that prevent accessibility to quality information for product costing.

- STEP-NC has provided a way forward by supporting high-level integration and facilitating bi-directional information exchange in manufacturing environments. In STEP-NC product design, process planning and manufacturing resources are represented in a structured object oriented format and hence this information is accessible for product creation processes, including product costing, in STEP-NC compliant manufacturing environment. Adoption of the standard however requires a new cost estimation method.

- A costing approach based on STEP-NC standard can enable high level integration with other manufacturer's CAx. This framework can bring the benefits of access to detailed product creation information such as those provided by STEP-NC to cost estimation process. To realise this standard compliant framework three related components are required: (i) Recognition of standardised PCP information. (ii) Retrieval of actual product creation data for the standard file and (iii) Generation of cost estimate.

- A prototype implementation of the framework extract product creation data from a STEP-NC file to generate cost estimates has been realised to identify development issues and advantages. A Computational platform for standard compliant integration of computer aided systems allows presentation of PCP information as a STEP-NC file that makes standard compliant cost estimation a relatively simple process. Conventional integrated cost estimation system on the other hand requires costly and time consuming data gathering and analysis activities.

- Industrially inspired test components has been utilised in conjunction with the prototype implementation of the framework to evaluate the concept. The prismatic parts designed in a CAD system were transferred into a CAM system to generate NC code program that was transformed into STEP-NC file. Product creation cost elements were retrieved from the standard file and used to generate cost estimates to show the seamless application of data to generate cost information feedback. The automatic transformation of the PCP data from the STEP-NC to provide cost-base guidance on alternatives highlights the advantages of utilising the unified cost estimation framework.

10.3 Contribution to knowledge

A novel integrated costing system for CNC manufacture has been developed for cost estimation in industry and for knowledge contribution in the domain of manufacturing standards. The system is based on standardised information model (STEP-NC) and user interface design which permits access to detailed product creation processes information.

The novelty of this research lies in the realisation of a standards based costing application, that is, standards based costing (SBC) for CNC manufactured prismatic components. The author has described how to generate reliable cost estimate for a milled part by utilising manufacturing standard approach and its realisation through the SBC platform. This has been demonstrated by using a case study milled component and generating cost information from the part's STEP-NC file representation. This has enabled the use of detailed product creation process information that exists within integrated environment for reliable costing. The major benefits of the SBC system are quantified as follows:

- **Facilitates Real-Time Costing**

  The usefulness of cost information to manufacturing enterprise depends not only on its timeliness but also it must not take more time than it's worth to generate. Designing, process planning and manufacture of a product are fast moving activities in modern product development environment. As product cost is a critical product attribute, cost estimation process must keep pace with evolution in product development to facilitate the launching of the right product at the right time with the right cost.

  The developed SBC automatically evaluates the key processes involved in product creation lifecycle for cost drivers and because SBS is fully integrated with manufacturers CAD, CAM, CAPP and machine tools system, it can tap into the richness of the information the design engineer and manufacturing expert has already built. There is no need for manual entry of the part or assembly geometry, which is a major driver of product cost, into the costing system. Instead, SBC extracts the needed design, process and resource cost drivers every time the product development engineers add to or changes relevant product development process and; the user of SBC sees this cost responsively change in the system's user interface.

- **Minimise reliance on historical database and expert knowledge**

  Cost information is most valuable at the point at which it can guide and support decisions on alternative processes during product creation. Until recently, product development engineers have had very little information on how their design, process planning, and resources decisions affect cost. What little information that was available almost always came from the historical database system and was for past products. This information is only useful if all future products and the environment in which they are manufacture will be exactly like the past.

  SBC has been specifically designed to minimised dependence on historical data base that are time consuming and costly to implement for product cost estimation process. The system capability to generate estimate with little or no reliance on historical database significantly reduces the time to get product cost estimate from days to minutes and makes it possible to see the impact of actual changes, as it occurs, on product cost. This supports fast exploration of the cost of design alternatives by product development engineers. In the past this type of predictive cost assessment were manually performed, by cost estimation expert; using time consuming analyses methods or complicated systems. Consequently, generation of product cost information takes too long to be effective in today's agile manufacturing practices. SBC capability to generate cost in real time meant that instead of being able to explore one or two alternatives, product development engineers can explore as many as necessary.

- **Applicable across product creation lifecycle**

  Different processes across the integrated manufacturing environment impact product costs during product creation lifecycle. At different stages in the lifecycle, different process has different amount of impact on product cost. The product design, process planning and manufacturing decisions all affect product costs. The developed SBC system is applicable at all of these stages of product creation to reduce cost by predictively understanding product costs in real time before production.

  For new designs, the SBC system can provide an early understanding of the costs of a particular design or a design element as needed by the engineers during decision on alternative design. The system benefits from its direct integration and bi-directional information exchange with CAD system; so the design engineer can see the cost consequences of changes made in real time via the SBC system graphical user interface (GUI). Therefore, as different alternatives of a design are explored, SBC facilitates cost comparisons to determine cost effectiveness of each design alternative.

  Process planners and manufacturing engineers also explores the costs associated with various machining process alternatives to realise constituent features of a given part. This includes exploring the cost impacts of various machining strategies and the machining parameters. Through the SBC system, the cost impacts of these process planning alternatives can be explored and with the system design changes proposed to the design engineer by manufacturing engineers can be evaluated by understanding their product cost implications.

- **Provides consistent and reliable cost estimate**

  An accurate costing system can be describe as a system which generates cost estimate that exactly matches the actual cost incurred for a given product realisation. However, in reality multiple factors including data uncertainties and shop floor dynamics such as constraint due to resource logistic mitigates against accuracy of costing system. Therefore, developing a reliable costing system with industrially acceptable ranges of accuracies is imperative. In the context of this research, reliability is the ability to consistently generate cost estimate results that are within acceptable accuracy. The generation of a reliable cost estimate requires a precise method of calculation that accounts for actual cost driving parameters, not unrepeatable expert opinion or black box iterated cost result.

  The SBC method is based on the utilisation of actual data used to realise a machined part. As these data determines the manufacturing feasibility and resources utilisation, they present cost driving parameters that aiming directly at the true product cost. The SBC methods provide a repeatable cost, no matter who is using the system. The cost in physical resources for a given part provided by the standards based method only change when a real change is made in the manufacturing environment.

