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MANUFACTURING PERFORMANCE IMPROVEMENT OF COMPLEX PRODUCTS BASED ON CODING AND PARAMETERISATION: A CASE STUDY

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Abstract: *This work presents a case study referring to the way in which a complex product design is linked to the manufacturing processes which are necessary to make it. The product is a mobile cement pump consisting of 8 sub-assemblies, 204 manufactured part types and a total of parts in excess of 1000. A custom coding system has been defined and implemented as a database application in order to standardize design and, most importantly, select parts, manufacturing processes and machine tools that fulfill specific criteria. Use of such information is demonstrated in detail for specific parts in the context of replacing previously employed manufacturing processes with new ones towards a more efficient manufacturing system. Furthermore, parametric CNC programs were linked to parametrically designed critical parts, such as a three-stage driving pulley depending on the motor employed. Automating the link of design and manufacture substantially enhanced both production rate and flexibility.*

Key words: *Part families, coding, manufacturing performance, parametric design, design for manufacturing.*

1. INTRODUCTION

In developing complex products, i.e. typically those with a large Bill-of-Materials (BoM), different approaches regarding process flow and its management have been proposed in literature [1]. Having started at specification drawing using Quality Function Deployment and relevant tools [2], Concurrent Engineering of products and processes require appropriate data models and software tools [3]. Emphasis is put on interfaces through Design-for-Manufacturing and Design-for-Assembly and secondarily on Design-for-Cost, Design-for-Quality and Design-for-Sustainability [4]. Agents, expert systems, optimization tools and intelligent systems are generally deployed [5]. In order to simplify parallel processes followed in product development, definition of part families is still a prominent practice followed by simple techniques such as Value Engineering [6]. Manufacturing process design has been linked to product design using generic process plans [7, 8] and generically defined and coded shape features [9]. The internet and, more recently, cloud-based approaches have been used as vehicles towards such implementations [10].

Often, an existing product needs to be improved in terms of manufacturing performance, i.e. in order to speed up its production and / or reduce the pertinent manufacturing cost and / or improve quality. This involves a sub-set of the tools and methods mentioned above [11] and becomes more interesting when complex products are addressed. Issues to be dealt with pertain to selection of the parts whose manufacturing processes need modification [12] and to exploiting similarities and variations in defining process plans [13] and corresponding cnc part programs, where relevant [14].

In this work, coding and parametrization are proposed as solutions to the above mentioned issues, and their application is demonstrated in the framework of a mobile cement pumping system consisting of hundreds of parts, as briefly described in Section 2. The coding structure, its database implementation and exploitation are described in Section 3. Parametric definition of a sample component (pulley family) is presented in Section 4, leading to parametric definition of a generic Computer Numerical Control (CNC) part program. Section 5 summarizes conclusions and points to future extensions.

2. PRODUCT STRUCTURE

The cement pumping machine is a product of Drakos SA and has been manufactured in evolving variants since 1974. It comprises of eight subsystems, see Fig. 1.

The product consists of more than 1000 parts, one fifth of which undergo in-house processing, whereas the rest are bought as standard parts, mostly screws, nuts, rings, bearings, O-rings, belts etc. The in-house manufactured parts are made of cast iron, structural steel, aluminium alloys and bronze, their initial shape being a casting, tube or sheet. Machining, drilling, grinding, welding, bending, carburizing, electroplating are among the manufacturing processes employed. Conventional machine tools are employed along with hand-operated tools. The lead time for completing one of these machines is 20 days and the annual production cannot exceed 40 units.

