Design of an injection molding machine

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Design of an injection molding machine.

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2. Summary

For research and educational purposes, the Faculty of Engineering and Surveying of the University of Southern Queensland, has started a program to develop a plastic extruder and an injection molding machine. The extruder (a single screw extruder in vertical position) has already been designed and manufactured. This project is on the design of the injection molding unit. To establish the background of injection molding technology, the history of the injection molding process and the different types of molding machines used in the past will be reviewed. The actual design, requirements and considerations are the next steps in the project. The design is closest to "two stage screw injection cylinder" type. It consist of two injection cylinders in order to let the extruder rotate continuously (the first one is filled while the other one injects the polymer). Each cylinder injects the plastic in one of the two molds. This injection molding unit is mounted on a mobile frame and has also an adjustable height. The injection plungers, the molds and the valve are all actuated by pneumatic cylinders. These cylinders will be controlled by PLC. PLC requires logic equations which can be derived by combinational logic, truth tables and Karnaugh diagrams. The last step will be the calculation (partly an estimation) of the total cost of the injection molding machine, it is possible to manufacture the design within the budget of A$13,000. In future the settings of the controllers have to be optimized empirically. This means that, by experiments, an optimum in cycle time (and different stages, like cooling time and injection time), temperatures of the different sections will have to be found.
3. Introduction.

Although injection moulding is not a recent development in plastic processing, it is still an area in which a lot of research is being done. At this university, University of Southern Queensland, Australia, an injection molding machine is needed for the research and educational program. Due to the low budget, the machine must be designed and manufactured at the university instead of purchasing a complete new machine. More importantly, it is believed that the idea of continuous plastication is incorporated in this design is an innovative idea, which results in this project being funded by an ARC grant. In recent years a vertical, single screw extruder has been developed and this extruder will form part of the injection molding machine. Besides the design of the machine ("hardware"), the pneumatic circuit and the controllers (hard- and software) have to be designed. Following a calculation and estimation of the costs, we will analyse the results to determine whether or not it is possible to manufacture the machine within the limits of the budget.
4. History.

4.1 Introduction.

Injection molding is, despite what many people think, not a recently invented process. The first injection molding machine that has been patented, was the machine of The Hyatt brothers in the United States in 1872. This machine was used to mold celluloid. Though it was an important invention it was not until the 1920s that new developments in this area were reported. These first German machines were totally on manually operated. Levers were used to clamp the mold and inject the plastic into a die. Improvements were made by the use of pneumatics that allowed the use of higher pressures and made the operator's job easier. The next big development was the introduction of hydraulics in the 1930's, which meant that the pressure could be increased further. Still the injection molding process was some hybrid die casting technology. In the 1950's the next generation of machines was introduced. The technology of these machines was very much the same as the modern machines although of course the control systems are much more sophisticated nowadays. The principle of injection molding is very simple. A certain thermoplastic material, in the form of granules, beads of powder, is put in a feed hopper. The material slide through the hopper into a barrel where it is heated en becomes molten. Then it is forced through a nozzle into a relatively cold mold. After a certain cooling (the time that takes to solidify the plastic again) time the mold opens and the plastic part is ejected and the cycle is repeated.

4.2 Types of injection molding machines.

The principle of the injection molding process has evolved through the years. Though the changes in the principle are not revolutionary, they are significant. Major progress is made in the field of controlling of injection molding machines.

Plunger injection molding.

One of the first machines, the plunger injection molding machine, is an evolution of the transfer molding machines. The principle of these machines is quite simple. The plastic (beads, granules or powder) is fed through a hopper into a barrel. A plunger pushes the plastic in to a barrel that is heated by heater bands. In this barrel, a torpedo splits the flow into fairly elaborate channels. The intent is to expose the polymer to as much heated surface as possible. As the plunger advances the now viscous plastic is injected into the mold cavity. While the plunger system is fairly simple, it is not possible to get a reasonable hourly throughput (even with sophisticated heating cylinders and torpedos to increase the quality of the melt). Another main disadvantage is the inaccuracy of the shot size.