- **Standardised manufacturing costing process**

  A major problem today in trying to reduce cost is that everyone is using different methods and data to calculate cost at different stage of the product creation lifecycle. Design, process planning and production planning engineers may all have their different methods for assessing product cost. Not only is this a waste of time for the organization as a whole, but more importantly, it causes confusion and missed opportunities for cost reductions. The SBC system has been designed to be applicable across the product creation lifecycle for productivity improvement. The system can be used at stages on product development to generate cost estimate using internationally recognised manufacturing standards that represents precise cost parameters that show relative cost effects of design, process and manufacturing decisions before product realisation.

The implementation on internationally recognised manufacturing standards capable of representing manufacturer's internal facilities as well as supplier's facilities enables effective reflection of manufacturing facilities capabilities as well as the associated cost structure. The SBC system requires little to no maintenance and provides an instant cost (for internal factories) or like price (for suppliers) for a given part to be manufactured.

Also, the utilisation of the exchangeable non-proprietary standard to share information on available manufacturing resources makes negotiation between collaborating manufactures fact-based. Instead of confusion on what is profitable for the collaborating parties, the should-cost of the product is readily established. Then the collaborating partners can openly arrive at a fair profit for all sides.

- **New approach to manufacturing cost estimation**

  The developed SBC system also has the potential to be a useful resource for teaching new approaches to manufacturing costing. It allows the subject to be introduced to product development engineers in a more structured and familiar manner. The CAx oriented approach of the system is more appealing to the new generation of product creation engineers and university students.

10.4 Future Work

In the course of this research a number of opportunities for advancing this research work have been identified. The evolving nature of manufacturing standards and the extensibility of the proposed standards based costing translate into vast potential to develop a fully integrated costing system for any manufacturing process with standards representation and provide a platform for future research.

10.4.1 **Extension of the SBC into other STEP-NC based processes**

As the SBC framework uses STEP-NC's structured data representation for a milled component, it is possible to extend the standard based costing to include other manufacturing process, such as turning operation and EDM, which are STEP-NC compliant. Figure 10.1 shows how the addition of further processes to the SBC framework enables extensive coverage of processes found in CNC manufacturing environment.

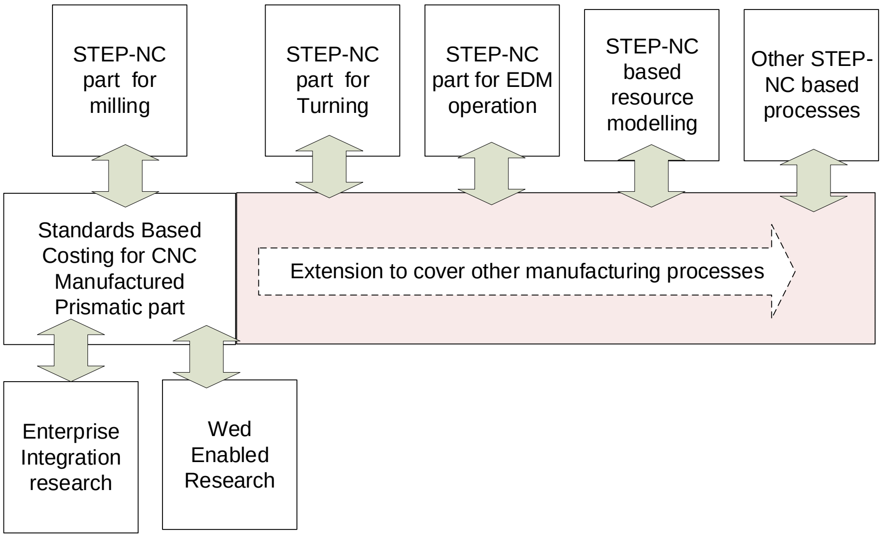


Figure 10.1 - Extension of the SBC into other STEP-NC based processes

10.4.2 **Non prismatic part application**

The SBC framework has only been developed for prismatic parts based on simple features such as pockets, slots etc that are machined using simplified machining strategies. To be able to provide time and cost estimation in industrial practice where manufacturing is not limited to prismatic parts, the SBC framework capability needs further development to include cutting tool travelled distance for sculptured surfaces.

10.4.3 **Online SDC framework**

The world wide web enables information to be stored and transferred in natural language. This allows for effective sharing of product creation information among geographically distributed collaborating manufacturers. Emerging web enabled facilities for information modelling definitions; the integrated resource definitions and increasing support for international standards make the web a viable technology for future developments of online SBC framework.

10.4.4 **Comprehensive Manufacturing Resource Models**

An important and pivotal requirement for the wide adoption of the SBC is the availability of resource definitions to provide detailed information about manufacturing resources and associated auxiliaries. The development of a comprehensive resource data model could enormously enhance the costing result by providing detailed cost relevant information about individual resources. CNC machine models and CAD/CAM system interface models, expressed in a common modelling language like universal modelling language (UML) would provide such a comprehensive resource model.

The SBC framework is mainly based on limited manufacturing resource information, in which certain cost relevant data are missing. The integration of a STEP-NC based comprehensive resource data model (Vichare *et al.* 2009), could enormously enhance the costing result by providing detailed cost relevant information about individual resources.

10.4.5 **Time estimation improvement**

It has been established in chapter 9 that the developed SBC prototype's time estimation algorithms for a number of operations need further improvement. The drilling operations algorithms have to be improved in order to take into account the real movement of the tool. The pocket milling operation algorithms can also be improved to closely reflect the actual tool path for both the rectangular and cylindrical closed pockets. Another option for improving the accuracy of the developed system is to calculate a table with different correction factors, depending on individual manufacturing feature and cutting tool geometries, and incorporate them in the equation for the relevant operation's time estimation algorithms.

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Appendix A. Publications Based on the Research

A number of scientific peer reviewed papers were published by the author during the course of the research documented in this thesis. In this appendix, the titles and, in the case of conference papers, the abstracts for these papers are presented.

Conference Papers

1. **Abayomi B. O debode**, Aydin Nassehi, Linda B. Newnes and Stephen T. Newman
   'Integrated machining time estimation using standardised micro-process planning information',
   Proceedings of the 21st International Conference on Flexible Automation and Intelligent Manufacturing Conference (FAIM2010) Taiwan, July 2010, pp831-839.