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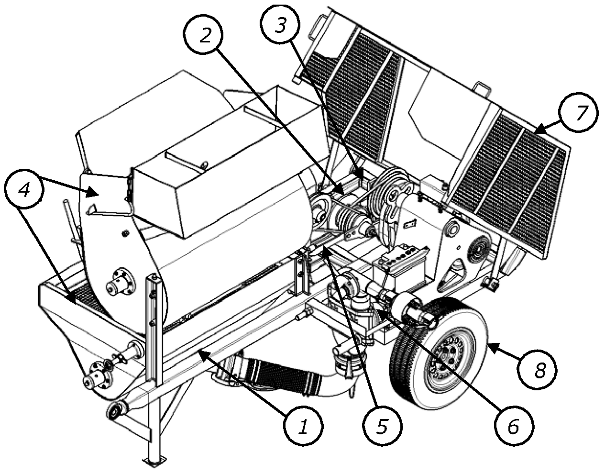


Fig. 1. Main product subsystems : (1) Frame incl. pump shell; (2) Motion transmission; (3) Clutch; (4) Stirring; (5) Vibration; (6) Pumping; (7) Cover; (8) Divided axle and wheels.

In order to speed up production, it is necessary to identify the parts whose manufacturing method should be updated as well as those which can be manufactured in parallel. This can be achieved systematically, if all necessary information is first recorded in a database and then filtered out via suitable queries, as described next.

3. CODING

3.1. Structure

The coding system comprises both design and manufacturing information as summarised in Table 1.

There are 9 fields, the first of which denotes the type of part in 3-characters (manufactured part: PCS, hexagonal head screws: HEX, allen screws: ALL, nuts: NUT, elastomer parts: RUB, bearings: BEA, belts: BEL, bought parts: FIX). The application pertains to PCS coded parts. The next four fields are devoted to a hierarchical description of the sub-assembly-part structure of the product. Each part belongs to at least one and possibly to up to four nested sub-assemblies (Sassy*i*) defined by two digits each. There are 8 top-level sub-assemblies, see Fig. 1, 6 of them having second level sub-assemblies. For instance, the pumping sub-assembly (06) possesses 4 different second-level sub-assemblies (Sassy2), one of which is the cam-crank-tappet system (03), see Fig. 2, which, in turn, possesses 3 sub-assemblies (Sassy3), one of which is the tappet (01). The latter has one sub-assembly (Sassy4), namely the tappet shell (01), which, in turn, has 3 parts, one of which is the sliding ring cylinder (03), see Fig. 2. Therefore, the code of this part is: PCS.06.03.01.01.03. If some sub-assembly in the hierarchy does not exist, the respective code is 00. All in all, there are 18 second-level, 6 third-level and one fourth-level sub-assemblies. Manufactured parts amount to 204. The 7th field is a 30 character coding of the manufacturing processes required for the prt at hand, since there are 15 processes, each one represented by a two-character code (Casting: CA, Drilling: DR, Internal threading: TH, Turning: TU, Planning: PN, Milling: MI, Grinding: FG, Gear making: TC, Carburizing: CB, Nitriding: AZ, Electroplating: AN, Sheet cutting: MC, Laser cutting: NC, Sheet bending: BE, Welding: WE). Hence, this follows the absolute representation, where the meaning of each sub-field does not depend on the value of the other sub-fields. If any of these manufacturing processes is not pertinent, then 00 is the value entered. In the example quoted, the manufacturing process coding reads: 00DR00TU000000000000000MC0000WE. The 8th field is a 24-character representation of the respective machine tool types, since there are 12 types of machine tools that cover the full spectrum of manufacturing processes (Lathe: LA, Mill: ML, Shaper: PL, Drill: DR. Hob: HO, Machining centre: VM, Grinder: FG, Sheet cutter: NC, Press brake: PB, Sheet bender: BM, Shearing machine: SH, Sawing machine: ES). Again, this corresponds to an absolute representation and, should a particular machine be impertinent, '00' is the value entered in the respective code part. In the example quoted, the machine tool coding reads: LA0000DR00000000000000ES.

Table 1

Coding system

Field	Type	Sassy1	Sassy2	Sassy3	Sassy4	Part	Proc	Mach
Col	1	2	3	4	5	6	7	8
Chars	3	2	2	2	2	2	30	24

Note that each manufactured part code is represented by a unique code identifying all sub-assemblies to which this part belongs. All codes have the same length, i.e. 67 characters (including digits).