Preplasticizer, two-stage plunger injection cylinder.

The principle of this machine is quite the same as the one described above. The difference is that the plastic is melted in another cylinder that is mounted at an angle to the shooting cylinder. The plastic is fed from a hopper into a barrel (preplasticizer cylinder) and is ejected across the torpedo into another cylinder. A plunger in this second cylinder injects the plastic into the mold (shooting cylinder). The major advantages of this machine are the accurate control of the shot amount, the lower injection pressure, temperature of the cylinder and the greater shot weight.

Preplasticizer, two-stage screw injection cylinder.

This system is identical to the system described above, except that the melting, homogenisation and
injection is done by a screw extruder instead of a plunger and torpedo. The advantage of this design lies in the improved homogeneity of the melt.

Reciprocating screw injection cylinder.

The concept of the reciprocating screw injection cylinder originated at Badische Anilin & Soda Fabrik A.G. in Ludwigshafen, Germany. The earliest commercial machine was made and marketed by Ankerwerke in 1956. The principle is again related to the systems used before. The raw material flows from the hopper into the cylinder. The rotating screw conveys the material forward as it is melted. Ahead of the screw the plastic collects and the screw is pushed backward. If a certain weight of plastic is collected, the screw stops rotating and a hydraulic ram moves the screw forward and inject the plastic into the mold. This concept has the primary advantage that the melt is very homogeneous and uniform.
5. Design.

At the University of Southern Queensland an extruder has already been developed. This extruder is a stationary single screw extruder (Axon, Sweden) in a vertical position. For research and educational purposes, an injection molding unit is required to do experiments in combination with the extruder. For innovative as much as financial reasons, the unit must be designed and manufactured at the university.

5.1 Design requirements and considerations.

The injection molding unit has to meet many requirements in many fields. Due to the small budget for research available, the overall costs of the injection molding unit are limited to approximately A$ 13,000. This includes material for the machine (steel), pneumatics and controllers.

The moving parts of the machine have to be actuated by pneumatic instead of hydraulic cylinders for both financial and practical reasons (no hydraulic circuit available). The clamping force and injection pressure are therefore limited.

The unit to be designed has to match with the extruder unit that is operating already. This means roughly that the unit has to be placed as shown in fig. 1.

![Diagram of the complete machine](image)

*Figure 1: draft of the complete machine.*

The plastic has to flow vertically into the molding unit due to the positioning of the extruder. Further, the frame of the molding unit has to match with the frame of the extruder. The molding unit and extruder have to remain separate in a way that the molding unit can be mounted on the extruder. The frame on which the unit is mounted has to be mobile.

Another important (and innovative) requirement is that the extruder has to work continuously. So the molding unit has got to consist of two cylinders with plungers. While the first cylinder is filled, the second one has to inject the plastic into the mold. Each cylinder injects the plastic into a mold (2 molds, which are controlled separately). Therefore the flow of plastic has got to be regulated by
Design of an injection molding machine.

The design of the machine can be split into roughly 10 sections, which will be described in this section. The flow of the polymer (process) and the corresponding component parts will be discussed.

5.2 Injection molding machine.

The design of the injection molding machine will be described in this section. The two injection cylinders will be placed at an angle of 90°. The forces acting, have to be kept in the molding unit (no forceful interaction between extruder and molding unit). The molding unit has to consist of a hot part and a cold part. This can either be a hot or a cold runner system.

5.2 a Transport of polymer from extruder into injection cylinder.

Process.

