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The development of a new STEP-NC code generator (GEN-MILL)

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The early NC machines and the current CNC utilise the same standard programming of G&M codes formalised as the ISO 6893 standard to machine parts with complex shape in a precise manner. However, the G&M code contains implicit technical information and does not meet the requirements of modern NC technology as it uses low level codes to describe tool movements and instructions. Literature shows that the current CNC is difficult to manage, modify and verify NC data easily. ISO 14649 referred to as STEP-NC is the result of an international effort to achieve full interoperability and bi-directional information exchange throughout the manufacturing network. STEP-NC has been designed in such a way that information remains in its context and without reducing to primitive instructions such as G&M code. This research will explore ISO 6983 (G&M code) together with ISO 14649 (STEP-NC) and utilise STEP-NC in overcoming the problems of G&M code and at the same time take advantage of current advances in computing and controllers. A new STEP-NC code generator (GEN-MILL) which focuses on the milling process that is able to generate STEP-NC codes based on Example 1 in ISO 14649 Part 11 was developed. The advantages of the proposed STEP-NC code generator (GEN-MILL) program was verified and evaluated by comparing the output generated by the software with ISO 14649 Physical File for Example 1. The STEP-NC code generator (GEN-MILL) can understand and generate STEP-NC codes through a STEP-NC compliant interface and will give industries and academicians more in-depth understanding and confidence to switch from G&M code to STEP-NC.

Keywords: STEP-NC; G&M code; ISO 14649; ISO 6983; CNC; NC

1. Introduction

Numerical Control (NC) is the term used to describe the control of machine movements and various other functions by instructions expressed as a series of numbers and initiated via an electronic control system. When NC machines were developed, the purpose of the NC machine was to machine parts with complex shape in a precise manner. Computerised Numerical Control (CNC) is the term used when the control system includes a computer. Numerical control is applied to a wide range of manufacturing processes such as metal cutting, woodworking, welding, flame cutting and sheet metal forming. Numerical control is economical for mass, batch and in many cases single-item production. Many factors contribute to this economic viability, the most important of these being (1) high productivity rates, (2) uniformity of the product, (3) reduced component rejection, (4) reduced tooling costs, (5) less operator involvement, and (6) complex shapes machined easily.

It is also the case that fewer employees were required as conventional machines are replaced by modern technology, but those that remain will of be high-calibre technicians with considerable knowledge of metal-cutting methods, cutting speeds and feeds, work-holding and tool-setting techniques and who are familiar with the control systems and programming for numerical control. Most CNC machines are programmed in the ISO 6983 G and M code language. Programs are typically generated by computer-aided manufacturing (CAM) systems that use computer aided design (CAD) information. However, ISO 6983 limits program portability for three reasons. First, the language focuses on programming the tool centre path with respect to machine axes, rather than the machining process with respect to the part. Second, the standard defines the syntax of program statements, but in most cases leaves the semantics ambiguous. Third, vendors usually supplement the language with extensions that are not covered in the limited scope of ISO 6983 (International Standard Organization 2002).

The ISO 6983 standard focuses on programming the path of the cutter centre location (CL) with respect to the machine axes, rather than the machining tasks with respect to the part. Thus, ISO 6983 defines the syntax of program statements, but in most cases leaves

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the semantics ambiguous, together with low-level limited control over program execution. These programs, when processed in a CAM system by a machine-specific post-processor, become machine-dependent (Xu and Newman 2006). The above-mentioned ISO 6983 is widely used as a standard of data interface for a numerical control (NC) apparatus in a manufacturing process. However, the ISO 6983 is a low-level international standard that just defines an axis movement command and switching commands, which cause problems to users and manufacturers as more are required in the manufacturing floor. Several CNC manufacturers attempt to solve this problem by adding standards high-level command code of their own to the existing ISO 2983 standards. However, since manufacturers have their own standard, compatibility of the part programs that differs is reduced. In addition, since the shop floor programming in manufacturing is using the basic G&M code as per what was in the ISO 6983, various production information such as machining features, machining process, machining technology, cutting tools, machining knowledge and feature information may not be included in the part program or worst become lost.