3.2. Database implementation

The coding system was implemented as a database in Microsoft Access™ database management system. The relational schema is shown in Fig. 3. The fully populated database occupies about 424 Mbyte of disk space.

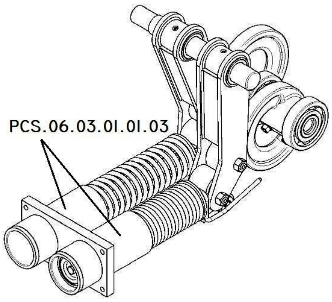


Fig. 2. Sliding ring cylinder coded.

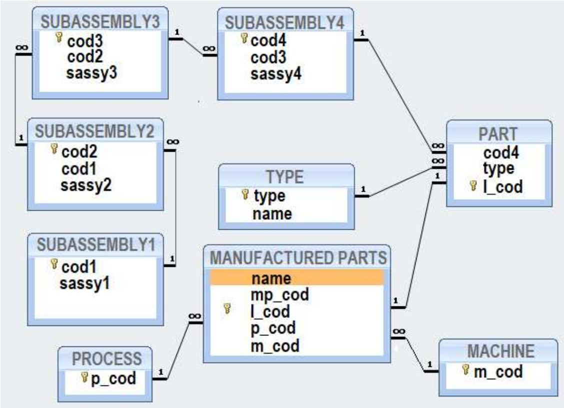


Fig. 3. Relational schema of coding database.

Name	Καπάκι μειωτήρα στροφών ατέρμονα κοχλία - κορώνας
Code	PCS0202000004CADRTHTU0000000000000000000000LA0000DR0000000000000000
Location code	0202000004
Process code	CADRTHTU0000000000000000000000
Machine code	LA0000DR0000000000000000

Machine tools: LA ☑ MI ☐ PN ☐ DR ☑ HO ☐ VM ☐ FG ☐ NC ☐ PB ☐ BM ☐ SH ☐ ES ☐

Manuf. processes: CA ☑ DR ☑ TH ☑ TU ☑ PN ☐ MI ☐ FG ☐ TC ☐ CB ☐ AZ ☐ AN ☐ MC ☐ NC ☐ BE ☐ WE ☐

name	code
Καπάκι μειωτήρα στροφών ατέρμονα κοχλία - κορώνας	PCS0202000004CADRTHTU0000000000000000000000LA0000DR0000000000000000
Στρογγυλό περικόχλιο για την σύσφιγξη του εντατήρα δόνησης	PCS0500000009CADRTHTU0000000000000000000000LA0000000000000000000000
Τροχαλία άξονα άνω αναδευτήρα	PCS0200000005CADRTHTUPN00000000000000000000LA00PN000000000000000000
Τροχαλία άξονα κάτω αναδευτήρα	PCS0200000006CADRTHTUPN00000000000000000000LA00PN000000000000000000
Τροχαλία διβάθμιου μειωτήρα στροφών	PCS0200000002CADRTHTU0000000000000000000000LA0000DR0000000000000000
Τροχαλία κινητήρα	PCS0200000001CADRTHTU0000000000000000000000LA0000DR0000000000000000
Τροχαλία μειωτήρα στροφών ατέρμονα κοχλία - κορώνας	PCS0200000004CADRTHTU0000000000000000000000LA0000DR0000000000000000
Φωλιά εντατήρα κοσκίνου	PCS0500000006CADRTHTU0000000000000000000000LA0000DR0000000000000000

Fig. 4. Database query form.

A query form to seek parts based on their manufacturing process or the machine tool involved or a combination of both has been constructed in Access^{TM}, see Fig. 4. For example, if the parts manufactured on a lathe (LA) and a milling machine (MI) and undergoing electroplating (AN) are sought, two parts are retrieved: upper stirring axle (code: PCS040300000100DRTHTU00MIFG000000AN00000000LAMI00000000FG0000000000) and lower stirring axle (code PCS040400000100DRTHTU00MIFG000000AN00000000LAMI00000000FG0000000000). Similarly, if all parts that are manufactured on a lathe and a drill are sought, then 27 instances are retrieved.

