IMPERIAL

MANUFACTURING TECHNOLOGY AND MANAGEMENT

CONTINUOUS AUTOMATED PRODUCTION OF A STEEL BRAKE DRUM

Group 7

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1. INTRODUCTION

This report details the automated continuous production of automotive brake drums, manufactured from supplied steel castings (refer to Figure 1). The brake drums undergo precise machining operations using CNC turning centres to achieve the final specifications (refer to Figure 2). As this is a dedicated production line, our facility works exclusively for this purpose within a larger manufacturing plant.

With an expected daily output of 240 finished brake drums, automation is essential to meet production targets, maintain consistent quality and ensure cost efficiency. The manufacturing process involves mill-turn machining on multiple faces, requiring safe and secure work-holding to prevent misalignment and damage to parts (before, during and after manufacture). To support production efficiency, essential documents such as the Bill of Materials (BoM), CNC tool set up sheets and a detailed production planning sheet are prepared. These documents detail the toolpaths, lead times and the steps involved, ensuring a steady flow of production while minimising downtime to meet the brake drum requirements each day. Additionally, detailed descriptions and justifications of selected tool inserts and their holders are provided.

A work centre/factory layout was developed to optimise workflow by minimising handling and transport distances between machining centres, robotic systems, inspection stations and packaging areas. This helps to reduce time lost in movement between centres, improving overall efficiency of production.

Finally, a detailed cost analysis has been conducted on the production line. Resources have been allocated based on the required production rate of 240 drums per day, and from this, a factory model and shift plan have been devised. Furthering this, the entire costing model has been built, reaching an expected cost per part of £22.55.

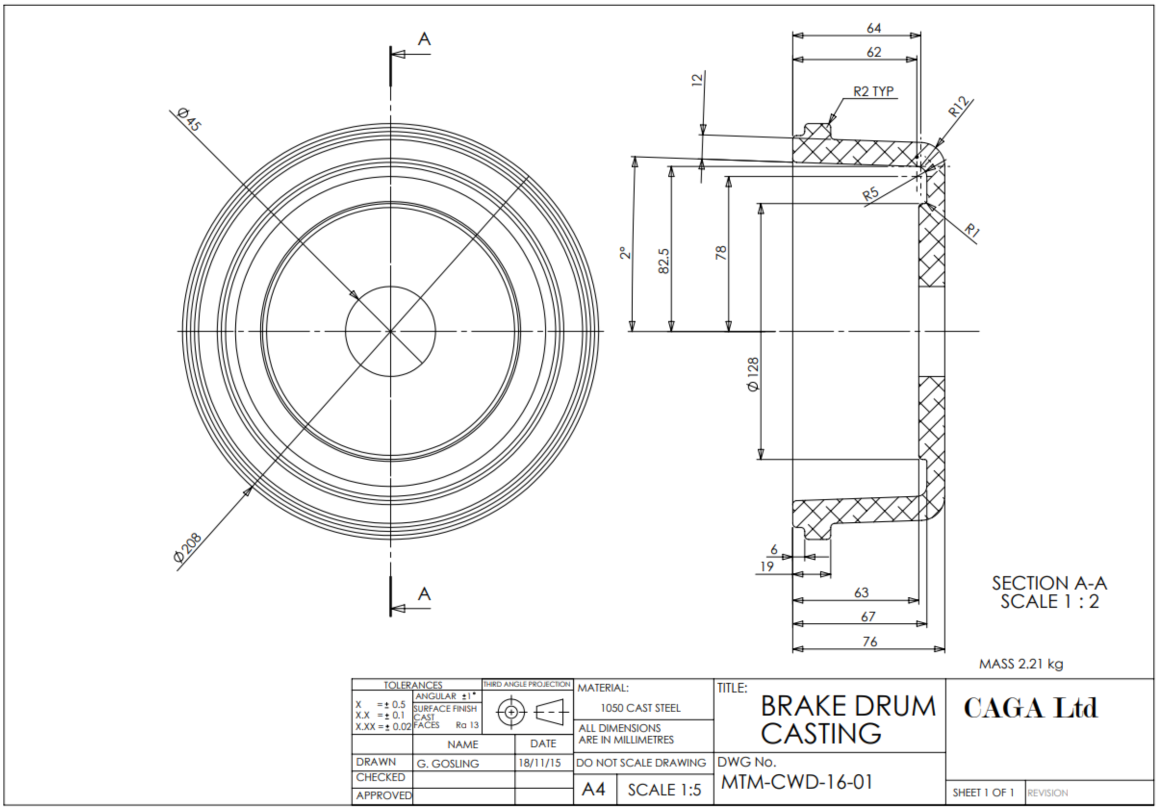


Figure 1: Technical Drawing of the supplied Brake Drum Casting

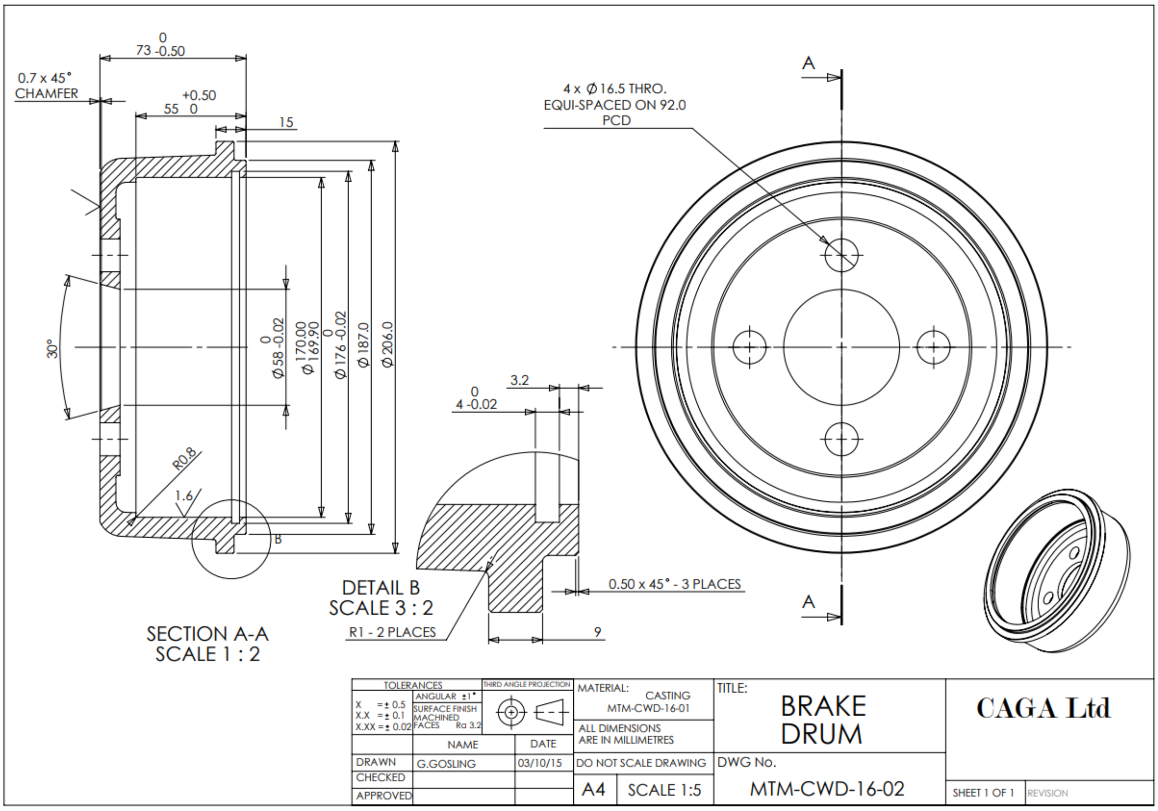


Figure 2: Technical Drawing of the finished Brake Drum after manufacture

2. MANUFACTURING METHOD

2.1 CHOSEN MACHINERY

The Haas DS-30Y CNC turning centre (as seen in Figure 3) was selected for its dual-spindle, which reduces lead times by eliminating the need for part turnover. Its automatic part transfer enables uninterrupted machining from both spindles. Automation allows for unattended operation, reducing the need for consistent observation from operators and lowering labour costs. The inclusion of an automatic door allows for efficient part loading and unloading without interrupting the machining process. Additionally, the centre's Y-axis control also allows for precise off-centre drilling in the drum.

Figure 3: Haas DS-30Y

Feature	Application
12-station BMT65 turret	The standard 12-station bolt on turret provides tooling capacity for the 10 required tools and allows for two duplicate tools reducing the number of changes required. The ability to quickly switch between tools on the turret improves efficiency and reduces lead times from tool changes. The rigidity of the BMT65 allows for the precision and repeatability [1] required for the high accuracy brake drum. It doesn't require any additional alignment, reducing setup times.

A2-6 Primary spindle, 254mm chuck, 4500 rpm	The 4500rpm capability is sufficient for all machining processes. A range of speeds can be chosen to balance material removal rate and a high surface finish. The 254mm diameter chuck can also securely hold the brake drum casting (208mm diameter). The A2-6 spindle nose supports brake drum torque requirements.
A2-5 Secondary-Spindle, 210mm Chuck, **4000rpm**	The secondary spindle is fully synchronised with the main spindle, allowing for in-cycle part handoff. This allows for the brake drum to be manufactured in a single set up.
Automatic Door	The inclusion of an automatic door allows for robot automation during manufacture. A robot arm will be able to enter and exit the work area without clashing, ensuring quick production.
C-axis Indexing	Although the machine supports both y-axis movement and C-axis indexing, the C-axis is preferred for machining the four inner holes, due to the importance of their positioning relative to the centre. Using C-axis indexing ensures high precision and repeatability in hole placement; otherwise, it immediately becomes a scrap part.
Coolant	Coolant flow in the system is controlled via an M-code, this integration is important to keep temperatures low during machining. Also, this addition allows for the removal of swarf and since the process is automated, it is important that swarf is constantly removed otherwise this can lead to a scrap part.

2.2 MACHINING STEPS

The planned machining steps for the brake drum on the main and sub-spindle are described below, including run times estimated using SolidWorks CAM. Setup times were determined based on engineering judgement. From this, the manufacturing lead times can be calculated (section 5.1). It is important to note that the set-up time is only applicable for the start of each batch, when tools and/or inserts are changed.