   Rapid and accurate cost estimation supports design and manufacturing engineers decision making in providing cost reducing alternatives. Early cost estimates at the design stage fail to give proper consideration to the manufacturing activity, particularly the actual machining time, which consequently results in estimate of questionable accuracy. Machining cost is considered proportional to machining time, which includes operational time and non-operational time. Where operation time includes rough cutting time and finish cutting time and its accurate estimation depends on using actual machining parameters. This poses a challenge, because current estimation systems lack the capability for bi-directional information exchange with other computer aided systems in an integrated manufacturing environment. The purpose of this paper is to present a machining time estimating methodology for CNC machined components based on a ISO manufacturing standard.

   The methodology is based on the use of standard representations of manufacturing features for CNC components are used as major cost parameters. The major part of the paper presents a methodology that is capable of utilizing actual product design, manufacturing processes and machining parameters information that are available in the STEP-NC standard (ISO 14649) to generate fast and accurate machining time estimates. This methodology is demonstrated through the capture of manufacturing information from STEP-NC for a CNC machined discrete milling component.

2. **Abayomi B. O debode**, Aydin Nassehi, Linda B. Newnes and Stephen T. Newman
   'A cost estimation system for CNC machine selection based on step-nc standards',
   Proceedings of the International Conference Management of Technology – Step to Sustainable Production (MOTSP 2012), Jun-2012, Zadar, Croatia, pp 185-192.

   A critical challenge in manufacturing cost estimation is the lack of high level integration with computer aided system (CAx) to access design and manufacturing resources cost data across the product development cycle. The evolving ISO 14649 standard (STEP-NC) contains product design and machining process planning data, that when combined with machine tool data will enable production planning and cost information to be accurately generated. This paper presents the development of a STEP-NC compliant system for machine tool selection using a machine tool database based on machining operations.

   This system aims to overcome existing cost estimation system limitations by incorporating manufacturing data for each individual machine tool into the estimation process. In addition, the approach provides planners with a suggested machine tool for a given component based on a predicted manufacturing time and cost comparison using STEP-NC data.

3. **Abayomi B. O debode**, Aydin Nassehi, Linda B. Newnes and Stephen T. Newman
   'STEP-NC compliant manufacturing cost estimation system for CNC milled part component',
   Proceedings of the 37th International Conference on Proceeding of the 37th International MATADOR Conference, Manchester, UK, 25th-27th July 2012, pp53-56.

   Manufacturers depend on cost estimation system, at the early stage of product development, to supports engineers decision on design alternatives toward reducing final product cost. Lack of detail information about a product and its manufacture to generate fast and accurate cost estimate is a critical challenge in integrated manufacturing environment today. Most cost estimation systems relies on expert opinion and nominal information about the product to generate cost estimate of questionable accuracy. High level integration of cost estimation system with manufacturer' other computer aided systems for seamless exchange of actual design and process information about a product can potentially improve the accuracy of cost estimate. However, each computer aided system, including current integrated cost estimation systems, uses vendor-specific programming for unidirectional communication with other manufacturing systems. This hinders seamless flow of actual information about the product that is required for fast and accurate cost estimation during product development. Implementation of a vendor-neutral communication language will facilitate bidirectional sharing of quality information for interoperability and accurate cost estimate.

   In this paper the evolving ISO 14649 standards (STEP-NC) is implement as a vendor-neutral mediun for high level integration of estimation system with other computer aided systems for fast and accurate cost estimation.

Appendix B. STEP-NC files for the case study components

B.1. STEP-NC files for the case study part in the standards document

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION(('ISO 14649-11 EXAMPLE 1',
      'SIMPLE PROGRAM WITH A PLANAR_FACE, A POCKET, AND A
      ROUND_HOLE'),
      '1');
FILE_NAME('EXAMPLE1.STP',
      '2002-02-02',
      ('YONG TAK HYUN','JOCHEN WOLF'),
      ('WZL, RWTH-AACHEN'),
      $,
      'ISO 14649',
      $);

FILE_SCHEMA(('MACHINING_SCHEMA','MILLING_SCHEMA'));

ENDSEC;

DATA;
#1= PROJECT('EXECUTE EXAMPLE1',#2,(#4),$,$,$);
#2= WORKPLAN('MAIN WORKPLAN',(#10,#11,#12,#13,#14),$,#8,$);
#4= WORKPIECE('SIMPLE WORKPIECE',#6,0.010,$,$,$,(#66,#67,#68,#69));
#6= MATERIAL('ST-50','STEEL',(#7));
#7= PROPERTY_PARAMETER('E=200000N/M2');
#8= SETUP('SETUP1',#71,#62,(#9));
#9= WORKPIECE_SETUP(#4,#74,$,$,());
#10= MACHINING_WORKINGSTEP('WS FINISH PLANAR FACE1',#62,#16,#19,$);
#11= MACHINING_WORKINGSTEP('WS DRILL HOLE1',#62,#17,#20,$);
#12= MACHINING_WORKINGSTEP('WS REAM HOLE1',#62,#17,#21,$);
#13= MACHINING_WORKINGSTEP('WS ROUGH POCKET1',#62,#18,#22,$);
#14= MACHINING_WORKINGSTEP('WS FINISH POCKET1',#62,#18,#23,$);
#16= PLANAR_FACE('PLANAR FACE1',#4,(#19),#77,#63,#24,#25,$,());
#17= ROUND_HOLE('HOLE1 D=22MM',#4,(#20,#21),#81,#64,#58,$,#26);
#18=
CLOSED_POCKET('POCKET1',#4,(#22,#23),#84,#65,(),$,#27,#35,#37,#28);
#19= PLANE_FINISH_MILLING($,$,'FINISH PLANAR
FACE1',10.000,$,#39,#40,#41,$,
#60,#61,#42,2.500,$);
#20= DRILLING($,$,'DRILL HOLE1',10.000,$,#44,#45,#41,$,$,$,$,$,#46);
#21= REAMING($,$,'REAM
HOLE1',10.000,$,#47,#48,#41,$,$,$,$,$,#49,.T.,$,$);
#22= BOTTOM_AND_SIDE_ROUGH_MILLING($,$,'ROUGH
POCKET1',15.000,$,#39,#50,#41
,$,$,$,#51,2.500,5.000,1.000,0.500);
```