3.3. Exploitation in process improvement

A number of conventional manufacturing processes were considered inappropriate in terms of accuracy attained and lead time. Thus, replacement by new ones based on CNC machine tools was sought. In order to quickly pinpoint such processes and the parts involved, the coding system was exploited.

One of the exemplary processes for improvement was oxy-fuel cutting originally performed by hand on metal sheets. This involved a lot of manual work not only for sheet metal cutting as such, but also for edge finishing using hand-held tools. Besides, mediocre dimensional accuracy led to many problems in part assembly.

This process was applied mainly to large parts of the frame sub-assembly (pump shell outer and intermediate walls, see Fig. 5(a)) and of the stirring sub-assembly for both upper and lower tanks (outer, inner, peripheral wall), see Fig. 5(b,c). Note that parts that are not flat undergo forming after being cut. Oxy-fuel cutting was also applied to smaller parts, mainly in the pumping sub-assembly (side wall of tappet and fixing flange of discharge pipe) as well as the belt tensioner base of the stirring sub-assembly, see Fig. 5(d).

Laser cutting of these parts for sheet thickness (steel) 12 mm at a feed rate 1 m/min was suggested and the corresponding processing time was calculated taking into account the total length of cut, setup time (20 min) sheet preparation and handling time for a batch size of 80 parts. Lead time for these parts ranged from 1 to 6.5 min, i.e. 7-20 times (mean 14) faster than before.

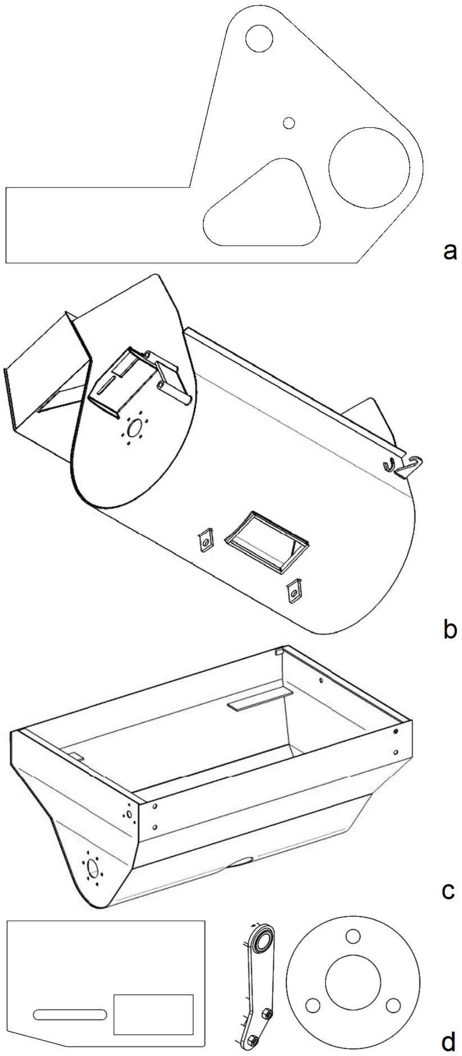


Fig. 5. Parts involving conventional sheet metal cutting: *a* − pump shell outer wall; *b* − upper stirring tank; *c* − lower stirring tank; *d* − belt tensioner base, tappet side wall, fixing flange.

The second beneficial improvement pertains to manufacturing of the casings and caps of the two-stage cast iron gear box and the aluminium casing of the worm-crown gear box that are comprised in the motion transmission sub-assembly, see Fig. 6. These involved turning, milling, drilling and thread cutting operations performed on conventional machine tools with a lead time of 13 hrs and 8 hrs respectively. Lead time with CNC machining dropped to 2 hrs and 1 hrs respectively.