Part Description	***BRAKE DRUM***		**Batch Size**	***24***
Part Number	*BRDR 001*			
Op. No.	**Operation Narrative**	**Work Centre**	**Set up time (mins)**	**Run time (mins)**
010	Clean machine down		**4**	
	Load CAM program from DNC		**3**	
	Assemble the 12 tools and holders		**20**	
	Load the 12 tools into turret		**10**	
	Define and load tool offsets		**10**	
	Load casting into main spindle chuck (Manual Operator)		**0.3**	
	Produce First Off		**5**	
	Inspect dimensions via Operator and Equator		**6**	
	Load casting into main spindle chuck (Robot assisted stock feed)			**0.3**
	Tool turret index – Probe	CNC Turning Centre		**0.03**
	Probe end of Stock			**0.3**
	Tool turret indexes to RH External Face & turn tool – Finish			**0.03**
	Cut - Finish Face 1mm deep (Ra 3.2)			**0.124**
	Cut - Finish Ext Turn (Ra 3.2) and Shoulder (Ra 3.2), chamfer (0.5mm)			**0.206**
	Tool turret indexes to RH Int Turn Bore tool – Finish			**0.03**
	Cut - Finish Int Bore 2.5mm deep (Ra 1.6)			**0.225**

	Tool turret indexes to RH Int Turn Face tool – Finish			**0.03**
	Cut - Finish Face (Ra 3.2)			**0.097**
	Tool turret indexes to RH Groove tool			**0.03**
	Cut – Rough Int Groove 4x3x2.5mm and 3.2mm from z DRO – Rough			**0.661**
	Cut – Finish Int Groove, 1.5mm deep (Ra 1.6)			**0.342**
	Transfer part to Sub Spindle			**0.05**
	Tool turret indexes to LH External Face tool			**0.03**
	Cut – Finish Face 1mm (skimmed, 3.2Ra)			**0.067**
	Tool turret indexes to LH External Turn tool			**0.03**
	Cut – Rough Ext Turn and Shoulder			**0.200**
	Cut - Finish Face, Ext Turn and chamfer on the shoulder			**0.427**
	Tool turret indexes to LH Internal Bore tool			**0.03**
	Cut - Rough Int Bore 6.5mm deep & 15° taper			**0.104**
	Cut - Finish Int Bore & Taper			**0.059**
	Tool Turret indexes to LH Centre drill			**0.03**
	Mark centre of hole, 46mm offset from centre on x axis **(x4)**			**0.2**
	Casting - C index 90° clockwise **(x4)**			**0.32**
	Pilot hole (4mm deep)			**0.408**
	Casting - C index 90° clockwise **(x4)**			**0.32**
	Tool turret indexes to LH ϕ16.5 Drill			**0.03**
	Drill through - ϕ16.4 Drill on pilot hole (x4)			**0.872**
	C index 90° clockwise **(x4)**			**0.32**
	Tool Retract			**0.08**
	Part collected by Robot and placed on pallet			**0.3**
Total Time			**54.3**	**5.98**

A CNC Turning Centre set up sheet is provided to document the turning and drilling tools used in the operation, specifying their material: carbide or high-speed steel (HSS). The sheet also details the tool holders and refers to which spindle it is used in, via RH (right-hand) for primary and LH (left-hand) for secondary. Additionally, a set up drawing at the bottom of the sheet illustrates the brake drum's placement within the hydraulic chucks and where the origins are indicated.

CNC Turning Centre - Set Up Sheet

Part Number	BRDR 001		Machine Tool	HAAS DS-30Y
Description	DRUM BRAKE - GROUP 7		Tool holder	12 Station BMT65
Operation No.	10		Program No.	1
Material & grade	1050 CAST STEEL		Prepared by	MAX B
Section & Size	ROUND Ø208		Date	16/02/2025
Work Holding	Main	3 Jaw Chuck	Matl. Loading	Automatic - Robotic Arm
Work Holding	Sub	3 Jaw Chuck		

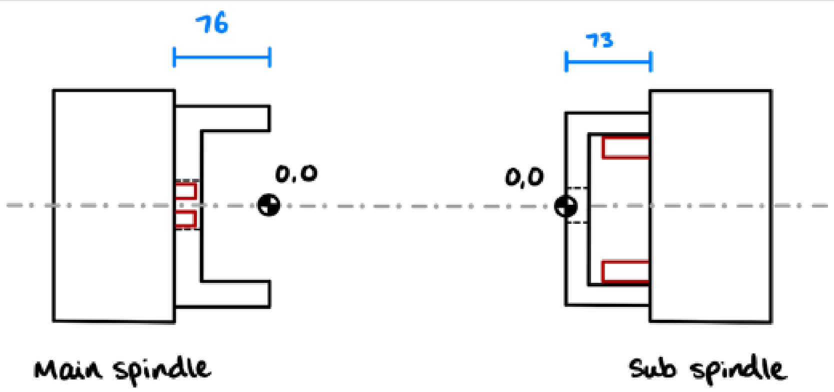
Turning Tools

Tool #	Generic Description	Matl	RH/LH	Tool code	Insert No.	Tool Location
1	Probe (WIPS-L)					1
2	EXTERNAL TURN & FACE	Carbide	RH	DCLNR 2525M 16	CNMG 16 06 08-PR 4425	2
3	INTERNAL BORE	Carbide	RH	C5-TR-V13UBR-35060C1	TR-VB1308-F 4415	3
4	INTERNAL FACE FINISH	Carbide	RH	PSKNR 2525M 15	SNMG 15 06 24-PR 4425	4
5	INTERNAL GROOVE CUT	Carbide	RH	570-32RSMAL3	MAGL 3 250 1025	5,6
6	EXTERNAL FACE	Carbide	LH	DSSNL 2020K 12	SNMG 12 04 16-PM 4425	7
7	EXTERNAL TURN	Carbide	LH	DCLNL 2525M 16	CNMG 16 06 08-PR 4425	8
8	INTERNAL BORE	Carbide	LH	A25T-SSKCL 12	SCMT 12 04 12-PR 4425	9

Milling/Drilling Tools

	Generic Description	Matl	Dia.	Exposed Length	Fixed/Live Axial/Radial	Tool Location
9	CENTER DRILL	HSS	5		AXIAL/ LIVE	10
10	DRILL	HSS	16.5	53.56	AXIAL/ LIVE	11,12

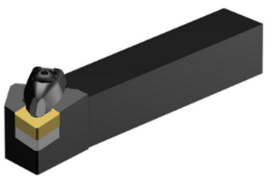
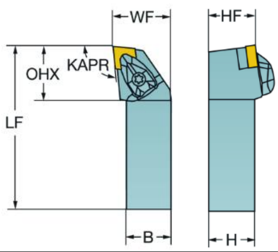
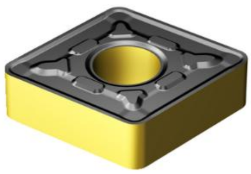
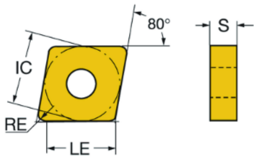
Set up drawing - show in *working holding including datum*

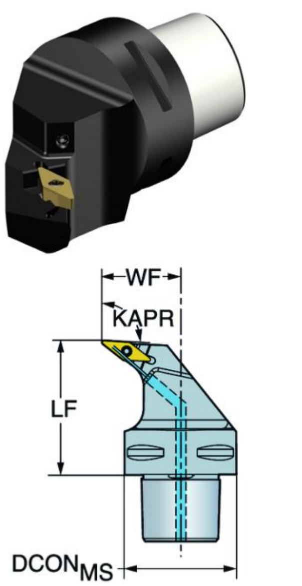
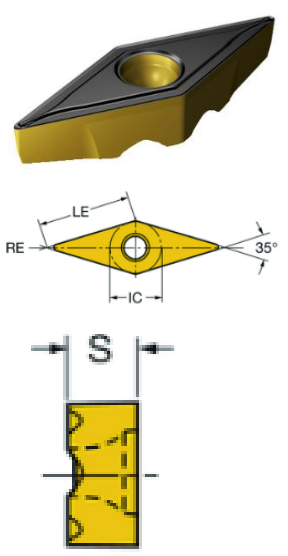


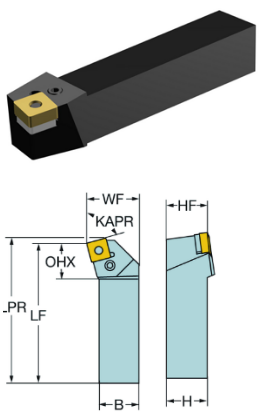
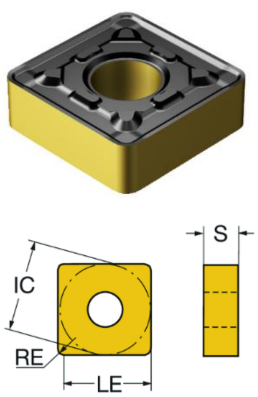
2.3 TOOLING SELECTION

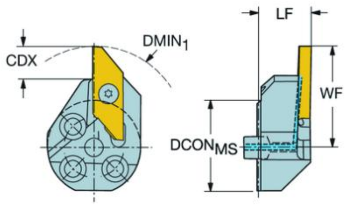
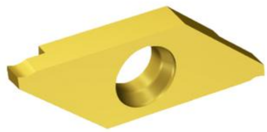
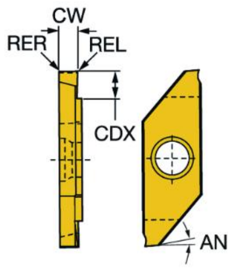
Table 1 includes all models of the machine tools and inserts selected and their corresponding operations. Aside from the HAAS centre drill[2], all were selected from the Sandvik Comorant range. Furthermore, all cutting speeds, depth of cuts, and feed rates were calculated using Sandvik's CoroPlus Tool Guide software [3]. Sequential operation numbers happen within the same CAM operations, however operation numbers with different first numbers happen within different operations (e.g. 101 vs 201).