With the rapid advancement of information technology associated with NC technology, the manufacturing environment has changed significantly since the last decade. However, the low-level standard, G&M codes, have been used for over 50 years as the interface between CAM and CNC, and are now considered as an obstacle for global, collaborative and intelligent manufacturing. STEP-NC has been developed for the exchange of information between CAD/CAM systems and NC controls (Maeder *et al.* 2002), where a new model of data transfer between CAD/CAM systems and CNC machines, known as STEP-NC, is being developed worldwide to replace G&M codes. STEP-NC (ISO14649) is a STEP-compliant data interface for numerical control, a new standard that has been developed and intended to replace the G-code. STEP-NC data model provides a hierarchical information data model for CNCs to support various manufacturing technologies such as milling or turning machines (Brunnermeier and Martin 1999). The STEP-NC interface, which is based on an object-oriented data model, has been developed in several recent research projects in which many industrial companies and universities have participated.

Figure 1 shows how the design data is communicated to manufacturing in current practice. Design creates the specification for a product as a 3D model. Detailing decides the manufacturing requirements for the product by making a drawing. Path planning generates tools paths. Manufacturing controls production. The job of design is performed by using a Computer Aided Design (CAD) system, detailing is performed by using a drawing Computer Aided Design and Drafting (CADD) system, path planning is performed by using a Computer Aided Manufacturing (CAM) system, and manufacturing is controlled using a CNC system.

In G&M code, information can be lost in the pipeline because incomplete data is sent from the CAD to the CAM, fixes to the geometry are made in the CAM and not communicated back to the CAD and only the surface data is communicated to the post. This means that no adjustments can be made on the control in response to changes in the available tooling, the control cannot optimise the machining process for the capabilities of the selected machine, and the operator cannot rely on software in the control to check the safety of the set-up and the program (Steptools 2009).

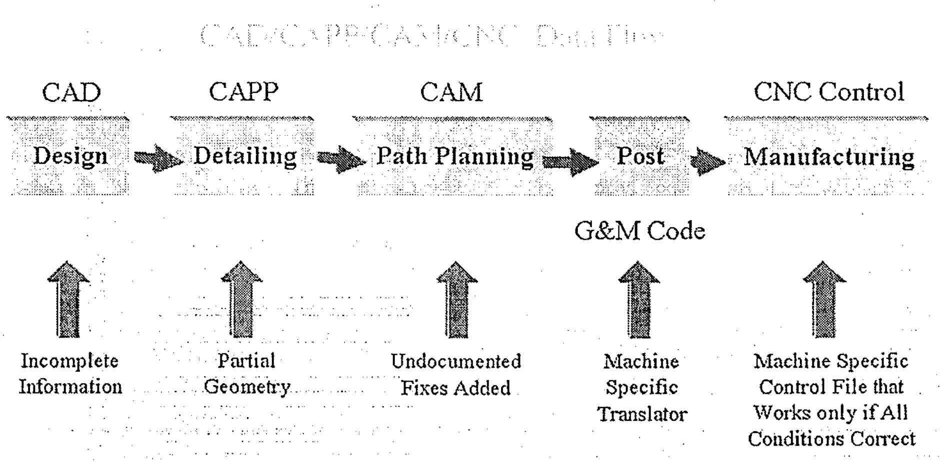

Figure 1. Current CAD/CAPP/CAM/CNC data flow.

2. STEP-NC related work

A solution to the drawbacks of ISO 6983, a new standard called ISO 14649, has been introduced. The ISO 14649 defines a method for incorporating a variety of production information in a new type part program that is different from the previous one using the G&M code. Accordingly, a system adopting the ISO 14649, or rather known as STEP-NC, should and would exhibit a highly improved compatibility with upcoming data, technology and other systems. Besides that, the part program for use in the STEP-NC would contain a variety of production information such as machining features, machining process, machining method, cutting tools, machining technology and geometry information, which was not available in ISO 6983.

A major benefit of ISO 14649 is its use of the existing data models from ISO 10303. As ISO 14649 provides a comprehensive model of the manufacturing process, it can also be used as the basis for a bi- and multidirectional data exchange between all other information technology systems (International Standard Organization 2002).