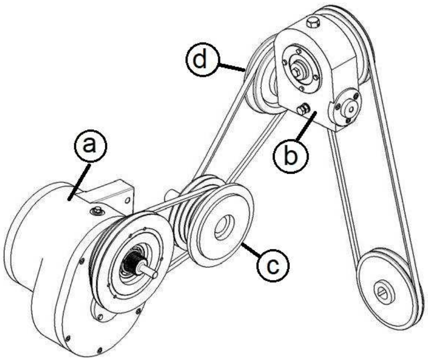


Fig. 6. Gearboxes (two-stage (a) and worm-crown (b)) and pulleys (driving (c) and driven-1 (d)).

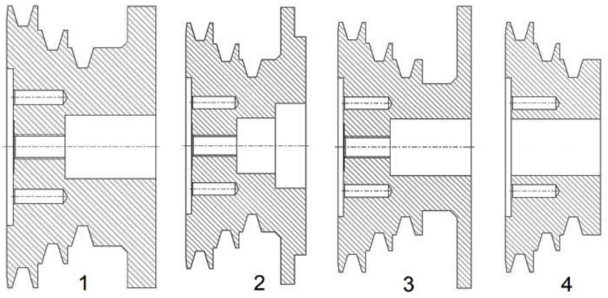


Fig. 7. Driving pulleys for different motors (1: HATZ SUPRA™, 2: RUGGERINI™, 3: PANCAR™, 4: electric).

4 PARAMETRIC PART DEFINITION

Several parts may be modified in order to reduce cost or weight or to improve quality. In addition, some parts come in variants, in line with product variants, a typical example being the driving pulley that needs to match the different models of motors that the client may require, see Fig. 7. Other examples of such parts are: the shaft of the upper and lower stirrers, the curved wall of the upper mixing tank, the curved wall of the lower stirrer shell etc.

Parametric design of such parts makes any modification simple and straightforward. Moreover, if this is linked to parametric definition of the CNC program according to which the part is manufactured, manufacturing of variants or modifications also becomes straightforward.

An example of this approach is given next regarding the driving pulley of the pumping system of the product.

4.1. Driving pulley diameter calculation

A generic driving pulley model is defined to cover all possible cases, see Fig. 8. The driving pulley has three stages (diameters), namely fast, medium and slow, which are used to regulate the speed of the pumping system cams. The cam shaft speed is 115, 78 and 50 rpm for the fast, medium and slow stages respectively. The belt connecting the driving and the driven pulleys at the two-stage gear box, see Fig. 6, is the same for all driving pulleys. The distance between centres of the driving and driven pulleys is the same for each stage.

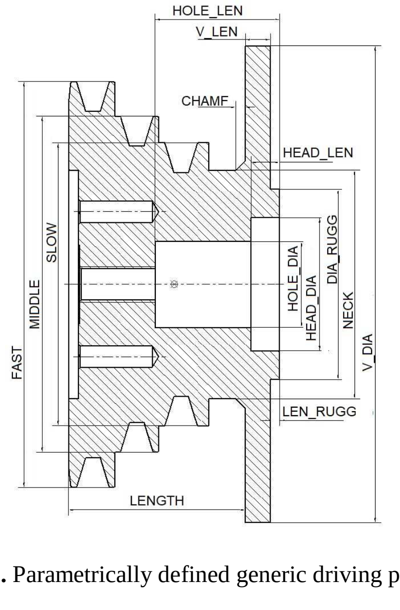


Fig. 8. Parametrically defined generic driving pulley.