Table 1: Insert selections, including insert and holder dimensions. Parameters such as cutting speed, feed rate, depth of cut and tool life count are defined

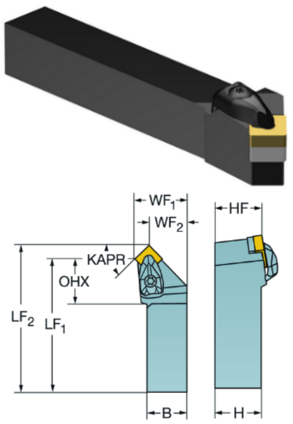
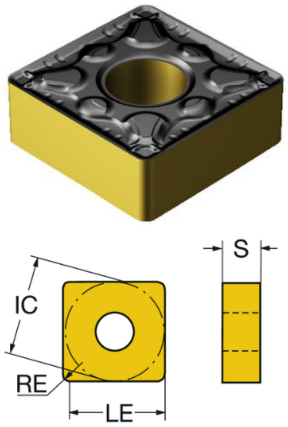
TOOL		**INSERT**	
Turret Location: 2			
[101]: Facing off drum			
DCLNR 2525M 16		**CNMG 16 06 08-PR 4425**	
  	**KAPR:** 95˚ **PSIR:** -5˚ **OHX:** 39 mm **WF:** 32 mm **LF:** 150 mm **B, H, HF:** 25 mm	  	**Angle:** 80˚ **IC:** 15.875 mm **RE:** 0.7938 mm **LE:** 15.3199 mm **S:** 6.35mm **Cutting edge count:** 4 **Grade:** 4425 **Coating:** CVD TiCN+Al2O3+TiN
Cutting speed (m/min	338	**Depth of cut (mm)**	2
Feed rate (mm/rev)	0.288		
[102]: Finishing off external shoulder			
Cutting speed (m/min)	338	**Depth of cut (mm)**	2
Feed rate (mm/rev)	0.288	**Tool life count**	45.45

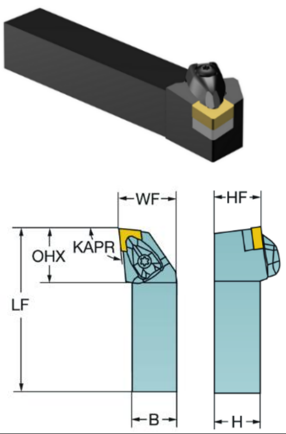
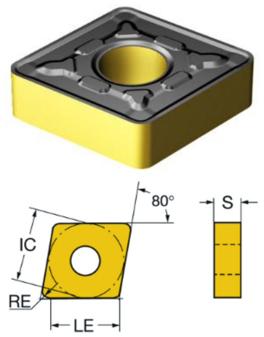
<table>
<tr><td colspan="4">Turret Location: 3</td></tr>
<tr><td colspan="4">[103]: Finishing of internal bore</td></tr>
<tr><td colspan="2">C5-TR-V13UBR-35060C1</td><td colspan="2">TR-VB1308-F 4415</td></tr>
<tr><td>
</td><td>KAPR: 93˚
WF: 35 mm
LF: 60 mm
DCONMS: 50 mm</td><td>
</td><td>Angle: 35˚
IC: 8 mm
RE: 0.7938 mm
LE: 12.2 mm
S: 4.525 mm
Cutting edge count: 2
Grade: 4415
Coating: CVD TiCN+Al2O3+TiN</td></tr>
<tr><td>Cutting speed (m/min)</td><td>392</td><td>Depth of cut (mm)</td><td>0.4</td></tr>
<tr><td>Feed rate (mm/rev)</td><td>0.206</td><td>Tool life count</td><td>66.67</td></tr>
</table>

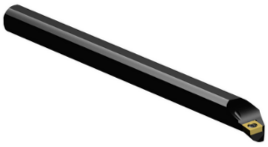
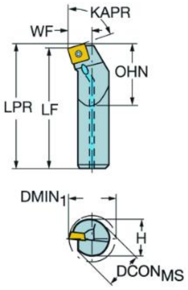
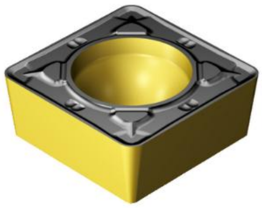
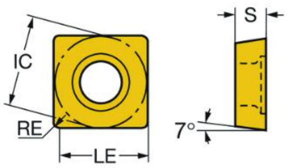
<table>
<tr><td colspan="4">Turret Location: 4</td></tr>
<tr><td colspan="4">[104]: Finishing of internal face</td></tr>
<tr><td colspan="2">PSKNR 2525M 15</td><td colspan="2">SNMG 15 06 24-PR 4425</td></tr>
<tr><td>
</td><td>KAPR: 75 ˚
PSIR: 15 ˚
OHX: 28.9 mm
WF: 32 mm
LF: 150 mm
LPR: 153.8 mm
B, H, HF: 25 mm</td><td>
</td><td>Angle: 90 ˚
IC: 15.875 mm
RE: 2.3813 mm
LE: 13.475 mm
S: 6.35 mm
Cutting edge count: 8
Grade: 4425
Coating: CVD TiCN+Al2O3+TiN</td></tr>
<tr><td>Cutting speed (m/min)</td><td>283</td><td>Depth of cut (mm)</td><td>3</td></tr>
<tr><td>Feed rate (mm/rev)</td><td>0.5</td><td>Tool life count</td><td>154.64</td></tr>
</table>

<table>
<tr><td colspan="4">Turret Location: 5,6</td></tr>
<tr><td colspan="4">[105]: Roughing of internal groove</td></tr>
<tr><td colspan="2">570-32RSMAL3</td><td colspan="2">MAGL 3 250 1025</td></tr>
<tr>
<td>

</td>
<td>WF: 30.5 mm
LF: 14 mm
CDX: 8.2 mm
DMIN1: 50 mm
DCONMS: 32 mm</td>
<td>

</td>
<td>RER: 0.05 mm
REL: 0.05 mm
Corner radius Tolerance: +- 0.02
CW: 2.5 mm
CDX: 3.7 mm
S: 3.175 mm
AN: 6 °
Cutting edge count: 2
Grade: 1025
Coating: PVD TiAlN+TiN</td>
</tr>
<tr><td>Cutting speed (m/min)</td><td>146</td><td>Depth of cut (mm)</td><td>2.5</td></tr>
<tr><td>Feed rate (mm/rev)</td><td>0.09</td><td></td><td></td></tr>
</table>

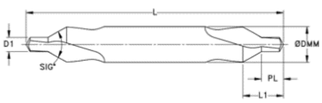
<table>
<tr><td colspan="4">[106]: Finishing of internal groove</td></tr>
<tr><td>Cutting speed (m/min)</td><td>146</td><td>Depth of cut (mm)</td><td>1.5</td></tr>
<tr><td>Feed rate (mm/rev)</td><td>0.135</td><td>Tool life count</td><td>14.96</td></tr>
</table>

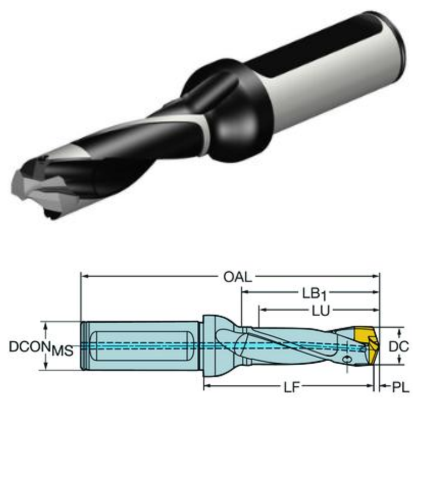
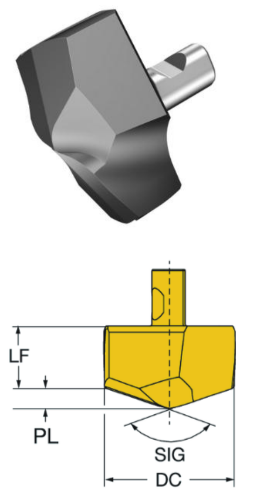
Turret Location: 7			
[201]: Facing off drum			
DSSNL 2020K 12		**SNMG 12 04 16-PM 4425**	
	**KAPR:** 45 ° **PSIR:** 45 ° **OHX:** 27.5 mm **WF:** 25 mm **LF:** 125 mm **B, H, HF:** 20 mm		**IC:** 12.7 mm **RE:** 1.5875 mm **LE:** 11.1 mm **S:** 4.7625 mm **Cutting edge count:** 8 **Grade:** 4425 **Coating:** CVD TiCN+Al2O3+TiN
Cutting speed (m/min)	338	**Depth of cut (mm)**	1
Feed rate (mm/rev)	0.408	**Tool life count**	223.88

Turret Location: 8			
[202]: Roughing of external shoulder and diameter			
DCLNL 2525M 16		**CNMG 16 06 08-PR 4425**	
	**KAPR:** 95 ° **PSIR:** -5 ° **OHX:** 39 mm **WF:** 32 mm **LF:** 150 mm **B, H, HF:** 25 mm		**Angle:** 80 ° **IC:** 15.875 mm **RE:** 0.7938 mm **LE:** 15.3199 mm **S:** 6.35 mm **Cutting edge count:** 4 **Grade:** 4425 **Coating:** CVD TiCN+Al2O3+TiN
Cutting speed (m/min)	317	**Depth of cut (mm)**	4.51
Feed rate (mm/rev)	0.35		
[203]: Finishing of external shoulder and diameter			
Cutting speed (m/min	338	**Depth of cut (mm)**	2.16
Feed rate (mm/rev)	0.288	**Tool life count**	32.59

<table>
<tr><td colspan="4">Turret Location: 9</td></tr>
<tr><td colspan="4">[204]: Roughing of internal bore</td></tr>
<tr><td colspan="2">A25T-SSKCL 12</td><td colspan="2">SCMT 12 04 12-PR 4425</td></tr>
<tr><td>

</td><td>KAPR: 75 °
PSIR: 15 °
OHX: 100 mm
WF: 17 mm
LF: 300 mm
LPR: 303.05 mm
B, H, HF: 23 mm</td><td>