In the new method of STEP-NC, enterprises can continue to use their existing systems for CAD, CADD and CAM, but the end result is sent to the CNC as a STEP-NC file instead of a G&M code file. Figure 2 shows the modified pipeline where only a small change needs to be done particularly on the interface, but the advantages are significant.

2.1. *Comparisons between G&M code and STEP-NC*

Based on various literature reviews published, the advantages of STEP-NC as compared to the current G&M code can be summarised. Table 1 gives a summary of how STEP-NC steps up as remedies for the shortcomings of the G&M codes. STEP-NC is a high level code as well as contains much more information as compared to G&M code. It supports coding of complex geometries with manageable changes features, whereas G&M code was structured for simple geometries with difficult changes manageability. Data movement in STEP-NC is bidirectional instead of just one direction only as per what G&M code does.

2.2. *Previous research*

Recently, a number of projects involving the areas of STEP-NC based interoperability and research and development for various CNC manufacturing processes have been started (Yusof 2009). Systems related to STEP compliance have been developed by academia

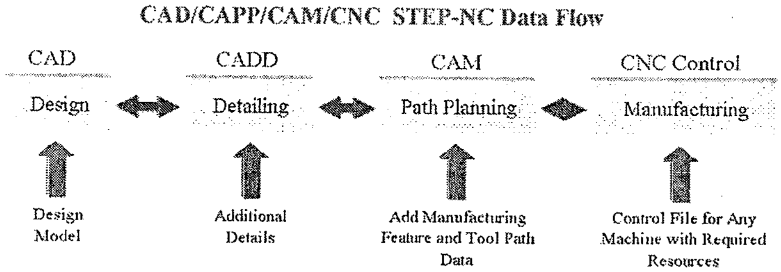

Figure 2. STEP-NC CAD/CAPP/CAM/CNC data flow.

Table 1. Comparison between G&M code and STEP-NC.

Items	G&M code (ISO 6983)	STEP-NC (ISO 14649)
Coding structure	Low level code	High level code
Informativeness	Low level information	High level information
Geometries	Simple geometries	Complex geometries
Changes manageability	Difficult	Manageable
Axis	Limited axis	Dependable axis
Speed	Low	High
Features	Primitive	Modern (intact)
Data representation	Implicit	Explicit
Data movement	Single	Bidirectional
Instinct	Unintuitive	Intuitive
Standardisation	Unstandardised	Standardised

all over the world (Yusof *et al.* 2009). The literature shows that most of the systems developed are turning and milling system. There are few of the lathe systems and shop floor jobs that have been studied. Their achievement is beyond what would have been thought. The ideas to create STEP-NC generator are many but the basic concepts used are fundamentally the same (Zamri Tan *et al.* 2009). Table 2 shows the system together with the programming language that is being used to develop it.

Most of the previous researchers use Visual C++ and Java as their development tools. The software STEPTurn uses STEP AP203 as its inputs. STEPTurn is a CAPP system bridging the gap between CAD and CAM (Heusinger *et al.* 2006). TurnSTEP which was developed in 2006 uses STEP-AP as inputs. TurnSTEP is claimed by Choi to be fully compliant with ISO 14649 and suitable for e-manufacturing (Choi *et al.* 2006). G2STEP which is the latest system to cover the machine functioning from pre-processor to STEP-NC part program generation including part program verification (Shin *et al.* 2007) generates STEP-NC part program as output with G code as input. Details of information on STEP-NC previous research can be referred in Table 2.