Based on the above, the external diameter d_κ of each of the three stages of the driving pulley is calculated, given the distance between centres of the driving and driven pulley (α), the external and mean diameter of the driven pulley (d, d_m), the internal and mean length of the belt (L_i, L_m), the rotational speed of the motor (n_k), the reduction ratio (i) and the desired rotary speed of the cam shaft of the pump (n_p). Standard machine elements calculations [15] start with input of d, d_m, i, n_k, n_p as well as the belt type (e.g. B48) and the revolution loss coefficient (Ψ). Then, L_i is calculated according to tables from belt type, $L_m = L_i + C$ (C depending on belt width, being looked up in a table), rotary speed of driving pulley as: $n = i \cdot n_p$, mean diameter of the driving pulley as: $d_{\kappa m} = d_m \cdot n / (1 - \Psi) / n_k$ and $d_\kappa = d_{\kappa m} + 2c$ (c depending on belt width, being looked up in a table). Then, the distance between centres is calculated to obtain a value for $L_{m'}$ equal to the prescribed L_m according to the equation:

$$L_{m'} = \frac{\pi\, d_m}{2}\left[\left(1+\frac{\operatorname{asin}\left(\frac{\Delta}{\alpha}\right)}{90}\right)\right] + \frac{\pi\, d_{\kappa m}}{2}\left[1-\frac{\operatorname{asin}\left(\frac{\Delta}{\alpha}\right)}{90}\right] + 2\sqrt{\alpha^2-\Delta^2} \tag{1}$$

where: $\Delta = (d_m - d_{\kappa m})/2$.

This calculation is executed initially for one of the three stages of the pulley, regarded as reference stage. The same length of belt has to apply to the other two stages, which means that $d_{\kappa m}$ for these stages has to be solved for in Eqn (1), retaining α constant as obtained from first stage calculation. This procedure has been programmed in an Excel™ spreadsheet.

4.2 Driving pulley parametric design

There are 14 parameters used for defining the pulley as shown in Fig. 8. These are given in a spreadsheet table linked to the parametric model in Autodesk Inventor™.

Many parameters are defined in terms of other parameters, e.g. CHAMF = 0.5 if LENGTH < 83, Fig. 8.

Each parameter value is constrained so that the final result is meaningful for an artefact. If a value is input which violates these constrains, an ERROR message appears, e.g. HEAD_DIA > 0.75·NECK, see Fig. 8.

Note that the parameters FAST, MIDDLE and SLOW draw their values directly from the calculation spreadsheet referred to in Section 4.1.

A solid model is constructed parametrically in Autodesk-Inventor™, fully driven by the MS-Excel™ spreadsheet with automatic constraint checking.

The pulleys are made of aluminium alloy series 4000.

4.3. Parametric process plan and tool path

The process plans differ according to the type of pulley, i.e. the type of the matching motor. However, within each type of process plan the tools and their main movements are basically the same, all variations pertaining to the different coordinates delimiting them. Path coordinates are directly calculated from those of the pulley in a MS-Excel™ spreadsheet application. Any pulley is manufactured on a turning centre in three setups, resulting in a separate spreadsheet per setup in the application. The following assumptions are made:

(a) the casting is 3–5 mm larger than the final shape of the pulley;

(b) the casting does not contain any slots or holes;

(c) maximum depth of cut for boring (internal turning) operations is 1.5 mm;

(d) maximum depth of cut for slotting operations is 2 mm.

In setup 1, see Fig. 9(i), rough facing is performed first with an external turning tool leaving a finishing allowance of 1 mm. Profiling up to the fast stage diameter is performed with the same tool (Path1). The middle and slow stage slots and the neck are processed with a second tool (Path2), whereas the internal surface, the seat and chamfer are processed with the same tool (Path3).