</td><td>IC: 12.7 mm
RE: 1.1906 mm
LE: 11.5 mm
S: 4.7625 mm
AN: 7 °
Cutting edge count: 4
Grade: 4425
Coating: CVD TiCN+Al2O3+TiN</td></tr>
<tr><td>Cutting speed (m/min)</td><td>314</td><td>Depth of cut (mm)</td><td>2.27</td></tr>
<tr><td>Feed rate (mm/rev)</td><td>0.373</td><td></td><td></td></tr>
</table>

<table>
<tr><td colspan="4">[205]: Finishing of internal bore</td></tr>
<tr><td>Cutting speed (m/min</td><td>320</td><td>Depth of cut (mm)</td><td>1.96</td></tr>
<tr><td>Feed rate (mm/rev)</td><td>0.353</td><td>Tool life count</td><td>92.02</td></tr>
</table>

<table>
<tr><td colspan="4">Turret Location: 10</td></tr>
<tr><td colspan="4">[301]: Centre drilling 4 holes</td></tr>
<tr><td colspan="2">Haas HSS 60° Centre Drill</td><td></td><td></td></tr>
<tr><td>

</td><td>ØDMM: 12.5 mm
D1: 5 mm
SIG: 60 °
L1: 12.8 mm
PL: 6.3 mm
L: 63 mm</td><td></td><td></td></tr>
<tr><td>Cutting speed (m/min)</td><td>177</td><td>Depth of cut (mm)</td><td>4</td></tr>
<tr><td>Feed rate (mm/rev)</td><td>0.27</td><td>Tool life count</td><td>36.76</td></tr>
</table>

Turret Location: 11, 12			
[302]: Drilling of 4 holes			
870-1600-16LX075-3		**870-1640-16-PM 4334**	
	**PL:** 2.58 mm **LU:** 53.56 mm **LB:** 56 mm **LF:** 69.42 mm **OAL:** 122 mm **DCONMS:** 19.05 mm		**ØDC:** 16.4 mm **SIG:** 142 ° **LF:** 7.51 mm **PL:** 2.4 mm **Grade:** 4334 **Coating:** PVD TiAlN
Cutting speed (m/min)	110	**Depth of cut (mm)**	10
Feed rate (mm/rev)	0.326	**Tool life count**	16.88

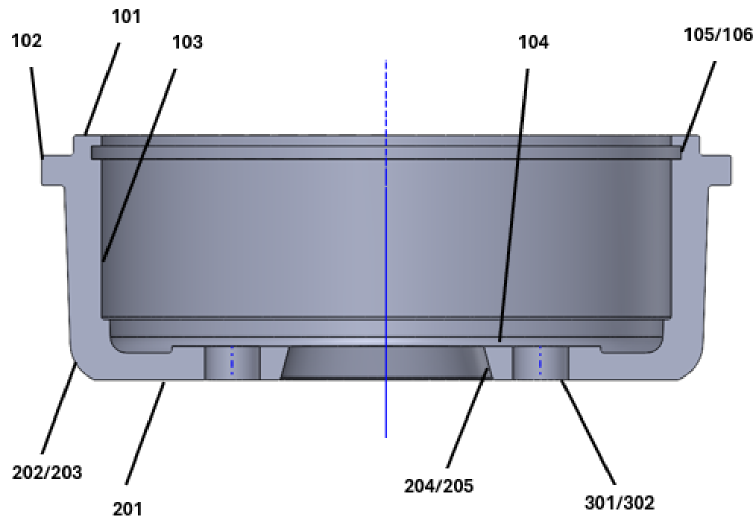


Figure 4: Each operation visualised on the brake drum, indicating its location

The machining operations outlined in Table 1 are visually represented in Figure 4. The BMT65 turret selected allows for 12 fastening locations. Turret space 1 was assigned to the WIPS-L touch probe, needed for calibration of the turret and spindles.

With only 9 tools, along with the touch probe required, the two additional spaces in the turret allows for spare tools to be allocated to extend production capabilities before tool changes are necessary. It is assumed that each tool edge has a lifetime of 15 minutes, therefore it was observed that the shortest tool lives were on the grooving tool (Operation 105/106 - 14.96 drums), and drill (Operation 302 - 16.88 drums). The quick tool wear is expected to be due to the double grooving operation, and 4 successive holes in the drilling operation. Hence, it was decided that these two tools would be given two turret spaces each, effectively doubling their tool life, therefore making the lowest effective operating tool life, a minimum of 29.92 drums. This allowed for a batch production run of 24 brake drums, rather than the 12 before the required insert replacements, overall reducing downtime.

The tool life count calculated by Sandvik is proportional to machining time. The estimated (maximum) tool life usage was determined by using the following formula:

$$Tool\ life\ usage = \frac{24}{29.92} = 0.802 = 80.2\%$$

It must be noted that for simplicity of the CAM, simplified tool holders were used with the correct inserts, whilst ensuring the actual tools provided sufficient clearance. The corresponding CAM programme and G-code can be found in the .zip file provided.*[1]

Tool selection was based on the stock material, 1050 cast steel, which corresponds to a P grade material/category. The Sandvik Tool Guide was used to determine the appropriate tools and inserts for the corresponding step. These were then trialled in the CAM simulations. Inserts and tools' shape and entry directions were picked based on interference with the drum, as well as the rotational direction of the spindle. All turning inserts were carbide and use the same coatings (TiCN+Al2O3+TiN) and applied via Chemical Vapor Deposition (CVD). These coatings reduce the chance of diffusion or abrasion to the insert over time. On the other hand, the groove tool and drill bit have slightly different properties. The groove tool has a TiAlN and TiN coating, which helps prevent built-up edge and attrition wear to maintain surface quality and tool longevity. This is particularly crucial, considering the brake drum has a sharp edge, so requires a consistently sharp cutting edge to produce a groove within tolerance. The drill bit is made

*[1] It is important to mention that when running Step 3 FINAL, the "STEP 2 FINAL" stock needs to be manually selected.

of hardened steel and a coating of TiAlN applied via Physical Vapor Deposition. It is important to ensure that the insert is harder than the material to prevent wear.

There were some considerations during tool selection:

- For a given required fillet/dimension, the largest possible radius tools were selected to maximise tool life.
    - Where needed, if the corner radius of the insert was found to be too large (recommended by Sandvik) for a step, a smaller corner radius insert was selected for the same tool holder.
- All boring tools were selected to ensure their diameter fit within the drum without interference.

It is also important to note that some decisions to proceed directly to finishing (skipping roughing) was intentional, matching Sandvik's recommendation. This is because based on the cutting depths that were required, it seemed suitable to directly finish off to reduce run time and to increase tool insert longevity. The tools are also required to be rigid when finishing to avoid tool vibration and deflection.

3. WORK HOLDING, PART HANDLING & WORK CENTRE LAYOUT

3.1 WORK HOLDING

Whilst turning, the brake drums will be held in the DS-30Y's standard chucks for the primary and secondary spindles. The primary spindle has a 254mm diameter hydraulic chuck from LNC Work holding, and the secondary spindle is fitted with a smaller 210mm hydraulic chuck from Kitagawa (the B-208 model). Both chucks have 3 jaws, but these will be replaced with the set of custom bored jaws shown in Figure 5.

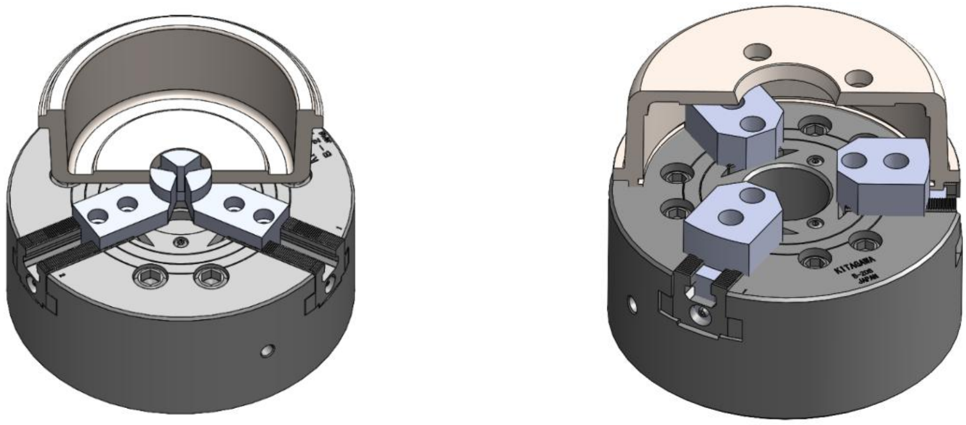


Figure 5: (Left) Custom Hardened Jaws for Setup 1 in Primary Spindle (Right) Custom Soft Jaws for Setup 2 in Secondary Spindle

Since the central through hole is machined in the second setup, hardened jaws will be used in the first setup to provide a longer life for the jaws. The second shoulder sits 11.5mm above the first, leaving 0.5mm clearance from the cutter when facing the internal boss, and the tail extends 60mm outwards to contact the whole outer surface for stability. Setup two allows more space for the jaws. Being wider and taller, these custom soft jaws which will provide a firmer grip on the part, whilst maintaining a large operating life due to the distributed pressure.

The soft jaws will be re-machined three times a year during the factory's maintenance shutdowns and fully replaced on the fourth, alongside the hard jaws. This would result in 21660 and 86640 uses for each set of jaws, respectively. They are either manufactured in the factory, if it makes its own tooling, or outsourced, costing £120 for soft jaws, and £200 for the hardened.

3.2 PART STORAGE

To leave the production line running overnight, there must be a capacity to store 240 castings, and then 240 finished drums. Since the drums are low and wide, they are incredibly stable, allowing them to be stacked vertically. Weighing only 2.21kg each, an arrangement of 3x4 drums stacked 5 high, totals only 133kg. Accounting for a 20kg palette, and 3kg per divider, 168kg is well within the limits of forklifts and pallet jacks.