3. Software development

3.1. *Methodology summary*

The novelty of this research was that it visualised the data transition from CAD/CAM to the STEP-NC software by having some of the input data keyed in manually and having the ISO 14649 Physical file for Example 1 as the output. Verification was done by comparing the output generated by the software with Physical File of Example 1 in ISO 14649. Most of the STEP-NC prototype or system developed accepted another file as its input. Those files were transferred or uploaded to the system directly which is good as no data modification or loss happened during transfer; thus, it is very suitable for advanced stages of STEP-NC studies. For early stage studies of STEP-NC, the proposed GEN-MILL would be easier for understanding and learning of the STEP-NC concept, as data flows can easily be visualised from the system itself. GEN-MILL simplified the visualisation of data flow inside STEP-NC, and users can fiddle freely with the inputs to see where the difference appears in the output. The approach for system development was also different as most of the other researchers use Visual C++ as their development tools but GEN-MILL uses Visual Basic as the development tools. The overall research methodology will follow four important phases. The first phase is a detailed study on the literature and standards on ISO 14649 (STEP-NC) and ISO 6983 (G&M code). During this phase a system study on the current NC condition is being looked into and a comparison between the current programming condition and the future one is being made, based on expectations raised. The results of the literature and standards study will initiate to the first phase of programming and the development of a prototyped STEP-NC software. The final phase of the whole research will be the presentation of the developed model and STEP-NC code generator (GEN-MILL). The research methodology summary can be visualised as in Figure 3.

Software development methodology is referring to the documented collection of guidelines, procedures and standards intended to ensure the development of quality application systems that meet the system's requirements in an efficient manner. The system development methodology involves a series of operations and procedures that are used to develop an application or system. In this section, the type of development process model to be used for the STEP-NC generator (GEN-MILL) development will be discussed. A prototype is a toy implementation of a system; usually exhibiting limited functional capabilities, low reliability, and inefficient performance. An important purpose is to illustrate the input data formats, messages, reports and the interactive dialogs to the end user. This is a valuable mechanism for gaining better understanding of the end user's needs. Another important use of the prototyping model is

Table 2. Research on STEP-NC code generation.

No	System	Programming language	Output generation
1	SCSTO	Java	STEP-NC physical led
2	STEPTurn		STEP-NC physical led
3	WOPTurn		Step-NC code
4	Step Reader	VB dynamic Variable	STEP-NC file
5	PROSFP	Visual C++	Part program physical file(text)
6	TurnSTEP	Visual C++	ISO 14649 physical file and e(XML)
7	G2STEP	Visual C++	STEP-NC Part Program
8	STEPcNC	Visual C++	STEP-NC file
9	AB-CAM (CAPP)		Native STEP-NC files

that it helps critically examine the STEP-NC or G&M code technical issues associated with the product development. Small-scale mock-ups of the system are developed following an iterative modification process until the prototype evolves to meet the end users' requirements. While most prototypes are developed with the expectation that they will be discarded, it is possible in some cases to evolve from prototype to working system. A basic understanding of the fundamental operational problem is necessary to avoid solving the wrong problem.

The software prototyping development model is the most suitable methodology to develop STEP-NC code generator (GEN-MILL). It is more manageable as opposed to the traditional waterfall model. This approach is broken down into eight development phases of software prototyping. They are requirement gathering, quick design, prototype build, refine requirements, prototype evaluation, design, implementation, test and maintain. There is a looping iteration in the quick design of prototype and the refine requirements stages. Before the final design, system prototype will be tested, evaluated and modified based on the current inputs and requirements, and refinement of requirements can be done whenever there are new functional capabilities are added by the control in order to improve the functionalities of the application.

The reason why the software prototyping model was chosen was because it helps to identify easily confusing or difficult functions and missing functionality as well as encourages innovation and flexible designs.

3.2. *STEP-NC requirements gathering*

In order to study the requirement of STEP-NC for system development, the content of STEP-NC code in Example 1 ISO 14649 Part 11 will be studied. For review purposes STEP-NC code study for the first three lines in Example 1 ISO 14649 Part 11 will be shown and visualised as shown in Figure 4. The first three top entities in Example 1 ISO 14649 are PROJECT, WORKPLAN and WORKPIECE. In the first three lines, these three entities act as main entities, but inside these entities itself; it was shown that it contains another entity or entities as its sub-entities.