```
#23= BOTTOM_AND_SIDE_FINISH_MILLING($,$,'FINISH
POCKET1',15.000,$,#39,#52,
#41,$,$,$,#53,2.000,10.000,$,$);
#24= LINEAR_PATH($,#54,#55);
#25= LINEAR_PROFILE($,#57);
#26= THROUGH_BOTTOM_CONDITION();
#27= PLANAR_POCKET_BOTTOM_CONDITION();
#28= GENERAL_CLOSED_PROFILE($,#59);
#29= TAPERED_ENDMILL(#30,4,$,.F.,$,$);
#30= MILLING_TOOL_DIMENSION(20.000,$,$,$,1.500,$,$);
#31= TWIST_DRILL(#32,2,.RIGHT.,.F.,0.840);
#32=
MILLING_TOOL_DIMENSION(20.000,31.000,0.100,45.000,2.000,5.000,8.000)
;
#33= TAPERED_REAMER(#34,6,$,.F.,$,$);
#34= MILLING_TOOL_DIMENSION(22.000,$,$,$,$,$,$);
#35= TOLERANCED_LENGTH_MEASURE(1.000,#36);
#36= PLUS_MINUS_VALUE(0.100,0.100,3);
#37= TOLERANCED_LENGTH_MEASURE(10.000,#38);
#38= PLUS_MINUS_VALUE(0.100,0.100,3);
#39= MILLING_CUTTING_TOOL('MILL 20MM',#29,(#125),80.000,$,$);
#40= MILLING_TECHNOLOGY(0.040,.TCP.,$,12.000,$,.F.,.F.,.F.,$);
#41= MILLING_MACHINE_FUNCTIONS(.T.,$,$,.F.,$,(),.T.,$,$,());
#42= BIDIRECTIONAL_MILLING(5.000,.T.,#43,.LEFT.,$);
#43= DIRECTION('STRATEGY PLANAR FACE1:
1.DIRECTION',(0.000,1.000,0.000));
#44=
MILLING_CUTTING_TOOL('SPIRAL_DRILL_20MM',#31,(#126),90.000,$,$);
#45= MILLING_TECHNOLOGY(0.030,.TCP.,$,16.000,$,.F.,.F.,.F.,$);
#46=
DRILLING_TYPE_STRATEGY(75.000,50.000,2.000,50.000,75.000,8.000);
#47= MILLING_CUTTING_TOOL('REAMER_22MM',#33,(#127),100.000,$,$);
#48= MILLING_TECHNOLOGY(0.030,.TCP.,$,18.000,$,.F.,.F.,.F.,$);
#49= DRILLING_TYPE_STRATEGY($,$,$,$,$,$);
#50= MILLING_TECHNOLOGY($,.TCP.,$,20.000,$,.F.,.F.,.F.,$);
#51= CONTOUR_BIDIRECTIONAL($,$,$,$,$,$);
#52= MILLING_TECHNOLOGY($,.TCP.,$,20.000,$,.F.,.F.,.F.,$);
#53= CONTOUR_PARALLEL(5.000,.T.,.CW.,.CONVENTIONAL.);
#54= TOLERANCED_LENGTH_MEASURE(120.000,#56);
#55= DIRECTION('COURSE OF TRAVEL DIRECTION',(0.000,1.000,0.000));
#56= PLUS_MINUS_VALUE(0.300,0.300,3);
#57= NUMERIC_PARAMETER('PROFILE LENGTH',100.000,'MM');
#58= TOLERANCED_LENGTH_MEASURE(22.000,#56);
#59= POLYLINE('CONTOUR OF POCKET1',(#121,#122,#123,#124,#121));
#60= PLUNGE_RAMP($,45.000);
#61= PLUNGE_RAMP($,45.000);
#62= ELEMENTARY_SURFACE('SECURITY PLANE',#73);
#63= ELEMENTARY_SURFACE('PLANAR FACE1-DEPTH PLANE',#80);
#64= ELEMENTARY_SURFACE('DEPTH SURFACE FOR ROUND HOLE1',#83);
#65= ELEMENTARY_SURFACE('DEPTH SURFACE FOR POCKET1',#94);
#66= CARTESIAN_POINT('CLAMPING_POSITION1',(0.000,20.000,25.000));
```