To protect the castings and finished products, they are held separate for storage and transport. This is done using a 20mm thick panel of chipboard, sandwiched between two rubber mats to form a divider. The rubber will cushion the parts and stop them from sliding due to any horizontal movement, and the chipboard will provide structure to the stack (as seen in Figure 6). Boards must be transferred from the stack of castings to the pile of finished products as each level is completed. Two vacuum pads are capable of this and are shown in Appendix 1. With the need to store 480 drums (240 castings and 240 completed with no spare stock), 40 dividers are required, and 8 Pallets.

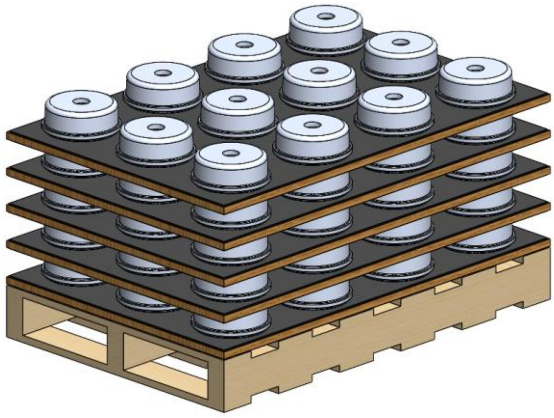


Figure 6: Storage of 60 Drums on a Pallet

3.3 ROBOT AUTOMATION

To automate the manufacturing process, the KUKA KR16 R1610 has been selected for part transfer as it provides several key advantages. As an articulated robot arm with 6 degrees of freedom (DOFs), it allows for flexible and precise movement, especially when moving in between the CNC turning centre door. Additionally, it has a rated payload of 16kg (and a maximum payload of 20kg), has a large working envelope in the y plane (as seen in Figure 7) and provides a maximum reach of 1.61m from a central base in the x plane. To ensure stability, the robot will be floor mounted. This makes it well suited for handling brake drum castings safely in a wide range, as well supporting the custom end effectors, the magnetic clamp (as will be described in the next section) and suction pads (see Appendix 1).

To allow for part loading and unloading in the chuck, the machine's automatic door must be synchronised with the robot's movements. It will also need to be synchronised with the Equator gauging system (section 4.1). Furthermore, as the machine is equipped with a hydraulic chuck, coordination between the opening/closing cycles must be defined and synced with the robot to avoid collisions. This requires defining the distances and times in the control system. As safety is a high priority, fencing/caging will be implemented into the factory layout (section 3.5) to ensure no damage occurs to the operator, motion sensors will also be working.

A table grid pick up system has been chosen, meaning that the pallets will be fixed in place during part loading and unloading. Positional data of the pallet design will need to be programmed into the robot to ensure it recognises the distances between parts (distance between centres of squares). It is a consideration that it can recognise part dimensions in both the raw and finished state to handle the components correctly, however since a magnetic chuck is used, it would be suitable for both raw and finished brake drum dimensions.

For finished part drop off, a dual table method will be used, with separate locations for incoming castings and finished brake drums. This set up allows for efficient workflow management.

Motion planning is critical:

- Approaching and moving away from the CNC machine door will use joint-type motion to reduce the risk of overwinding the joint.
- Loading and unloading the casting into the chuck, it will use cartesian motion to ensure precise linear movement for accurate placement

This automated system allows for unattended operation, for improving productivity while minimising manual intervention.

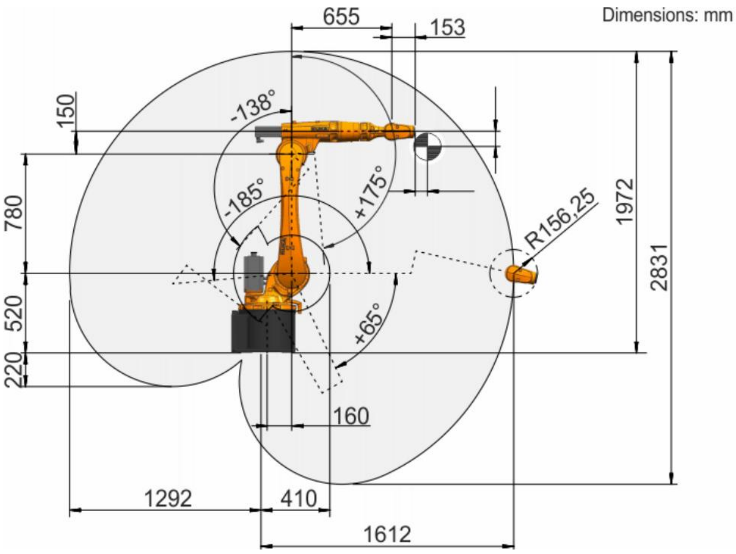


Figure 7: (Left) KUKA KR16 R1610 (Right) Working envelope in millimetres

3.4 PART LOADING

When loading and unloading the part into the CNC turning centre, the use of a magnetic clamp was favourable. It comes with one large benefit, it allows us to hold the outside of the casting, and finished drum, therefore allowing the drum to be picked up and placed down, regardless of orientation (as seen in Figure 8). Permanent magnet chucks are also safe against a power loss as they would hold their state until released. Furthermore, the profile is lesser than the diameter of the drum, whereas jaws capable of grasping the outer diameter would not be. The shallow draft angle of the outer surface is appropriate for holding with a permanent magnet clamp which can be purchased as a custom order from companies, such as HVR MAG[4] for approximately £4,000. Provided the poles are not too large, the magnetic field will not penetrate the surface of the drum, preventing the clamp from affecting or damaging any sensitive equipment [5]. Additionally, this means the

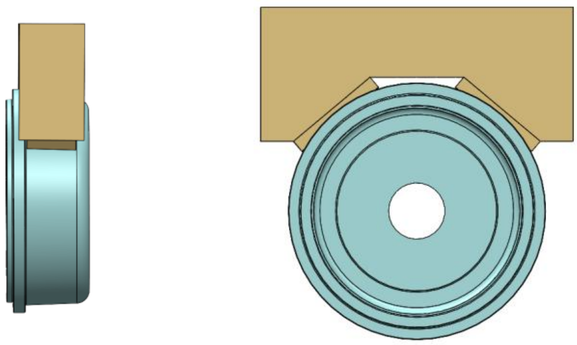


Figure 8: Custom Magnetic clamp for transport using a ROBOTIC arm

clamp will not attract or pick up adjacent objects as the field's range is small. The drum wall is machined to 17mm thickness at the thinnest point which is comfortably larger than the cited 12mm standard minimum thickness [5].

3.5 WORK CENTRE LAYOUT

Combining this together, when considering the design of our factory layout, a key factor was determining the number of CNC turning centres required to produce the expected output of finished brake drums. After calculations, it was determined that two CNC machines were needed to achieve the targeted 240 drums per day and to account for unexpected delays in production (e.g. in the event of machine downtime, the second machine ensures continued production).

As illustrated in Figure 9, our layout consists of two CNC machines, two KUKA robots, a total of 4 pallets (two for castings, holding 24 brake drums total and two for the finished drums, holding the same amount) and in the middle of the robots, where the working envelope overlap is the Equator Gauging system. It is ideal that the two Haas machines will work out of phase of each other and therefore, produce a brake drum every six minutes.

This will also allow the robots to share the Equator in the middle. There is fencing around the exterior to provide protection to operators from the robots. The fencing also extends around the Equator, including an automated slide gate to remain shut when a user enters so that the second production line may remain in operation. Doors on both sides of the factory allow for easy access for bringing castings into the area and for bringing the finished drums out. It is expected that the part route will come in from the left-hand side and exit out the right-hand side being transported on pallet jacks. Pallets are changed during tool changes to prevent a second downtime in each run, and to allow access for the operator for changing tools.

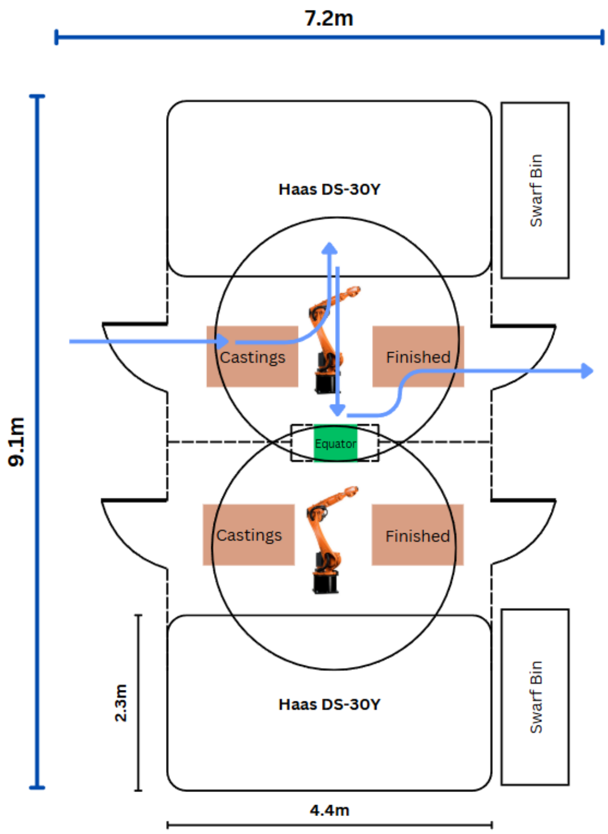


Figure 9: A scaled drawing of the factory layout

In total, this workspace takes up approximately 64m^2 of space in the factory. This does not include storage space, which is later accounted for in factory overheads. The width of the factory layout is made up of the length of the Haas DS-30Y, 4.4m. However, required swarf conveyor clearance (section A4) increases this to 5.9m. Swarf bins make up the remaining 0.6m. The factory layout length is made up of 2 pallets, the Equator, and the width of the turning centres. Giving a length of 9.1m, with ample room for operator access.

This layout aims to balance cost efficiency with operator accessibility, ensuring a compact design that minimises floor space while maintaining a practical and ergonomic workspace for the operators. This also aims to reduce the movement time that operators would have to take.

Four blue lines, shown in Figure 9, display the castings route through the cell. Firstly, entering on the pallet, before being loaded into the turning centre. After machining, the drums are moved directly to the Equator gauging system, before being placed on the second pallet, which is in turn, wheeled out before tool changes.