Identify (MAIN) Mandatory entities involved:

(1) - PROJECT
(2) - WORKPLAN
(3) - WORKPIECE

For example, for main entity PROJECT, the entity WORKPLAN and WORKPIECE act as its sub-entities. When referred to, the entity WORKPLAN

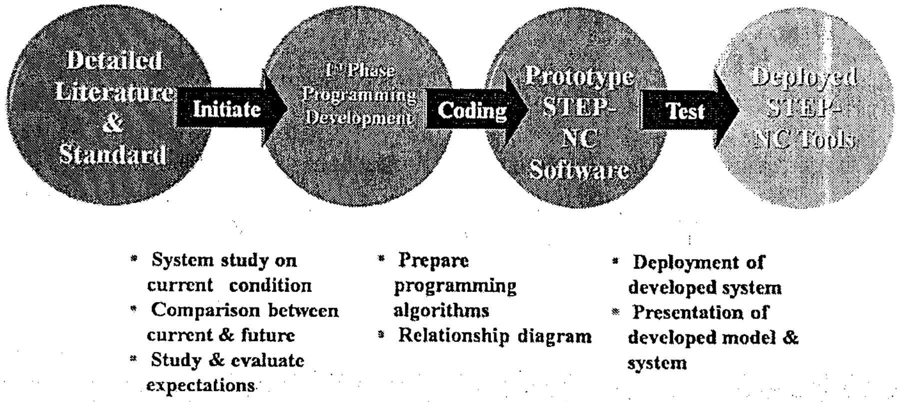

Figure 3. Research methodology summary.

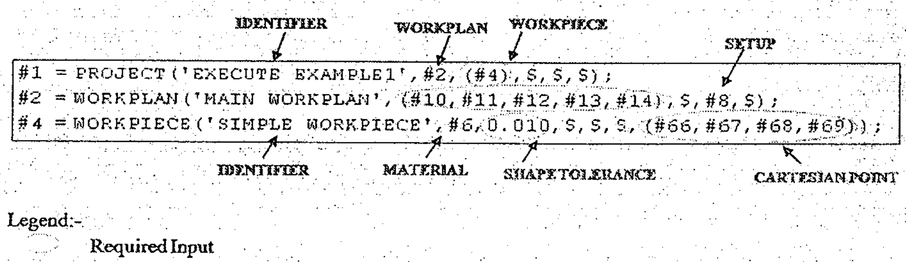

Figure 4. STEP-NC code for the first three lines from Example 1 ISO 14649 Part 11.

and WORKPIECE also act as main entity. This means that an entity can play the part as a main entity as well as sub-entity to another entity. Based on Figure 4, it is explained that, the main entity PROJECT has three known sub-entities, which are, IDENTIFIER, WORKPLAN and WORKPIECE, as for the main entity WORKPIECE, it has four known sub-entities, which are IDENTIFIER, MATERIAL, SHAPE TOLERANCE and list of CARTESIAN POINT.

Identify entities that act as subtype to MAIN Mandatory entities

From PROJECT - WORKPLAN, WORKPIECE
From WORKPLAN - MACHINING_WORKINGSTEP, SETUP
From WORKPIECE - MATERIAL, CARTESIAN_POINT

The prototype system developed will focus first on identifying the input that is required to come out with a STEP-NC code which is identical with Example 1. Initial prototype development requirement will proceed on a list of inputs collected from the STEP-NC code study. Programming language chosen to develop STEP-NC code generator GEN-MILL will be Visual Basic, because it is easily learned and used by beginner programmers. The language not only allows programmers to create simple GUI applications but can also develop complex applications. Programming in VB is a combination of visually arranging components or controls on a form, specifying attributes and actions of those components, and writing additional lines of code for more functionality. Since default attributes and actions are defined for the components, a simple program can be created without the programmer having to write many lines of code.

3.3. *Identify input data between the required scope*

In order to organise and identify variables needed for the prototype system development, detailed lists of STEP-NC entities and sub-entities involved in Example 1 ISO 14649 Part 11 for round hole will be listed and extracted from the manual provided by ISO. Based on Tables 3 and 4, the system will identify the SUBENTITY column as the variable and the REMARKS column will be the description of the variables.

Table 3. Sub-entity details for entity project.