```
#67= CARTESIAN_POINT('CLAMPING_POSITION2',(100.000,20.000,25.000));
#68= CARTESIAN_POINT('CLAMPING_POSITION3',(0.000,100.000,25.000));
#69= CARTESIAN_POINT('CLAMPING_POSITION4',(100.000,100.000,25.000));
#71= AXIS2_PLACEMENT_3D('SETUP1',#95,#96,#97);
#73= AXIS2_PLACEMENT_3D('PLANE1',#98,#99,#100);
#74= AXIS2_PLACEMENT_3D('WORKPIECE',#101,#102,#103);
#77= AXIS2_PLACEMENT_3D('PLANAR FACE1',#104,#105,#106);
#80= AXIS2_PLACEMENT_3D('PLANAR FACE1',#107,#108,#109);
#81= AXIS2_PLACEMENT_3D('HOLE1',#110,#111,$);
#83= AXIS2_PLACEMENT_3D('HOLE1',#112,#113,#114);
#84= AXIS2_PLACEMENT_3D('POCKET1',#115,#116,#117);
#94= AXIS2_PLACEMENT_3D('POCKET1',#118,#119,#120);
#95= CARTESIAN_POINT('SETUP1: LOCATION ',(150.000,90.000,40.000));
#96= DIRECTION(' AXIS ',(0.000,0.000,1.000));
#97= DIRECTION(' REF_DIRECTION',(1.000,0.000,0.000));
#98= CARTESIAN_POINT('SECPLANE1: LOCATION ',(0.000,0.000,30.000));
#99= DIRECTION(' AXIS ',(0.000,0.000,1.000));
#100= DIRECTION(' REF_DIRECTION',(1.000,0.000,0.000));
#101= CARTESIAN_POINT('WORKPIECE1:LOCATION ',(0.000,0.000,0.000));
#102= DIRECTION(' AXIS ',(0.000,0.000,1.000));
#103= DIRECTION(' REF_DIRECTION',(1.000,0.000,0.000));
#104= CARTESIAN_POINT('PLANAR FACE1:LOCATION ',(0.000,0.000,5.000));
#105= DIRECTION(' AXIS ',(0.000,0.000,1.000));
#106= DIRECTION(' REF_DIRECTION',(1.000,0.000,0.000));
#107= CARTESIAN_POINT('PLANAR FACE1:DEPTH ',(0.000,0.000,-5.000));
#108= DIRECTION(' AXIS ',(0.000,0.000,1.000));
#109= DIRECTION(' REF_DIRECTION',(1.000,0.000,0.000));
#110= CARTESIAN_POINT('HOLE1: LOCATION ',(20.000,60.000,0.000));
#111= DIRECTION(' AXIS ',(0.000,0.000,1.000));
#112= CARTESIAN_POINT('HOLE1: DEPTH ',(0.000,0.000,-30.000));
#113= DIRECTION(' AXIS ',(0.000,0.000,1.000));
#114= DIRECTION(' REF_DIRECTION',(1.000,0.000,0.000));
#115= CARTESIAN_POINT('POCKET1: LOCATION ',(45.000,110.000,0.000));
#116= DIRECTION(' AXIS ',(0.000,0.000,1.000));
#117= DIRECTION(' REF_DIRECTION',(-1.000,0.000,0.000));
#118= CARTESIAN_POINT('POCKET1: DEPTH ',(0.000,0.000,-30.000));
#119= DIRECTION(' AXIS ',(0.000,0.000,1.000));
#120= DIRECTION(' REF_DIRECTION',(1.000,0.000,0.000));
#121= CARTESIAN_POINT('P1',(0.000,0.000,0.000));
#122= CARTESIAN_POINT('P2',(0.000,80.000,0.000));
#123= CARTESIAN_POINT('P3',(-50.000,80.000,0.000));
#124= CARTESIAN_POINT('P4',(-50.000,0.000,0.000));
#125= CUTTING_COMPONENT(80.000,$,$,$);
#126= CUTTING_COMPONENT(90.000,$,$,$);
#127= CUTTING_COMPONENT(100.000,$,$,$);

ENDSEC;

END-ISO-10303-21;
```

B.2. STEP-NC files for the case study part (I)

```
ISO-10303-21;

HEADER;

FILE_DESCRIPTION(('GENERATED ISO 14649-11 FILE','AUTOMATIC OUTPUT OF
UPCi FROM A CNC PART PROGRAMME'), '1');

FILE_NAME('EXAMPLE.STP', '2012-10-17', ('Abayomi O
Debode'),('UNIVERSITY OF BATH, BATH,UK'),$,'ISO 14649',$);

FILE_SCHEMA(('MACHINING_SCHEMA','MILLING_SCHEMA'));

ENDSEC;


DATA;


ISO-10303-21;

HEADER;

FILE_DESCRIPTION(('GENERATED ISO 14649-11 FILE','AUTOMATIC OUTPUT OF
UPCi FROM A CNC PART PROGRAMME'), '1');

FILE_NAME('EXAMPLE.STP', '2013-08-14', ('Abayomi O
Debode'),('UNIVERSITY OF BATH, BATH,UK'),$,'ISO 14649',$);

FILE_SCHEMA(('MACHINING_SCHEMA','MILLING_SCHEMA'));

ENDSEC;


DATA;
#1=PROJECT('RECOGNISED ISO 14649 PART 21  FILE FROM G&M
CODES',#2,(#3),$,$,$);
#2=WORKPLAN('MAIN WORKPLAN',(#4,#5,#6,#7,#8),$,#9,$);
#3=WORKPIECE('WORKPIECE50.0X100.0X20.0',$,$,$,$,#21,());
#4=MACHINING_WORKINGSTEP('WS PLANAR_FACE1',#10,#11,#12,$);
#5=MACHINING_WORKINGSTEP('WS DRILLING ROUND HOLE 6.6',#10,#44,#45,$);
#6=MACHINING_WORKINGSTEP('WS REAMING ROUND HOLE 6.6',#10,#44,#46,$);
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#7=MACHINING_WORKINGSTEP('WS ROUGH POCKET2',#10,#69,#70,$);
#8=MACHINING_WORKINGSTEP('WS FINISH POCKET2',#10,#69,#71,$);
#9=SETUP('SETUP',#150,#10,(#151));
#10=ELEMENTARY_SURFACE('SECURITY PLANE',#13);
#11=PLANAR_FACE('PLANAR_FACE1',#3,(#12),#17,#18,#19,#20,$,());
#12=PLANE_ROUGH_MILLING($,$,'PLANAR_FACE1',$,$,#26,#27,#28,$,#29,#30,#31,
$,$);
#13=AXIS2_PLACEMENT_3D('SECURITY PLANE PLACEMENT',#14,#15,#16);
#14=CARTESIAN_POINT('SECURITY PLANE: LOCATION',(0.0,0.0,10.0,0.0,0.0));
#15=DIRECTION('AXIS',(0.0,0.0,1.0));
#16=DIRECTION('REF_DIRECTION',(1.0,0.0,0.0));
#17=AXIS2_PLACEMENT_3D('PLANAR_FACE1 PLACEMENT',#34,#35,#36);
#18=ELEMENTARY_SURFACE('PLANAR_FACE1 DEPTH PLANE',#37);
#19=LINEAR_PATH($,#41,#42);
#20=LINEAR_PROFILE($,#43);
#21=BLOCK('WORKPIECE BLOCK',#22,50.0,100.0,-20.0);
#22=AXIS2_PLACEMENT_3D('WORKPIECE BLOCK PLACEMENT',#23,#24,#25);
#23=CARTESIAN_POINT('WORKPIECE BLOCK: LOCATION',(0.0,0.0,0.0));
#24=DIRECTION('AXIS',(0.0,0.0,1.0));
#25=DIRECTION('REF_DIRECTION',(1.0,0.0,0.0));
#26=MILLING_CUTTING_TOOL('T8',#32,(),$,$,$);
#27=MILLING_TECHNOLOGY(2972.0,.TCP.,$,800.0,$,$,$,$,$);
#28=MILLING_MACHINE_FUNCTIONS(.F.,$,$,$,$,(),$,$,$,());
#29=PLUNGE_RAMP($,$);
#30=PLUNGE_RAMP($,$);
#31=BIDIRECTIONAL($,$,$,$,$);
#32=FACEMILL(#33,$,$,$,$);
#33=MILLING_TOOL_DIMENSION(66.0,$,$,$,0.0,$,$);
#34=CARTESIAN_POINT('PLANAR_FACE1',(90.0,20.0,0.0));
#35=DIRECTION('AXIS',(0.0,0.0,1.0));
#36=DIRECTION('REF_DIRECTION',(1.0,0.0,0.0));
#37=AXIS2_PLACEMENT_3D('PLANAR_FACE1 DEPTH',#38,#39,#40);
#38=CARTESIAN_POINT('PLANAR_FACE1 DEPTH',(0.0,0.3,-1.0));
#39=DIRECTION('AXIS',(0.0,0.0,1.0));
```