4. METROLOGY

4.1 PART MEASUREMENT

A Renishaw Equator 300 gauging system with the added automatic transfer system will be used to measure every critical dimension on a part (Figure 10). The Equator 300 offers a comparison uncertainty of ±2μm over a 300mm diameter, 150mm height range and a 25kg maximum weight, within which the drum comfortably fits. The system's selection of probes allows for the measurement of every critical dimension without the need to rotate the part. Alongside this, the automatic transfer system and large operating temperature range, this metrology solution will integrate flawlessly with the continuous production line, directly on the shop floor. The factory is also likely to already own the gauge checking system which will be used to recalibrate the gauging system.

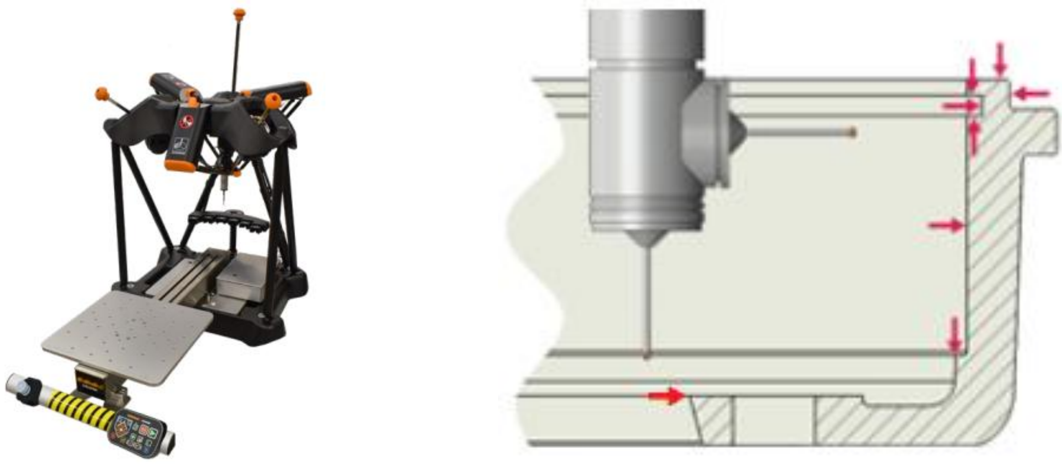


Figure 10: Use of the Equator probe (Left) to measure the critical dimensions (Right)

Full automation of the metrology solution affords room to verify several product dimensions, without affecting the production lead time. 9 key dimensions have been selected for measurement. Shown by red arrows in Figure 10, they are the internal surface diameter, and shoulder location; width, depth and location of the internal groove; Outer diameter, and drum height; and the internal diameter of the tapered through hole. These measurements will be taken continually about the radius to measure the diameters, also accounting for variation in placement on the plate and checking for warping of the drum. The external shoulder, and 4 through holes have not been selected for measurement due to their low tolerance. Additionally, surface finish is not being measured as Ra 1.6 is beyond the accuracy of the Equator but should be well within the capabilities of the machining centre. Therefore, the gauging system will run a pass of the internal surface and check for larger surface deviations resulting from a critical machining error but will otherwise assume the tolerance is met.

Since the metrology process is fully automated, as one part is completed every 6 minutes, the Equator's rapid measurement time allows inspection of every single part produced. After replacing the tooling, the operator will observe one run-cycle, and if the gauging system reports a failed tolerance, any issues can be immediately rectified. However, the main benefit arises during normal running. In the event of a critical machine failure, such as damaged tooling, the continuous inspection will catch this immediately and can halt production on that line until the operator returns to rectify the issue. This will prevent loss from defect production.

4.2 CALIBRATION

Due to repeated movements over thousands of production cycles, the tracks of the turning centres will wear unevenly. Fortunately, the computational axis controls allow this to be accounted for. During the four annual shutdowns, a ball bar will be used to measure the deviation caused by this wear, and the turning centres can automatically account for this.

Similarly, the Equator gauging system will also need recalibrating. This will be done at the same time during each of the four annual maintenance shutdowns. In the unfortunate event that the gauging systems calibration deviates too quickly for this frequency of recalibrations, it could be done by a second skilled technician during a tool change once a month or whenever is required, in addition to the replacement of the probe end, and inspecting visually during every tool change.

5. COSTING

5.1 FINITE CAPACITY PLAN

The production line will be installed in an existing factory operating 24 hours a day, 7 days a week, except for 4 annual maintenance closures. During normal operation, each turning centre completes 5 tool changes per 24-hour period, with each tool change lasting 60 minutes.

5.1.1 PRODUCTION AND SCHEDULING

Using two turning centres, the manufacturing lead time (MLT) must be 12 minutes to produce 240 drums a day whilst keeping to a regular shift pattern, shown in Figure 11. MLT can be calculated as:

$$MLT = \frac{Setup\ time}{Batch\ size} + Run\ time + Transport\ time$$

$$MLT = \frac{60}{24} + 5.98 + 3.52 = 12$$

For a 60-minute setup time, the transport time would be 3.52 minutes - longer than necessary. This provides comfortable flexibility to accommodate unforeseen setup issues or runtime faults. Figure 11 shows a typical 24-hour production cycle:

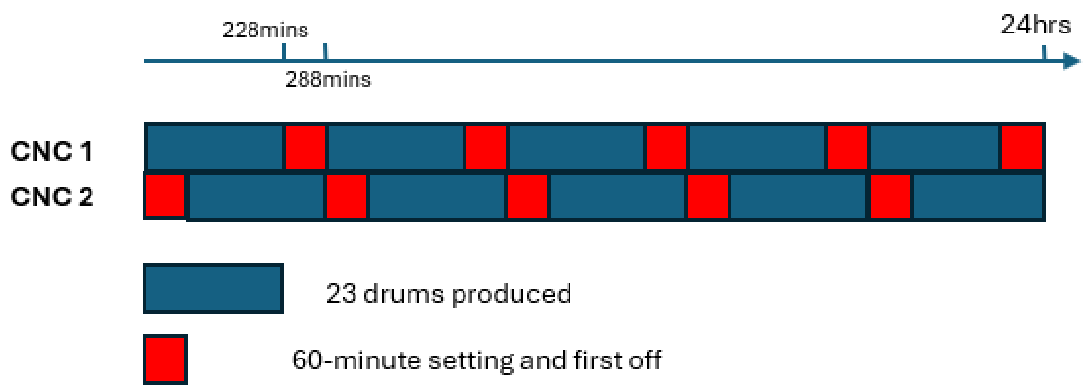


Figure 11: 24-hour production cycle

In this plan, the first drum in each batch is considered the “first-off” and is included within the setup time. The machine cycles are then offset by 60 minutes so that the setter can spend 2 hours on the machines before rotating onto another task. Maintenance closures are accounted for in costing calculations by distributing all costs across 361 operational days. For simplicity, we assume 240 drums are produced per day, only on these 361 days. However, if the 960 drum deficiency this creates is an issue, there is sufficient leeway in the "transport time" to create a daily overproduction equal to the loss.

5.1.2 UTILISATION OF TURNING CENTRES

Utilisation (U) is "an estimate of how many actual production hours will be worked in all available hours of the shift pattern" [6] and can be calculated for our process from the 24 operating hours for each machine, with the 5 hours of tool changing subtracted.

$$U = \frac{Duration\ of\ production\ run}{Duration\ of\ shift\ pattern} = \frac{24 - 5}{10} = 190\%$$

With 2 machining centres, and a 190% utilisation, the production facility has a capacity of 38 hours. This is to be expected as we run two production lines continually for 19 hours each.

$$FC = Resources\ \times Shift\ Pattern \times Utilisation = 2 \times 10 \times 1.9 = 38\ hours$$

5.2 PROCESSING COSTS

5.2.1 LABOUR

During the 5 x 60-minute downtimes for each machine, tooling will be changed by a skilled technician, whilst the coolant levels are checked, and the swarf bins emptied by one unskilled labourer for the whole duration of production. 10 hours of setting time for each 24-hour cycle gives us a setter work percentage of

$$\frac{10}{24} = 42\%$$

Labour cost per hour for standard operation can be calculated:

$$C_{l1} = 15 + (25 \times 0.42) = £25.41$$

During shutdown days, it is assumed that a skilled technician will spend 6 hours servicing each machine. This adds an additional 24 hours of labour. Distributed over the whole year this cost equates to:

$$C_{l2} = \frac{6 \times 4 \times 25}{361 \times 24} = 6.8 \text{ pence per hour.}$$

All of this comes to a final labour cost of

$$C_l = 15_{operator} + 10.41_{setter} + 0.068_{Servicing} = £25.478$$

5.2.2 DEPRECIATION

Each turning centre, costing £122,000, has a service life of 5 years, resulting in a total operational time of $5 \times 361 \times 24 = 43{,}320$ hours. The robotic arms cost £21,900 each and are expected to operate for the same duration, alongside its £4,000 magnetic chuck, and £1,000 suction pads. Subsequently, the hourly cost due to machine depreciation is

$$C_{d1} = \frac{122{,}000 + 21{,}900 + 4{,}000 + 1{,}000}{5 \times 361 \times 24} \times 2 = £6.874$$

Eventually, the pallets and dividers used to store and transport the drums will also need replacing. It is estimated that pallets and dividers will last 10 years if treated well. 8 pallets and 40 dividers are required costing £15, and £110 each respectively (See section A1). Their hourly depreciation cost therefore comes to:

$$C_{d2} = \frac{15 \times 8}{20 \times 361 \times 24} + \frac{110 \times 40}{10 \times 361 \times 24} = £0.051$$

Similarly, the Equator gauging system and ball bar will require replacement every 10 years. They cost £19,000 and £8,500 so their hourly depreciation is:

$$C_{d3} = \frac{19000 + 8500}{10 \times 361 \times 24} = £0.317$$

The tool holders will need replacing due to continuous usage. Considering fatigue failure and creep deformation, a 5-year retirement age seems appropriate. The total cost of toolholders comes to £1,375.20, so their depreciation will be

$$C_{d4} = \frac{1375.2}{5 \times 361 \times 24} \times 2 = £0.064$$

Lastly, the annual replacement of the custom chuck jaws will add an hourly depreciation of:

$$C_{d5} = \frac{120 + 200}{361 \times 24} \times 2 \ = £0.05$$

The final depreciation costs (per hour) come to a total of

$$C_d = 6.874_{Machinery} + 0.0514_{Storage} + 0.317_{Metrology} + 0.064_{Toolholders} + 0.05_{ChuckJaws} = £7.356$$

5.2.3 OVERHEADS

The total production line footprint is 64m^2 totalling $1{,}200 \times 64 = £76{,}800$ a year. Additionally, there must be room to store a stock of castings, and the finished ones. Assuming every day, a delivery of 240 castings arrives, and the previous days completed castings are shipped out, there must be space to store at least 480 drums. With 60 drums to a pallet, and each pallet having an area of $1.2 \times 0.8 \approx 1.0m^2$, that would total $1 \times 1{,}200 \times 8 = £9{,}600$ annually. However, it is unlikely that the factory will not have shelves strong enough to hold the 170kg pallets. Assuming 4 levels of shelving, the yearly cost is reduced to a quarter of that, £2,400. This comes to an hourly cost of

$\frac{76{,}800+2{,}400}{361\times24} = £9.14$ for space, accounting for the 4 shutdown days. It is also assumed that this value includes lighting costs.