The plastic flows from the extruder into the injection unit. A barrel is screwed onto the extruder and contains a strainer plate and a cone shaped die. The strainer plate has two functions; it homogenizes (straightens) the flow further by restricting the flow through small channels (2mm diameter) and it prevents the screw from falling out of the barrel. A cylinder with an inside cone shape is used to reduce the diameter of the polymer flow from approximately 15mm to the diameter of the flexible hose (10mm). The actual connection between the extruder and the injection molding machine is made by a flexible metallic hose which allows a little bit of disalignment between the extruder and the injection molding unit. This hose is made of double braid stainless steel and it is possible to mount heaterbands on it to keep the polymer on the right temperature. The hose is connected to another barrel in the mainblock. This barrel contains the valve that converts the polymer to one of the injection cylinders. The first stage of the injection molding cycle the polymer flows from the upper side of valve (extruder side) to the injection chamber of the first cylinder (position 0). In the second stage the valve rotates 90° and the polymer flow goes into the injection chamber of the second cylinder (position 1). This flow is going from the extruder to the first injection cylinder. The mechanism that makes the valve turn consists of a chain that is actuated by the sprocket of the rotational cylinder. This chain is also connected with a sprocket on top of the valve. This mechanism will conduct less heat from the barrel (hot) to the cylinder (cold) than a gear-gear contact would do.

Parts.

This process includes eleven main parts. It begins with the topbarrel (fig. 5.2.a.1) that contains a strainerplate (fig. 5.2.a.2) and a cone shaped die (fig. 5.2.a.3). Then we have the flexible metallic hose that is connected to the barrel (fig. 5.2.a.4) of the mainblock (fig. 5.2.a.5). The mainblock contains the valve (fig. 5.2.a.6) that consists of two merely symmetric parts (fig. 5.2.a.7 & 5.2.a.8). On top of the valve a sprocket (5.2.a.9) is mounted as part of the rotational mechanism. Between the sprocket on top of the valve and the barrel and between the valve and the mainblock, two rings of PTFE (fig 5.2.a.10 & 5.2.a.11) are placed to seal and reduce the friction. Also the connection between the valve and the injection cylinder is sealed by PTFE rings. PTFE is not the best sealing material, but it has a very good temperature resistance and a low friction coefficient. The assembly of these components is given in fig 5.2.a.12.

5.2 b Transport of polymer from the injection cylinder to the nozzle.

Process.

After the filling of the injection chamber the valve will rotate. The polymer will be injected into
the mold under high pressure. The polymer flows through the second channel in the valve. The second flow goes from horizontal at the front side of the valve to vertical at the bottom side of the valve. The flow will go into the block that will convey it into the nozzle.

Parts

This second process involves just three parts, two of them were mentioned before; the valve (fig. 5.2.a.6, 5.2.a.7 & 5.2.a.8) and the mainblock (fig. 5.2.a.5). The third one is the block that is mounted underneath the mainblock that converts the flow from vertical to horizontal (fig. 5.2.b.1). This block consists of five separate parts (fig. 5.2.b.2, 5.2.b.3, 5.2.b.4, 5.2.b.5 and 5.2.b.6).

5.2.c Injection cylinders.

The injection cylinders is to inject the polymer through the pipes and valve into the mold. The recommended injection pressure is about 8000 psi (for a shot weight of 10 grammes and a plunger diameter of 15mm) or 55.1 bars. This pressure must be produced by a cylinder of diameter 160mm. The maximum, theoretical force this cylinder can make is:

\[ F = P_{\text{inj}} \times A_{\text{plunger}} \]  \hspace{1cm} (eq. 2.1)

Where as \( F \) is the force needed to inject the polymer into the valve at a pressure of 551 bars (55.1 N/mm\(^2\)) \( P_{\text{inj}} \) is the injection pressure needed to mold 10 grammes of polyethylene (551 bars) and \( A_{\text{plunger}} \) is the area of the cylinder (\( 752 \times \pi \)).

The force therefore is: \( F = 9737 \) N. The air pressure needed for the pneumatic system will be (at an efficiency of 83\%):

\[ P_{\text{air}} = \frac{F}{A_{\text{cyl}}} \]  \hspace{1cm} (eq. 2.2)

The theoretically needed pressure will be:

\[ P_{\text{air, th}} = \frac{9737}{80^2 \times \pi} = 0.488 \text{ N/mm}^2 \]

The needed pressure (theoretically) is 4.88 bars. If we consider the efficiency (≈ 83\%) the pressure needed is 5.87 bars.

5.2.d Injection mechanism.