```
#40=DIRECTION('REF_DIRECTION',(1.0,0.0,0.0));
#41=TOLERANCED_LENGTH_MEASURE(189.0,$);
#42=DIRECTION('PLANAR FACE DIRECTION',(0.0,1.0,0.0));
#43=NUMERIC_PARAMETER('null',119.3,'mm');
#44=ROUND_HOLE('ROUND HOLE 6.6',#3,(#45,#46),#47,#48,#49,$,$);
#45=MULTISTEP_DRILLING($,$,'DRILLING ROUND HOLE
6.6',$,$,#50,#51,#52,$,$,$,$,$,#53,0.0,6.3,6.3,$);
#46=REAMING($,$,'REAMING ROUND HOLE
6.6',$,$,#56,#57,#58,$,$,$,$,$,#59,.F.,$,$);
#47=AXIS2_PLACEMENT_3D('ROUND HOLE 6.6 PLACEMENT',#62,#63,#64);
#48=ELEMENTARY_SURFACE('ROUND HOLE 6.6 DEPTH PLANE',#65);
#49=TOLERANCED_LENGTH_MEASURE(12.0,$);
#50=MILLING_CUTTING_TOOL('T9',#54,(),$,$,$);
#51=MILLING_TECHNOLOGY($,.TCP.,0.16,3031.0,$,$,$,$,$);
#52=MILLING_MACHINE_FUNCTIONS(.F.,$,$,$,$,(),$,$,$,());
#53=DRILLING_TYPE_STRATEGY($,$,$,$,$,$);
#54=TWIST_DRILL(#55,2,$,$,$);
#55=MILLING_TOOL_DIMENSION(6.2,$,$,$,0.0,$,$);
#56=MILLING_CUTTING_TOOL('T7',#60,(),$,$,$);
#57=MILLING_TECHNOLOGY(805.43,.TCP.,$,3687,$,$,$,$,$);
#58=MILLING_MACHINE_FUNCTIONS(.F.,$,$,$,$,(),$,$,$,());
#59=DRILLING_TYPE_STRATEGY($,$,$,$,$,$);
#60=REAMER(#61,$,$,$,$);
#61=MILLING_TOOL_DIMENSION(6.6,$,$,$,0.0,$,$);
#62=CARTESIAN_POINT('ROUND HOLE 6.6 LOCATION',(10.0,50.0,0.0));
#63=DIRECTION('AXIS',(0.0,0.0,1.0));
#64=DIRECTION('REF_DIRECTION',(1.0,0.0,0.0));
#65=AXIS2_PLACEMENT_3D('ROUND HOLE 6.6 DEPTH',#66,#67,#68);
#66=CARTESIAN_POINT('ROUND HOLE 6.6 DEPTH',(10.0,50.0,-14.0));
#67=DIRECTION('AXIS',(0.0,0.0,1.0));
#68=DIRECTION('REF_DIRECTION',(1.0,0.0,0.0));
#69=CLOSED_POCKET('POCKET2',#3,(#70,#71),#72,#73,(),$,#74,#75,$,#76);
#70=BOTTOM_AND_SIDE_ROUGH_MILLING($,$,'ROUGH
POCKET2',$,$,#77,#78,#79,$,#80,#81,#82,3.0,12.0,0.5,1.0);
```

```
#71=BOTTOM_AND_SIDE_FINISH_MILLING($,$,'FINISH
POCKET2',$,$,#77,#85,#86,$,#87,#88,#89,3.0,1.0,0.0,0.0);
#72=AXIS2_PLACEMENT_3D('POCKET2 PLACEMENT',#90,#91,#92);
#73=ELEMENTARY_SURFACE('POCKET2 DEPTH PLANE',#93);
#74=PLANAR_POCKET_BOTTOM_CONDITION();
#75=TOLERANCED_LENGTH_MEASURE(0.0,$);
#76=GENERAL_CLOSED_PROFILE($,#97);
#77=MILLING_CUTTING_TOOL('T10',#83,(),$,$,$);
#78=MILLING_TECHNOLOGY(1261.0,.TCP.,$,4504.0,$,$,$,$,$);
#79=MILLING_MACHINE_FUNCTIONS(.F.,$,$,$,$,(),$,$,$,());
#80=PLUNGE_ZIGZAG($,$,$);
#81=PLUNGE_TOOLAXIS($);
#82=BIDIRECTIONAL ($,$,$,$,$,$);
#83=ENDMILL(#84,4,$,$,$);
#84=MILLING_TOOL_DIMENSION(14.0,$,$,$,0.0,$,$);
#85=MILLING_TECHNOLOGY(374.0,.TCP.,$,8000.0,$,$,$,$,$);
#86=MILLING_MACHINE_FUNCTIONS(.F.,$,$,$,$,(),$,$,$,());
#87=PLUNGE_ZIGZAG($,$,$);
#88=PLUNGE_TOOLAXIS($);
#89=CONTOUR($,$,$,$,$,$);
#90=CARTESIAN_POINT('POCKET2',(26.0,36.0,-0.97));
#91=DIRECTION('AXIS',(0.0,0.0,1.0));
#92=DIRECTION('REF_DIRECTION',(1.0,0.0,0.0));
#93=AXIS2_PLACEMENT_3D('POCKET2 DEPTH',#94,#95,#96);
#94=CARTESIAN_POINT('POCKET2 DEPTH',(12.5,0.5,-12.0));
#95=DIRECTION('AXIS',(0.0,0.0,1.0));
#96=DIRECTION('REF_DIRECTION',(1.0,0.0,0.0));
#97=COMPOSITE_CURVE('BOUNDARY:
POCKET2',(#98,#99,#100,#101,#102,#103,#104,#105),.F.);
#98=COMPOSITE_CURVE_SEGMENT(.CONTINUOUS.,.T.,#106);
#99=COMPOSITE_CURVE_SEGMENT(.CONTINUOUS.,.T.,#109);
#100=COMPOSITE_CURVE_SEGMENT(.CONTINUOUS.,.T.,#117);
#101=COMPOSITE_CURVE_SEGMENT(.CONTINUOUS.,.T.,#120);
#102=COMPOSITE_CURVE_SEGMENT(.CONTINUOUS.,.T.,#128);
```