Sub-entity	Remarks
its_id	identifier (string)
main_workplan	WORKPLAN
its_workpieces	SET[0:?] of WORKPIECE
its_owner	(Optional) PERSON_AND_ADDRESS
its_release	(Optional) DATE_AND_TIME
its_status	(Optional) APPROVAL

ENTITY: PROJECT
ENTITY: WORKPIECE

3.4. *Relationship between round hole entities*

All the entities that are involved in the production of round hole in Example 1 ISO 14649 Part 11 were gathered and a detailed study on each entity was done. There were cases where a sub-entity of an entity was another or referred to another entity. A relationship existed between most of the entities that resembled a parent to child relationship in system or database development which can be seen in Figure 5.

3.5. *Quick design of STEP-NC input screen interface*

Figure 6 represents the input screen interface that was developed for the prototype system. After studying the STEP-NC code for round hole that are listed in Example 1 ISO 14649 Part 11, the required inputs are classified and categorised into four main groups, which are the main section, round hole section, drilling section and reaming section. For the initial prototype, lots of inputs were required from the user side.

3.6. *Build STEP-NC screen prototype*

Based on the inputs provided, a prototype system that can manipulate the inputs to form a full STEP-NC code for round hole, identical to the one provided by Example 1 ISO 14649 Part 11 was developed. The coding structure that points one entity to another in a recursive way was structured. Figure 7 is the output produced by the prototype system.

3.7. *Evaluation of the prototype*

The prototype system developed did provide an insight of what the systems required that was difficult to understand just by reading the standards provided by ISO. The data or entity flow from one point to another is much more traceable as the prototype provides a virtual presentation of how the data flows from one point to another and where does it end, as well as what is required by the data. Lots of inputs were required to be keyed in by the users in the prototype stage. This should not be so, as a good system would only require little inputs by users. The possibility that one common entity was referred to or pointed by many different entities was also taken into consideration. It could be a one to many relationships, many to one relationship or