The stroke of the air cylinder is 100 mm. To allow the machine to mold variable shotweights (i.e. different molds) the stroke must be adjustable. The mechanism, shown in fig. 5.2.d.1, allows the operator to adjust the stroke between 0 and 100mm. This is useful to make little adjustments to optimize the process and allows the use of other molds with different volumes. The rod end of the cylinder and the plunger are actually not connected. The rod end pushes the plunger into the injection chamber (in the outgoing stroke) and returns without the plunger. The plunger will be pushed back by the pressure of the polymer until it makes contact with the rod end again. This mechanism consists of 9 parts. The injection chamber (fig. 5.2.d.2), plunger (fig. 5.2.d.3) and barrel (fig. 5.2.d.4) with cover (fig. 5.2.d.5), the air cylinder with flanges (fig. 5.2.d.6, 5.2.d.7 and 5.2.d.8). Finally, we got a flange (fig 5.2.d.9) and nut (fig. 5.2.d.10) to adjust the stroke.

5.2.e Transport of polymer through the nozzle into the mold.

\[ \text{Source: Butler Design, Fulltex-Bipel Ltd, UK.} \]
Process

The most important part of the machine is the mold with the nozzle. The machine consists of two identical molds and nozzles. The polymer flow goes into the nozzle (free flow nozzle) and the channel is restricted to a diameter and a land of 1.5mm. The ingoing flow has a diameter of 10mm, the outgoing (to the sprue) a diameter of 6mm. The channel of 1.5 mm has a recommended taper at the ends of 90°. The nozzle is clamped between the tube block and a flange. The flange is the first part of the cold section of the machine. Between the tube block and the flange insulation rings and bars are placed. From the nozzle the flow goes straight into the mold. The sprue has a taper angle of 2.85° (available in the workshop). The cavity consists of two cylinder shaped parts. The dimensions of these parts are: diameter 15mm and a height of 10mm. The runner system (balanced) consists of the two cylinders (diameter 3mm) which go from the sprue to the cavity. The two mold parts (the stationary and the moving) are identical except for the sprue and ejector pins. In the moving mold part 3 ejector pins are placed, two in the cavities and one in the middle underneath the sprue. The cavities have a taper angle of 1 degree (recommended 1/4 to 2 degrees). Underneath the sprue, a cylindrical recess, without a taper angle, is made (with ejector pin) to pull the molded part out of the stationary mold part.

Parts.

The actual mold consists of four parts. The nozzle (fig 5.2.e.1), the flange (fig. 5.2.e.2) clamps the nozzle to the mainblock, the stationary (fig 5.2.e.3) and moving (fig. 5.2.e.4) mold part. In the stationary mold part four leader pins are placed to keep the moving mold part in the correct position.

5.2.f Mold design.

The design of the mold is merely a matter of experience. There are no exact design rules the different cavities have to oblige to. The only rules of thumb are the ranges in between the dimensions of the gates and runners must be. The diameter of the runners must be somewhere between .5 and 5 mm (depends on the size of the cavities). The gate must be about half the diameter of the runner. The land of the gate has to in the same order. Further a taper angle in the cavities of the stationary mold part is recommended. This machine has an cold runner system. This means that the runner are part of the molded part and are ejected after every cycle. The mold is equipped with cooling channels to cool the polymer. The cooling must be fast to freeze off the gate and shorten the molding cycle. But if the cooling is to fast, the plastic will solidify before the cavities are filled. The optimum has to be found empirically. Another point to consider is the balancing of the runners. It is necessary that the polymer reaches the cavities at the same time and at the same pressure. Therefore the number of cavities is usually a multiple of two. In this design we only got two cavities with a cylindrical shape (symmetric). The diameter of these cavities is limited because of the clamping force. A coin shape would be preferable considering cooling and ejecting, but the clamping force needed for a coin shape part of ten grams cannot be delivered by pneumatics (by using extremely long arm in the clamping mechanism). The final design of the mould consist of:

- 2 cylindrical cavities, diameter 15mm, height 20mm (10mm in each mold part), taper angle 1°.
- 2 cylindrical runners, diameter 3mm, length ±13mm.
- 2 gates between cavity and runner (half -cylindrical), radius 1.5mm, length ±2mm.
- 1 sprue, length 48mm, initial diameter 6mm, final diameter ±10.8mm, taper angle 2.85° (in the stationary mold part only)

The molds are made of mild steel, not the most appropriate material for molds (usually hardened steel is used). Hardened steel cannot be machined here and it would make the molds much more expensive (costs of molds are in the order of A$10,000.-). These molds of mild steel will not last as many cycles as a hardened steel mold would, but it will be sufficient for this machine because it will not be in continuous operation. The accuracy of the machines in the workshop is lower than the unusual size of the venting channel, so the air will escape without making venting channel.
Might there be any air entrapment, a couple of scratches near the cavities will provide sufficient venting. The mold consists of five cavities, the cylindrical parts, the sprue and the runners. The projected area of these cavities can be calculated.

Area of cylindrical part (max. diameter is $7.5 + 10 \sin \theta = 7.67$ mm)  

\[
(7.67)^2 \pi = 185.0
\]

Area of sprue (max. diameter is $3 + 48 \sin 2.85^\circ = 5.39$ mm)  

\[
(5.39)^2 \pi = 91.2
\]

Area of runner (diameter is 3 mm, length is 15 mm)  

\[
3 \times 15 = 45.0
\]

Total area is $2 \times 185 + 91.2 + 2 \times 45 = 551.2$ mm$^2$

5.2.g Ejector mechanism.

Process.

The mold contains three ejector pins, two pins that eject the cylinders out of the cavities and one ejector pin underneath the sprue that ejects the cylinder in the middle. The ejector pins are actuated when the pins hit the ejector plate. The ejector plate is welded on the block that connects the tie bars of the mold mechanism and the tie bars of the cylinders that actuate the mold. In the extreme position (mold opened) the relative movement of the pins will be 14 mm. When the mold closes, a spring will push the pins back in the original position.

Parts.

The ejector mechanism (fig. 5.2.f.1) for one mold consist of nine parts; the ejector pins (2) (fig 5.2.f.2) that ejects the cylindrical parts, the rest of these pins (2) (fig 5.2.f.3) that hit the ejector plate (fig. 5.2.f.4), springs (2) that move the pins back, an ejector pin that ejects the cylinder in the middle and a pin that connects the two main ejector pins with the one in the middle (fig 5.2.f.5). The assembly of the ejector pins is given in fig 5.2.f.6. The spring (Chrome Vanadium die spring) has an outside diameter of 9.5 mm and a inside diameter of 4.7 mm. When the mold is closed, a force pushes each pin back in its hole. The free length of the spring is 31.75 mm. The maximum deflection is 50%; the deflection the spring will have in the mold is 44%. The mold (opened and closed) is shown in fig 5.2.f.7 and 5.2.f.8. The moving mold part is mounted on a flange (fig 5.2.f.9) that slides over the tiebars. This flange is actuated by a mechanism that will be discussed in the next paragraph. This mechanism consists of two arms (fig 5.2.f.10 & 5.2.f.11), two trunnions (fig 5.2.f.12) and a spherical bearing rod end (Joucomatic) that connects the arms with the rod of the air cylinder.

5.2.g Mold mechanism.

The mold mechanism is the mechanism that actuates the moving mold part. To increase the clamping force, the air cylinder does not push the mold parts together directly, but it pushes a mechanism (two arms) down. The next figure is a draft of the mechanism.
When the mold is closed, the distance between point A and B is 398mm. The angle the arms make with the horizontal plane is 4.05 degrees. The air cylinder 100mm diameter deliver a force of 4000 N at 6.0 bars. The air pressure in this pneumatic circuit will be 6.5 bars, the delivered force therefore will be 4300 N. At an angle of 4.05 degrees the force in horizontal direction will be as drafted in the next figure:

The moment the mold has closed, the situation is static. There has to be an equilibrium between the forces in x and y direction. The equation are:

\[ F = F_1 \sin \alpha + F_2 \sin \alpha = (F_1 + F_2) \sin \alpha \]  
\[ F_1 \cos \alpha = F_2 \cos \alpha \rightarrow F_1 = F_2 \]  

The maximum force the cylinder can deliver is 4300 N. The angle in between the arm and the horizontal plane is 4.05 degrees. The forces F1 and F1 will be:
\[ F_1 = F_2 = 0.5 \times \frac{4300}{\sin(4.05')} = 32978 \, N \]

The force in horizontal direction (clamping force) will be:
\[ F_{\text{hor}} = F_1 \cos \alpha = 32878 \times \cos(4.05') = 32896 \, N \]

The maximum force the injected polymer induces is the maximum pressure times the projected area. This force is:
\[ F_{\text{polymer}} = P_{\text{polymer}} \times A_{\text{proj}} = 55.1 \, \text{N/mm}^{-2} \times 551.2 \, \text{mm}^2 = 30371 \, N \]

The needed clamping force is lower than the maximum force the mechanism can deliver.

**5.2.h Frame.**

The injection molding unit has to be placed on a frame that can be moved. The construction will be made of 100 x 100 x 4 square hollow section beams. Further the frame has to be adjustable to cover the difference in height between the barrel of the extruder and the barrel of the injection molding unit. The frame consist of a mainframe with wheels (fig 5.2.h.1), a beam (T-shape, fig 5.2.h.2) that supports the cylinders of the mold mechanism, and three pillars that support the mold mechanism, the injection cylinders and the mainblock (fig 5.2.h.3, 5.2.h.4 & 5.2.h.5).
6. Pneumatics and logic control.

6.1 Pneumatics.

The air cylinders will be controlled by valves and other pneumatic components. The air cylinders used are double acting, so the valves have to have at least 4 ports. Solenoid-spring return valves are used for the control. Solenoid valves with 5 ports (5/2 valve) are cheaper than the ones with 4 ports (4/2), so the 5/2 valves are chosen. The spring return makes the valve go back in its original position when the valve is deenergized. If necessary a solenoid-solenoid (memory element) valve can be used, but then a set and a reset signal has to be given to the valve, while only a set signal is needed in the present selection of spring return valves. The speed of the cylinders is controlled by exhaust flow control valves, by adjusting the flow rate through the valve the speed of the cylinder can be regulated. Further a service unit (lubricator, filter and pressure regulator for primary circuit) and pressure regulators for secondary circuit are used. The next figure shows the diagram of the pneumatic circuit.

![Diagram of the pneumatic circuit](image)

Figure 4: Diagram of the pneumatic circuit.

6.2 Logic control

The control of the valves can be done by a PC, PLC or a combination (P/C). For all of them (especially PLC) it is necessary to convert the position/time diagram into logic equations. These logic equations can be derived by using combinational logic. If memory elements are used, sequential logic is used to derive the equations.

**Combinational Logic.**

The control of the valves can be done by combinational logic. The valves are solenoid-spring return valves so we do not need a reset signal. The problem will be solved in five stages. The first one is the modelling of the diagram that tells us when what cylinder moves and in what
Design of an injection molding machine.

position it is (position-time diagram). The cylinders are equipped with magnetic position detectors so that a signal will be given when the cylinder reaches one of its extreme positions. Our system consists of 5 cylinders. Two cylinders that actuate the injection plunger, two cylinders that actuate the moving plates of the mold and one rotational cylinder that makes the valve rotate. When a cylinder is in its end position (full length) the binary code is 1, when its back in the starting position its 0. For cylinder A it is a1 (1) and a0(0). The diagram is printed in the next figure. The cylinders are named as follows:

a: first cylinder of the mold mechanism
b: second cylinder of the mold mechanism
c: first cylinder of injection mechanism
d: second cylinder of injection mechanism
e: rotational cylinder of valve.

Figure 5: The time-position diagram for the five cylinders.