```
#103=COMPOSITE_CURVE_SEGMENT(.CONTINUOUS.,.T.,#131);
#104=COMPOSITE_CURVE_SEGMENT(.CONTINUOUS.,.T.,#139);
#105=COMPOSITE_CURVE_SEGMENT(.CONTINUOUS.,.T.,#142);
#106=POLYLINE('POLYLINE FOR CONTOUR: POCKET2',(#107,#108));
#107=CARTESIAN_POINT('POLYLINE POINT 1',(13.0,34.0,7.97));
#108=CARTESIAN_POINT('POLYLINE POINT 2',(0.0,34.0,7.97));
#109=TRIMMED_CURVE('TRIMMED CURVE FOR CONTOUR OF
POCKET2',#110,(#111),(#112),.T.,.CARTESIAN.);
#110=CIRCLE('CIRCLE',#113,6.0);
#111=CARTESIAN_POINT('TRIM POINT 1',(0.0,34.0,7.97));
#112=CARTESIAN_POINT('TRIM POINT 2',(-6.0,28.0,7.97));
#113=AXIS2_PLACEMENT_3D('CIRCLE PLACEMENT',#114,#115,#116);
#114=CARTESIAN_POINT('CIRCLE CENTER',(0.0,28.0,7.97));
#115=DIRECTION('Z DIRECTION',(0.0,0.0,1.0));
#116=DIRECTION('X DIRECTION',(1.0,0.0,0.0));
#117=POLYLINE('POLYLINE FOR CONTOUR: POCKET2',(#118,#119));
#118=CARTESIAN_POINT('POLYLINE POINT 1',(-6.0,28.0,7.97));
#119=CARTESIAN_POINT('POLYLINE POINT 1',(-6.0,0.0,7.97));
#120=TRIMMED_CURVE('TRIMMED CURVE FOR CONTOUR OF
POCKET2',#121,(#122),(#123),.T.,.CARTESIAN.);
#121=CIRCLE('CIRCLE',#124,6.0);
#122=CARTESIAN_POINT('TRIM POINT 1',(-6.0,0.0,7.97));
#123=CARTESIAN_POINT('TRIM POINT 2',(0.0,-6.0,7.97));
#124=AXIS2_PLACEMENT_3D('CIRCLE PLACEMENT',#125,#126,#127);
#125=CARTESIAN_POINT('CIRCLE CENTER',(0.0,0.0,7.97));
#126=DIRECTION('Z DIRECTION',(0.0,0.0,1.0));
#127=DIRECTION('X DIRECTION',(1.0,0.0,0.0));
#128=POLYLINE('POLYLINE FOR CONTOUR: POCKET2',(#129,#130));
#129=CARTESIAN_POINT('POLYLINE POINT 1',(0.0,-6.0,7.97));
#130=CARTESIAN_POINT('POLYLINE POINT 1',(13.0,-6.0,7.97));
#131=TRIMMED_CURVE('TRIMMED CURVE FOR CONTOUR OF
POCKET2',#132,(#133),(#134),.T.,.CARTESIAN.);
#132=CIRCLE('CIRCLE',#135,6.0);
#133=CARTESIAN_POINT('TRIM POINT 1',(13.0,-6.0,7.97));
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```
#134=CARTESIAN_POINT('TRIM POINT 2',(19.0,0.0,7.97));
#135=AXIS2_PLACEMENT_3D('CIRCLE PLACEMENT',#136,#137,#138);
#136=CARTESIAN_POINT('CIRCLE CENTER',(13.0,0.0,7.97));
#137=DIRECTION('Z DIRECTION',(0.0,0.0,1.0));
#138=DIRECTION('X DIRECTION',(1.0,0.0,0.0));
#139=POLYLINE('POLYLINE FOR CONTOUR: POCKET2',(#140,#141));
#140=CARTESIAN_POINT('POLYLINE POINT 1',(19.0,0.0,7.97));
#141=CARTESIAN_POINT('POLYLINE POINT 1',(19.0,28.0,7.97));
#142=TRIMMED_CURVE('TRIMMED CURVE FOR CONTOUR OF
POCKET2',#143,(#144),(#145),.T.,.CARTESIAN.);
#143=CIRCLE('CIRCLE',#146,6.0);
#144=CARTESIAN_POINT('TRIM POINT 1',(19.0,28.0,7.97));
#145=CARTESIAN_POINT('TRIM POINT 2',(13.0,34.0,7.97));
#146=AXIS2_PLACEMENT_3D('CIRCLE PLACEMENT',#147,#148,#149);
#147=CARTESIAN_POINT('CIRCLE CENTER',(13.0,28.0,7.97));
#148=DIRECTION('Z DIRECTION',(0.0,0.0,1.0));
#149=DIRECTION('X DIRECTION',(1.0,0.0,0.0));
#150=AXIS2_PLACEMENT_3D('SETUP ORIGIN',#152,#153,#154);
#151=WORKPIECE_SETUP(#3,#155,$,$,());
#152=CARTESIAN_POINT('SETUP LOCATION',(0.0,0.0,0.0));
#153=DIRECTION('AXIS',(0.0,0.0,1.0));
#154=DIRECTION('REF_DIRECTION',(1.0,0.0,0.0));
#155=AXIS2_PLACEMENT_3D('WORKPIECE50.0X100.0X20.0 SETUP',#156,#157,#158);
#156=CARTESIAN_POINT('WORKPIECE50.0X100.0X20.0SETUP
LOCATION',(0.0,0.0,0.0));
#157=DIRECTION('AXIS',(0.0,0.0,1.0));
#158=DIRECTION('REF_DIRECTION',(1.0,0.0,0.0));
ENDSEC;