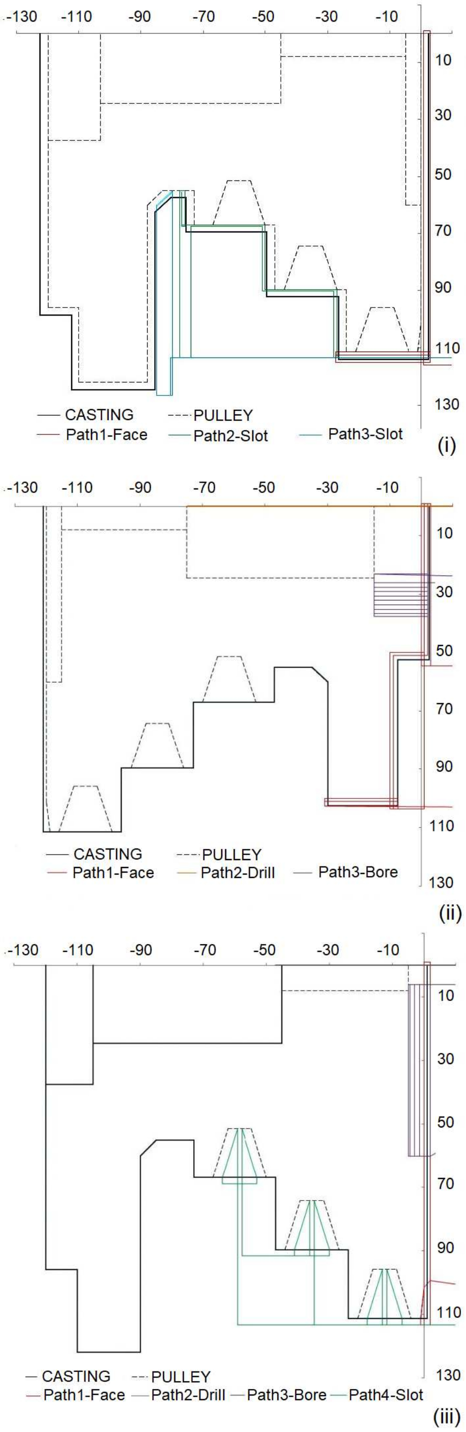


Fig. 9. Parametrically defined toolpaths in setups (i)-(iii).

In setup 2, see Fig. 9(ii), the centering ring and the seat are processed to their final dimensions with an external turning tool (Path1). Then, the hole is processed with a drilling tool (Path2) and the hole head is enlarged with a boring tool (Path3). The number of hole making passes is automatically calculated from the difference of the hole and hole head radii.

In setup 3, see Fig. 9(iii), the external turning tool is used for finishing the face and chamfer (Path1). The drilling tool enlarges the hole (Path2), the boring tool enlarges the recess (Path3), the slotting tool enlarges the 3 stage slots (Path4) and finally, the hole is threaded (Path5).

4.4. CNC program

CNC programs for Heidenhein^{TM} controllers have resulted automatically and directly from the parametric tool path.

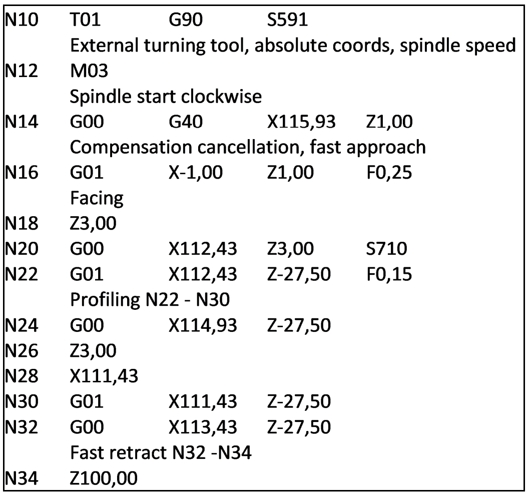
Mostly, the parametric nature is implicit, since all parameter values have already been calculated at the parametrisation stage of the toolpath, see Section 4.3, and the calculated values are just passed to the CNC program at the corresponding coordinate place-holders.

Thus, in setup 1, rough facing stage is translated into the code shown in Fig. 10.

In addition, to a lesser extent, the parametric language available for these controllers is used, too. In this language, all variables are written as Qnn, nn ranging from 01 to 99 and all arithmetic, trigonometric etc. operators are symbolised as Dmm, mm ranging from 01 to 12, e.g. D00 is ‘=’, D01 is ‘+’. D07 is ‘cosine’, etc. and Pqq, qq ranging from 01 to 99, is an automatically entered parameter, essentially asking for the pertinent data, e.g. ‘D07 Q03 P01 55’ is interpreted as ‘cos(55)=Q03’.