Unprocessed castings and finished brake drums will also need transporting. Assuming one unskilled labourer spends 2 hours loading and unloading castings and finished drums on trucks, as well as 2 more moving them to and from storage and the production line, their labour totals $\frac{15\times(2+2)}{24}$= £2.50 an hour of handling.

Additionally, an administrator may divide their time equally between all production lines in the factory. Assuming there are 4 other production lines in the factory, the administrator would allocate 1/5$_{th}$ of their 8-hour workday to the drum production line. Similarly, a 2-person cleaning staff would do the same. This results in $\frac{25 \times 8}{5} = £40$ per day administration, and $\frac{15\times2\times 8}{5} = £48$ of cleaning, translating to an hourly equivalent of

$\frac{40+48}{24}$ =£3.667. Administration and cleaning will still be required during shutdown days, so an additional $\frac{4}{361\times24}\times(40+48)=4.10$ pence must be added, totalling £3.708 for cleaning and administration every hour.

Finally, the turning centres also require an air supply of 120L per minute at 7 bar. We assume the factory has its own integrated air supply and compressors, which the production line will utilise. The forklift and pallet jack used to transport the pallets will also be placed into this calculation, in addition to the Equator's calibration system as all are factory assets for which compensation for use will be needed. To simplify the calculations, it will be assumed the factory charges use for this equipment at £3,000 annually, which can be converted to $\frac{3000}{361\times24}$ =£0.346 per hour.

Therefore, the total hourly overheads allocated to the brake drum production line will be

$$C_o = 9.14_{storage} + 2.5_{handling} + 3.708_{administration\,\&\,cleaning} + 0.346_{hire} = \text{£}15.695$$

5.2.4 CONSUMABLES

The Haas DS-30Y has a 108L cooling tank, which is topped up regularly during production, and completely purged each maintenance shutdown. This might result in around 6 tanks worth of coolant being used, or 684L. Assuming coolant costs £0.15 per litre to buy, and £0.20 for disposal, this would result in $\frac{(0.15+0.2)\times684}{361\times24}\times2=\text{£}0.056$ per hour of production.

Other consumables will include paper towels, hand soap, paper and printer ink, toilet roll, and the storage shelves, but these expenses are distributed across the factory. Further consumables may even include items such as breakroom coffee, and depreciation from office equipment such as printers, chairs, computers. We shall assume this totals £0.02 per hour.

Consumables therefore total an hourly expense of:

$$c_c = 0.056_{coolant} + 0.02_{other} = \text{£}0.076$$

5.2.5 POWER

Each machine operates with a duty cycle of 0.25. This is assumed to be the average across the whole day and therefore includes time when the machines are idle during tool changes. The turning centre consumes 15.4kW, alongside the 5.2kW robotic arm, and 190W Equator gauging system, totalling 20.79kW. For a fixed electrical cost of £0.20/kWh,

$$C_{pow} = 0.25 \times 0.2 \times ((15.4 + 5.2) \times 2 + 0.19) = £2.070$$

5.3 TOOLING

To minimise downtime, tooling is replaced at regular intervals, even if some life remains, allowing batches of 24 to be produced. This does increase the tooling costs but results in net savings through the reduced setup times. The cost per part of each tool has been calculated as

$$\frac{C_t}{N} = \frac{Cost\ of\ insert}{N.cutting\ edges} \times \frac{1}{N.parts\ produced}$$

This equation accounts for the early replacement of inserts, whereas cutting time would not. The total tooling cost eventually works out to be a surprisingly large £6.26 per part. The whole workings can be found in the Appendix, where the deficiency of a cost-based analysis is shown.

5.4 FINAL COST

The final cost can be found from the manufacturing costs equation:

$$M_c = C_m \cdot V + \sum (C_p \cdot T) + \frac{C_t}{N}$$

Where $C_m \cdot V$ is the material cost, in our case casting cost, £6.15 each, C_p is processing costs per hour, which includes labour, overheads, depreciation, power and consumables:

$$\sum C_p = C_l + C_d + C_o + C_c + C_{pow}$$

$$\sum C_p = 25.478 + 7.356 + 15.695 + 0.076 + 2.07 = 50.675/hr$$

$$\sum (C_p \cdot T) = 48.044 \times 0.2 = £10.135/part$$

Manufacturing lead time, T, is 0.2 hours giving us a final cost per part of $M_c = £22.545$

6. CONCLUSION

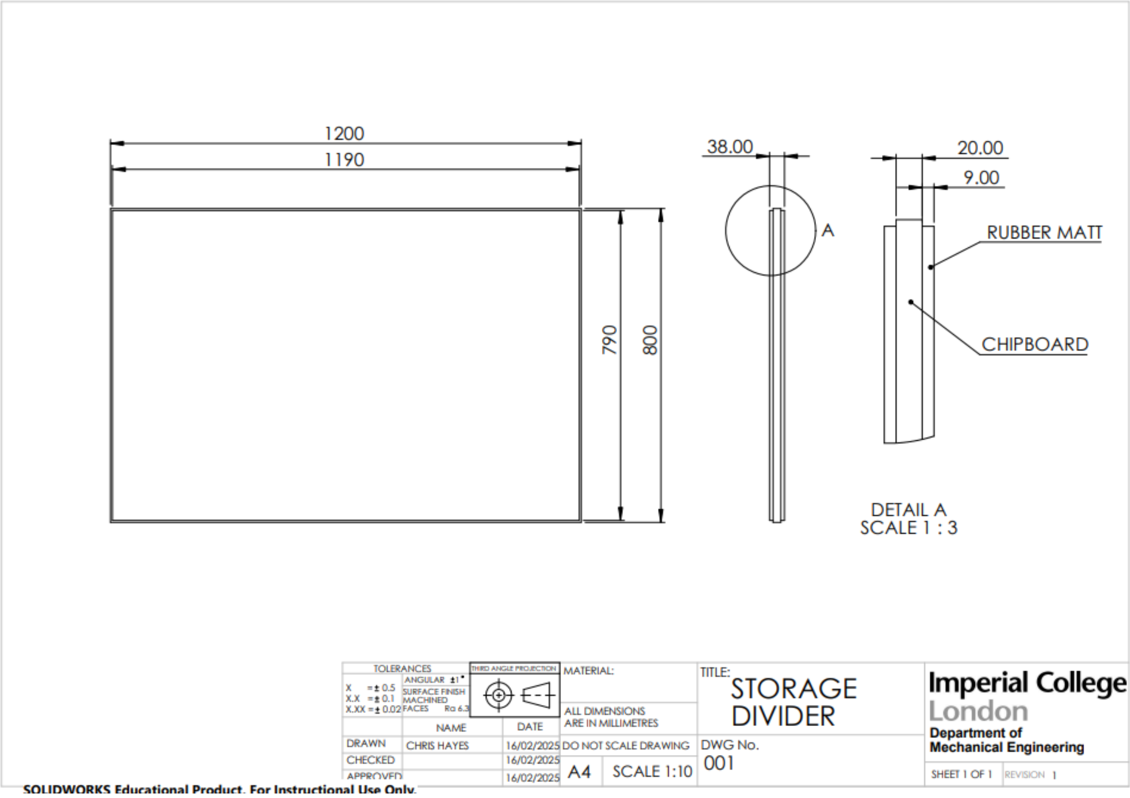
This report detailed the automated production of 240 brake drums per day, in batches of 24. Automation was achieved using two Haas DS-30Y machines, working together with two robotic arms and a single Equator gauging system. A compact factory layout was designed to optimise workflow, minimising part transfer times while maintaining adequate space for operator access.