END-ISO-10303-21;
```

Appendix C. FeatureCAM time estimation reports for the case study parts

C.1. FeatureCAM time estimation report for case study part (I)

MANUFACTURING OPERATION SHEET

Part: Part 1
Setup: Setup1 (1 of 1)
Date: Thursday, April 18, 2013 14:08:58
Time: 2:26.7
Stock: L 100.000 mm x W 50.000 mm x T 20.000 mm
Mat: ALUMINUM, 111.00 Brinell,0.82 kN/mm^2

Op: 1 face1 (face)
F/S: 8000 RPM, 4572 MMPM (0.191 MMPT)
Tool: #1 (Copy of facemillM3200, 40.000 mm)
Depth: 1.000 mm
Other: Stepover: 34.000 mm (85%)
Time: 0:20.9
Est. kW:2.12

Op: 2 rect_pock1 (rough1)
F/S: 6306 RPM, 1261 MMPM (0.100 MMPT)
Tool: #2 (endmillM1000:reg, 10.000 mm)
Depth: 8.000 mm (in 3 steps, 2.667 mm each)
Other: Stepover: 5.500 mm
Time: 0:36.9
Power: 0.25 (est. 0.25) kW

Op: 4 rect_pock1 (finish)
F/S: 8000 RPM, 576 MMPM (0.036 MMPT)
Tool: #3 (endmillM0600:reg, 6.000 mm)
Depth: 8.000 mm
Other: Stepover: 0.750 mm
Time: 1:32.0
Est. kW:0.05

Op: 5 hole1 (drill)
F/S: 3031 RPM, 0.120 MMPR
Tool: #4 (TD_M0800:J, 8.000 mm)
Center: 50.000 mm 10.000 mm -1.000 mm
Depth: 14.403 mm
Other: Pecks: 2, Cycle: Deep Hole
Other: Steps: 8.000 mm 8.000 mm 8.000 mm
Time: 0:12.2

C.2. Time estimation report for case study part (II)

MANUFACTURING OPERATION SHEET

Part: Part 2
Setup: Setup1 (1 of 1)
Date: Thursday, April 18, 2013 15:40:36
Time: 5:70.1
Stock: L 100.000 mm x W 50.000 mm x T 20.000 mm
Mat: ALUMINUM, 111.00 Brinell,0.82 kN/mm^2

Op: 1 face1 (face)
F/S: 8000 RPM, 4572 MMPM (0.191 MMPT)
Tool: #1 (Copy of facemillM3200, 40.000 mm)
Depth: 1.000 mm
Other: Stepover: 34.000 mm (85%)
Time: 0:17.7
Est. kW:2.12

Op: 2 pocket1 (rough1)
F/S: 5912 RPM, 946 MMPM (0.080 MMPT)
Tool: #2 (Copy of endmillM1600:reg, 8.000 mm)
Depth: 12.000 mm (in 2 steps, 6.000 mm each)
Other: Stepover: 2.664 mm
Time: 2:10.0
Power: 0.21 (est. 0.21) kW

Op: 3 pocket1 (finish)
F/S: 8000 RPM, 2304 MMPM (0.072 MMPT)
Tool: #3 (endmillM1200:4reg, 12.000 mm)
Depth: 12.000 mm
Other: Stepover: 1.000 mm
Time: 0:15.6
Est. kW:0.38

Op: 4 pocket2 (rough1)
F/S: 3941 RPM, 1261 MMPM (0.160 MMPT)
Tool: #4 (endmillM1600:reg, 16.000 mm)
Depth: 12.000 mm
Other: Stepover: 5.328 mm
Time: 2:26.2
Power: 1.10 (est. 1.10) kW

Op: 5 pocket2 (finish)
F/S: 6063 RPM, 1164 MMPM (0.096 MMPT)
Tool: #4 (endmillM1600:reg, 16.000 mm)
Depth: 12.000 mm
Other: Stepover: 1.250 mm

Op: 6 slot1 (rough1)
F/S: 7882 RPM, 1261 MMPM (0.080 MMPT)
Tool: #5 (endmillM0800:reg, 8.000 mm)
Depth: 10.000 mm (in 2 steps, 5.000 mm each)
Other: Stepover: 2.664 mm
Time: 0:19.2
Power: 0.23 (est. 0.23) kW

Op: 7 slot2 (rough1)
F/S: 7882 RPM, 1261 MMPM (0.080 MMPT)
Tool: #5 (endmillM0800:reg, 8.000 mm)
Depth: 10.000 mm (in 2 steps, 5.000 mm each)
Other: Stepover: 4.400 mm
Time: 0:21.4
Power: 0.38 (est. 0.38) kW

Op: 8 slot3 (rough1)
F/S: 5255 RPM, 1261 MMPM (0.120 MMPT)
Tool: #6 (Copy of Copy of endmillM0800:reg, 12.000 mm)
Depth: 10.000 mm
Other: Stepover: 3.996 mm
Time: 0:31.2
Power: 0.69 (est. 0.69) kW

Op: 9 hole1 (drill)
F/S: 3031 RPM, 0.120 MMPR
Tool: #7 (TD_M0800:J, 8.000 mm)
Center: 20.000 mm 15.000 mm -1.000 mm
Depth: 18.403 mm
Other: Pecks: 3, Cycle: Deep Hole
Other: Steps: 8.000 mm 8.000 mm 8.000 mm
Time: 0:17.8

Op: 10 hole2 (drill)
F/S: 3031 RPM, 0.120 MMPR
Tool: #7 (TD_M0800:J, 8.000 mm)
Center: 80.000 mm 15.000 mm -1.000 mm
Depth: 18.403 mm
Other: Pecks: 3, Cycle: Deep Hole
Other: Steps: 8.000 mm 8.000 mm 8.000 mm
Time: 0:07.6