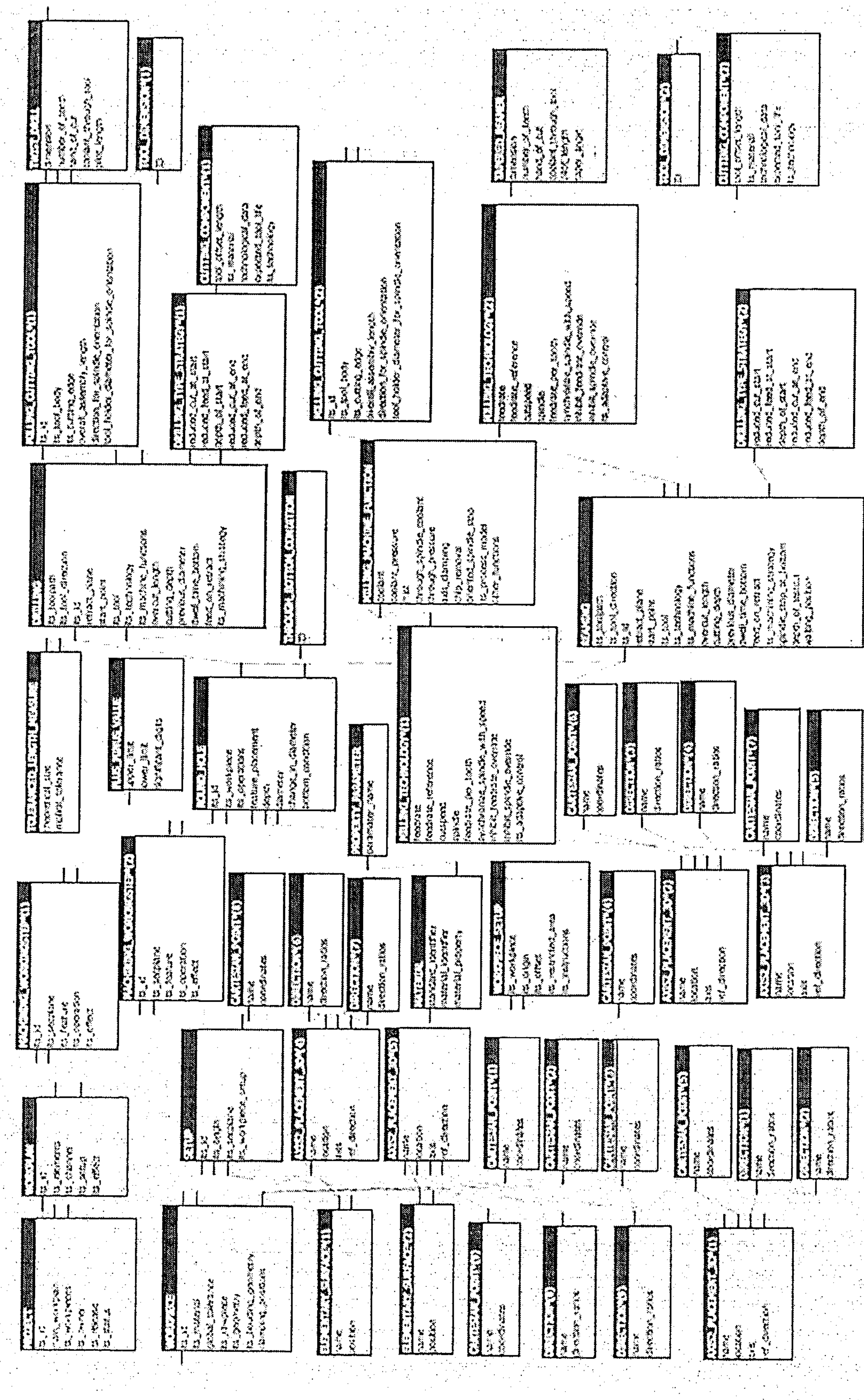

Figure 5. Entity relationship of Example 1 ISO 14649 Part 11 for round hole.

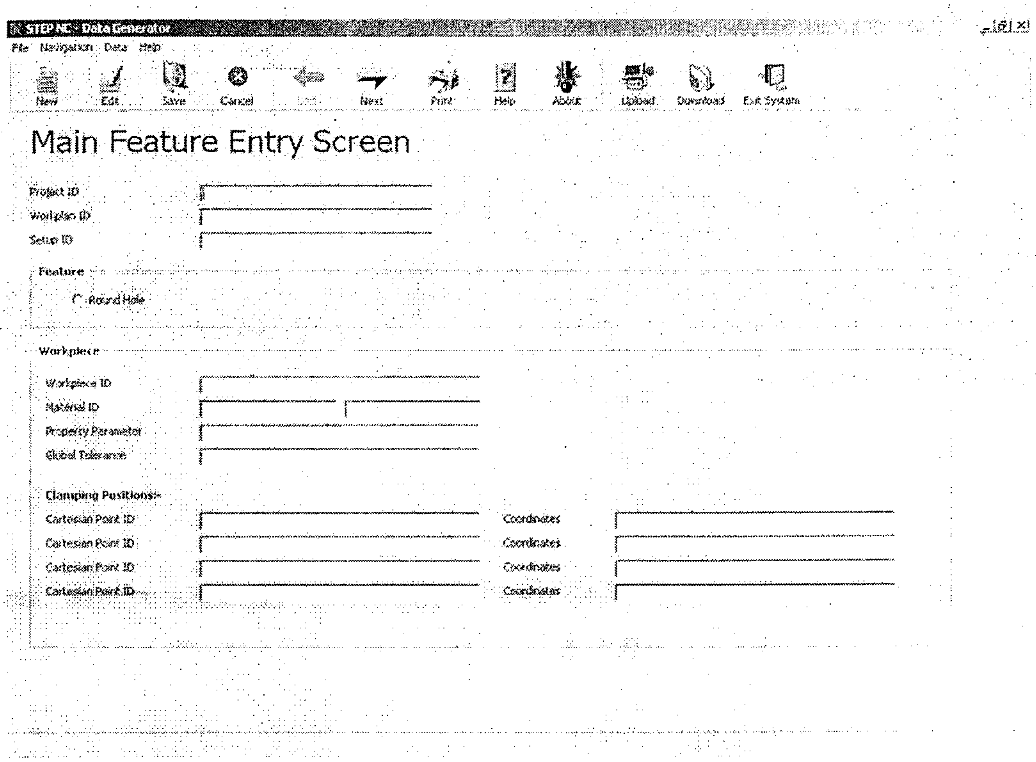

Figure 6. Input from the prototype system.