Thus, in setup 2, hole head making stage is translated into the following code, making use of a subroutine, as shown in Fig. 11.

In blocks N16 to N30 the parameters for hole head making are defined. In block N100 the step is defined as depth of cut *e*. In block N102 subroutine L1 is repeated as long as radius of cutting is smaller than Q08. In this way an infinite number of hole-hole head combinations can be dealt with.



```
N10   T01       G90       S591
      External turning tool, absolute coords, spindle speed
N12   M03
      Spindle start clockwise
N14   G00       G40       X115,93   Z1,00
      Compensation cancellation, fast approach
N16   G01       X-1,00    Z1,00     F0,25
      Facing
N18   Z3,00
N20   G00       X112,43   Z3,00     S710
N22   G01       X112,43   Z-27,50   F0,15
      Profiling N22 - N30
N24   G00       X114,93   Z-27,50
N26   Z3,00
N28   X111,43
N30   G01       X111,43   Z-27,50
N32   G00       X113,43   Z-27,50
      Fast retract N32 -N34
N34   Z100,00
```

Fig. 10. CNC code example for Facing in Setup 1.

```
N16   D00   Q01   P01   26,00
      Initial hole head radius 26mm
N18   D00   Q02   P01   39,50
      Final hole head radius 39.5mm
N20   D00   Q03   P01   -10,00
      Hole head length 10mm
N22   D00   Q04   P01   15,00
      Difference in radii 15mm
N24   D00   Q05   P01   1,50
      Depth of cut step e=1.5mm
N26   D00   Q06   P01   10,00
      Number of passes 10
N28   D00   Q07   P01   0,00
      Remainder 0
N30   D02   Q08   P01   Q02   P02   Q05
      Q08 = final radius – depth of cut step
…
N88   M06   T04
      Boring (internal turning) tool
N90   G98   L1
      Subroutine 1 start
N92   G90   G00   X     Q01   Z2,00  S1704
      Fast move in X, Z, spindle speed
N94   G01   Z     Q03   F0,25
      First pass in hole enlargement
N96   X     23,00
      Retract in cutting feed
N98   G00   Z2,00
      Retract in fast feed
N100  D01   Q01   P01   Q01   P02   Q05
      Radius increase by pass step e
N102  D12   P01   Q01   P02   Q08   P03   1
      If  radius < Q08 repeat subroutine 1
N104  G00   X     Q02   Z2,00  S2047
      Fast approach, spindle speed
N106  G01   Z     Q03   F0,15
      Last pass
N108  X23,00
      Retract in cutting feed
```

Fig. 11. CNC code example for Hole head making in Setup 2.

5 CONCLUSIONS

Complex product comprise of a large number of parts, hundreds or thousands. In order to systematically select parts that need attention, a coding system is necessary and needs to be implemented as a database. This was demonstrated in the case of a product containing more than 1000 parts, of which more than 200 were manufactured in-house. In our case, the parts that were selected for improvement were those involving specific manufacturing processes that were considered either outdated (oxy-fuel instead of laser cutting of sheet) or counter-productive (conventional instead of CNC machining). In fact the new process plans resulted in lowered lead time by at least one order of magnitude.

Complex products also come in variants in order to match customers' needs. Product variants translate into variants of crucial parts, such as, in our case, the driving pulley transmitting motion from the motor to the pumping system. This part is also manufactured in-house in a potentially large number of variations owing to the motor as well as to the cement flow rate required by the customers. Thus, its parametric design leading to automatically produced CNC code adds to the flexibility and productivity of its manufacturing and of the system as a whole.

The exemplified techniques can be adopted universally irrespective of the particular product and manufacturing processes, leading to improvement in manufacturing performance.

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