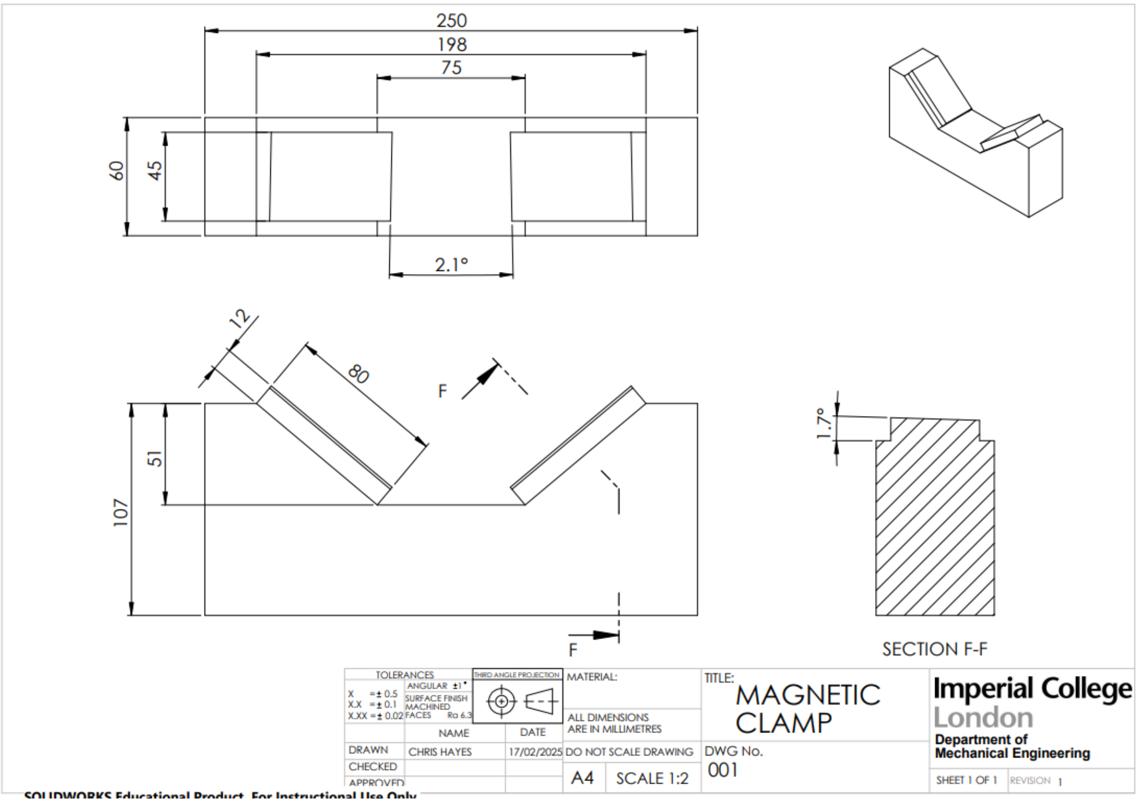
The 12-station turret accommodates all 10 required tools, with two additional spots for duplications of the groove tool and drill bit compensating for their relatively shorter tool life. Overall, increasing the productivity by reducing downtime for tool changes. The time efficient use of the Equator gauging system allows for every part to be inspected before final processing and allows for quick detection of scrap parts to maintain high quality standards. Additionally, the secure and space-efficient pallet packaging design ensures that the brake drums are protected during handling and transportation.

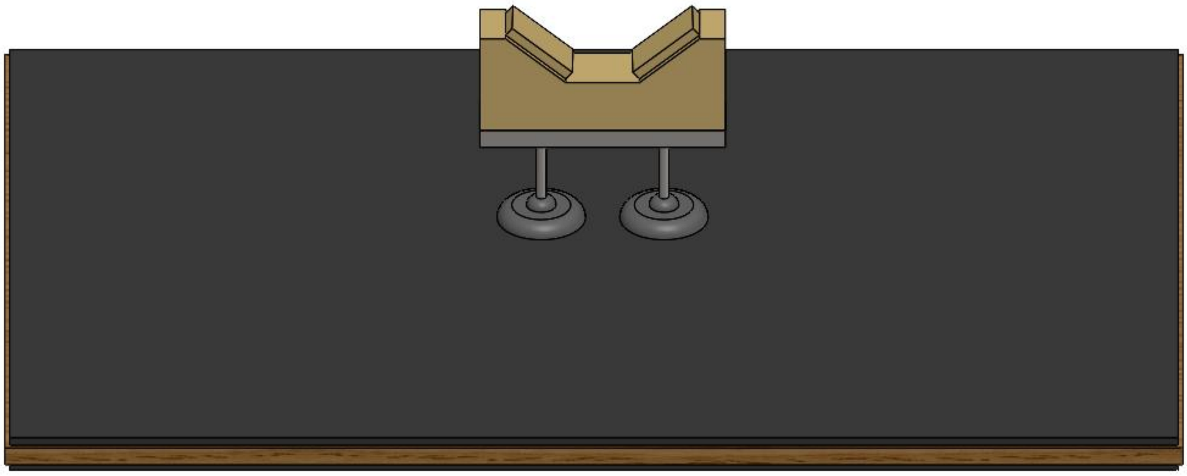
The cost analysis provides an insight into the allocation of resources, identifying key areas that contribute to cost per part, which is projected to be £22.55. Cost reductions may be most effective in labour expenses, either by reducing contingencies or allowing an operator to monitor more than 2 machines simultaneously. Depreciation is another significant expense, which could be lowered by producing a more efficient batch size. However, to avoid overcomplicating, we have chosen a streamlined approach. This well organised allows for the efficient production of brake drums.

APPENDIX

A1 – PART HOLDING AND STORAGE







Two vacuum pads are used to transport the drum dividers from one pallet to the next. This is done while the 13th pallet is being machined and does not slow production. The two pads are fitted onto the robotic arm, on the opposite side to the magnetic clamp, and are actuated pneumatically. Assuming a pad diameter of 10mm, a divider weight of 3kg, and a suction force of 0.5atm (50.66kPa), the pads are capable of lifting the divider with a safety factor of $(3 \times 9.81)/(2 \times \pi(0.005)^2 \times 50.66 \times 10^3) = 3.70$.

Costs of the pallets [7], chipboard [8], and rubber [9] matting used to store the components is simply the cost cited online, assuming assembly cost would be equal to the discount possible from a bulk purchase.

A2 – SUPPLEMENTARY TOOLING COST CALCUATIONS

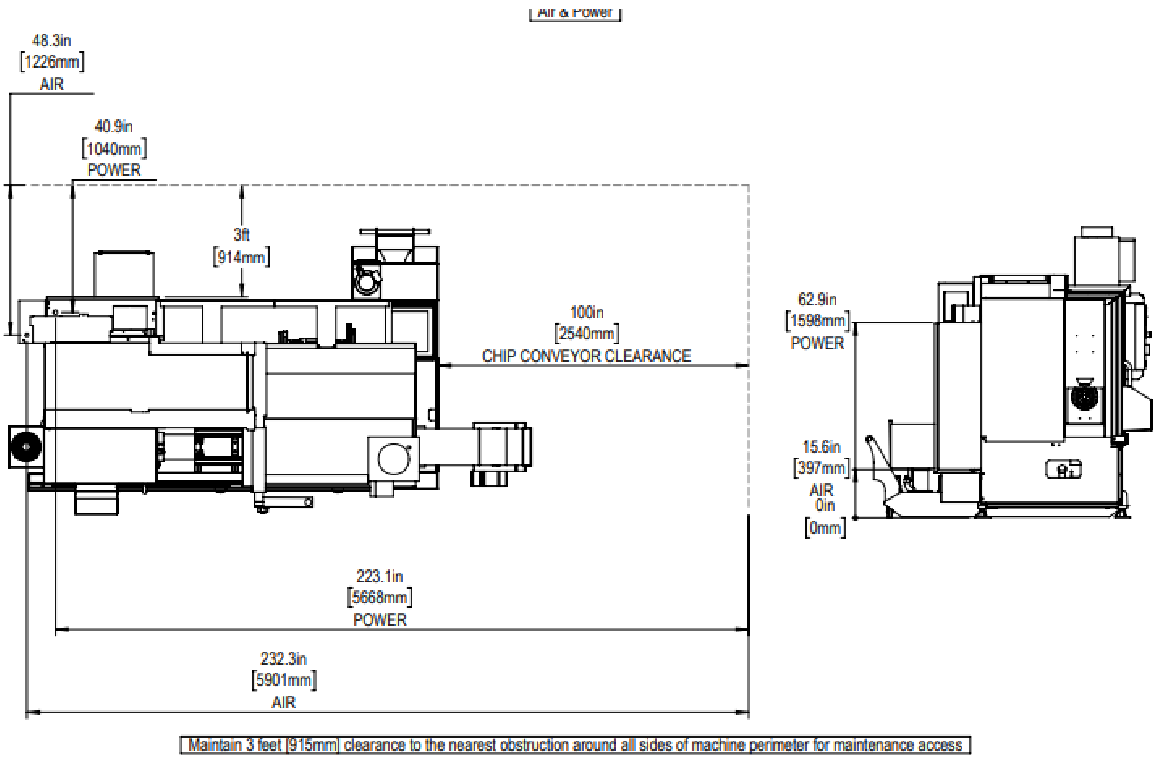
As discussed in section 5.3, the tooling cost has been calculated per number of parts produced by the insert before changing. This covers the cost of underuse, as shown in the table below. The table contains every piece of tooling, and its cost per part if it were to be used to failure, and as it is used with the current shift setup. Recall tools are replaced only every 24 drums, so those with parts produced of 12, appear twice in the turret.

Insert costs								
Insert	cost/unit	N. edges	tool life (minutes)	cutting time per part (s)	N. parts can be produced	time based cost (£)	N. parts actually produced	parts based cost (£)
CNMG 16 06 08-PR 4425	£2.17	8	15.00	19.80	45.00	0.006	24	0.0113
TR-VB1308-F 4415	£1.92	4	15.00	13.50	67.00	0.0071	48	0.01
SNMG 15 06 24-PR 4425	£2.17	2	15.00	5.82	155.00	0.007	144	0.0075
MAGL 3 250 1025	£7.65	8	15.00	60.16	15.00	0.0638	12	0.0797
SNMG 12 04 16-PM 4425	£1.37	8	15.00	4.02	224.00	0.0008	216	0.0008
CNMG 16 06 08-PR 4425	£2.17	4	15.00	27.62	33.00	0.0164	24	0.0226
SCMT 12 04 12-PR4425	£1.55	4	15.00	9.78	92.00	0.0042	72	0.0054
Centre drill	£7.00	1	15.00	10.00	90.00	0.0778	72	0.0972
870-1600-16LX075-3	£273.00	1	30.00	24.00	75.00	3.64	72	3.7917
870-1640-16-PM 4334	£107.00	1	30.00	30.00	60.00	1.7833	48	2.2292
					Total:	£5.61		£6.26

A3 – EXPENSES

Part/Expense	**Cost (£)**	**Quantity**
Haas DS-30Y	122,000	2
Equator Gauging System	19,000	1
KUKA KR 16 R1600)	21,900	1
Floor Space	$1200/m^2$	Xm^2
Power	0.2/kWh	
Pallets	15	8
Dividers	110	40
Soft Jaws	120	
Hard Jaws	200	
Skilled labourer	25/hr	1
Unskilled labourer	15/hr	1
Coolant (price and disposal)	0.35/litre	
General Consumables		

A4 – HAAS DIMENSIONS



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