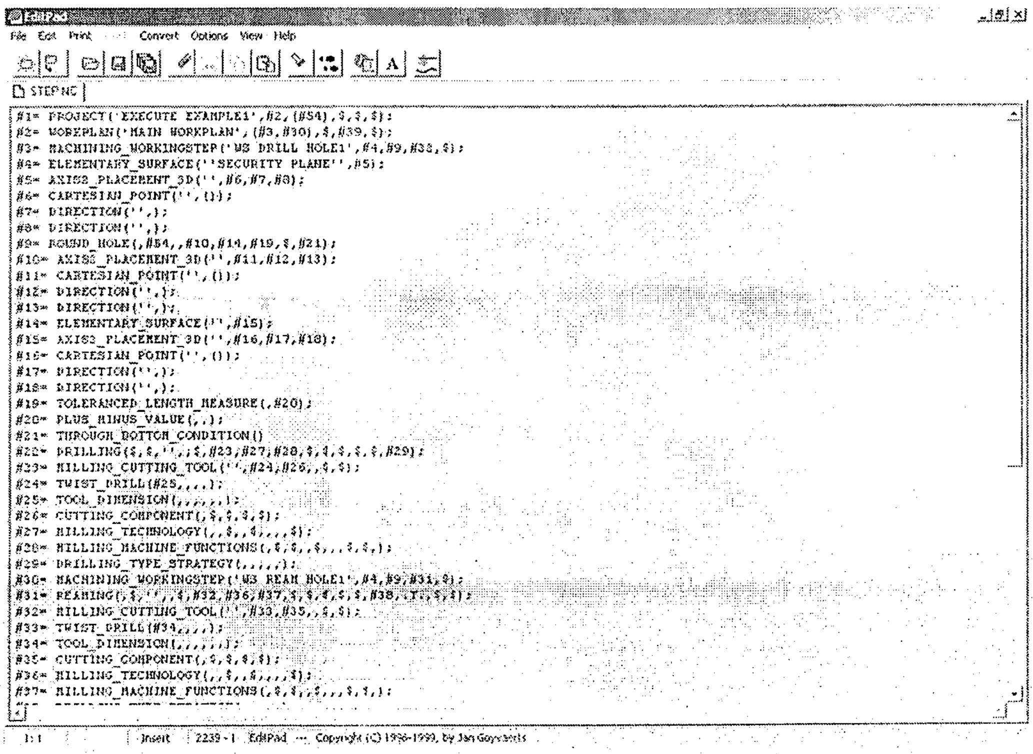

Figure 7. Output from the prototype system.

many to many relationships. The coding for each situation would be different and a different set of programming might be taken into consideration for the final system, as the prototype just provides a glimpse of what is to come and what is required.

The prototype developed provides an insight of how STEP-NC works but it does not provide a solution to the system that needs to be developed, which is the round hole from Example 1 ISO 14649 Part 11. The initial requirements that were gathered for the prototype development were restudied and re-evaluated. Certain criteria like redundant inputs or improper outputs were refined and corrected.

3.8. Implement

System implementation was on the capability of the STEP-NC code generator (GEN-MILL) to generate STEP-NC code based on the example provided by ISO. More features might be added to the system once things have run in full motion with as little input by users. System test was done by comparing the output generated by the STEP-NC code generator (GEN-MILL) with the STEP-NC code that is available in Example 1 ISO 14649 Part 11. STEP-NC code in Example 1 ISO 14649 Part 11 has been proven workable, and benchmarking is being done by producing results that are identical to it.

4. Conclusions

ISO 6983 or G&M code has been used in manufacturing industries long enough that it lacks the capabilities to integrate and assimilate with the advancement of current development and technology. Using currently available software tools, ISO 14649 can be interpreted significantly faster (Kramer *et al.* 2006). A detailed in-depth study with explanations of the differences between G&M code and STEP-NC and in what way is the STEP-NC better than G&M code has provided a better insight into the capabilities of both standards. As a result the STEP-NC code generator (GEN-MILL) was developed based on Example 1 in ISO 14649 Part 11, which will focus on the milling process. The system was developed based on a structured methodology and used a software prototyping development model.

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