The second stage is to make a truth table for each step (greek numbers) and the end points (arabic numbers). The procedure is as follows: if a cylinder is in an end position the binary code is one (cylinder A is in end position: a1 = 1, a0 = 0). The signal A=1 is given when the piston is moving towards the end position or if it is in the end position. The signal A=0 is given when the piston is moving back or is in its starting position. So the truth table contains 15 columns (a0,a1,b0,b1.....e1,A,B,C,D,E) and 20 rows (0,1,1,II,2,III.........X).
The truth table

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Table 1: Truth table for time-position diagram.

The third step is to convert the data from the truth table to a Karnaugh diagram. A Karnaugh diagram is a graphical solution method to derive the abbreviated equation of a logic function. We have to make a diagram for each cylinder (for each signal A, B, C, D, E) to derive the logic equations. The Karnaugh diagram consist of squares. Each of the squares represent an elementary conjuction. If we got to cylinders X with end positions X1 and X2 the diagram is as follows:

```
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<th>X1.X2</th>
<th>X1.X2</th>
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</thead>
<tbody>
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<td>X1.X2</td>
<td>X1.X2</td>
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</tbody>
</table>
```

Figure 6: Karnaugh diagram.

When there is an line above a variable it means "not"; X1 means not -X1. For our pneumatic system we got 5 cylinders and ten positions. The Karnaugh diagram therefore consists of $2^{10}$ squares. Each combination of a0, a1, b0 etc gives one unique square in the diagram. So we convert the truth table to a Karnaugh diagram by finding a square for each combination of the truth table and putting the value (0 or 1) for the signal (A, B, C, D and E) in that square. There are only twenty combination so most of the squares are empty. These are called "don't cares", you can give it either a 1 or a 0. The fourth step is to reduce (abbreviate) the equation by taking as many as possible squares with only ones or "don't cares" together. To abbreviate the equations, as many as possible elementary conjuctions (squares) with ones and "don't cares" have to be added together in as few as possible steps, until all squares with ones are covered. The grey pattern in the diagrams are the squares added together. For example in the diagram for C, b1 are all the squares underneath the line with "b1" above it. Finally it results in a logic equation. This logic equation can be put in an logic scheme with "or-", "and-", "not-" etc ports. The Karnaugh diagrams are printed in the appendix. The equations that follow from the Karnaugh diagram are:
Design of an injection molding machine.

\[
A = Sc_1d_1e_1 \\
B = c_0d_1e_0 + b_0c_1 \\
C = \bar{a}_0 + \bar{b}_1 + d_0 + c_1\bar{e}_1 \\
D = a_1 + c_0 + \bar{b}_0\bar{c}_0 + d_1\bar{e}_0 \\
E = \bar{a}_0 + d_0 + \bar{c}_0\bar{e}_1
\]

The last step is to represent these logic equations in a logic scheme. These schemes and equations allow us to control the pneumatics by PLC.

*Figure 7: Logic scheme for the pneumatic circuit.*
7. Calculation of the cost.

A budget of A$13,000.00 is very small to design a machine like this. The workshop at this University is however able to produce the different parts at much lower price than a commercial company. The materials, pneumatics and controllers have to be purchased from outside the University. The cost of materials and pneumatics are exact, the cost of controllers is still an estimation.

### Materials

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<tr>
<th>Material/Part Description</th>
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<th>Price /each (A$)</th>
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### Pneumatics

#### Air cylinders

- 160mm, stroke 100mm
- 100mm, stroke 100mm
- Rotational, 20mm, 180°

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**TOTAL**                                        |                     |    | 12930.57        |                 |

The cost of the total design is below the budget limit of A$13,000. The air cylinders of 100mm are available at the workshop so the total costs will be less than calculated. It might be possible to control the pneumatics with a PC and a DCI Smartlab 8255 I/O card. This would reduce the cost significantly because this card is much cheaper than PLC.
8. Conclusions, discussions and recommendations

Main goal of this project is reached, an injection molding machine is designed and the actual manufacturing can start. The design is related to a type of injection molding machine that is called “two stage screw injection molding machine”. It has however a quite innovative feature; the extruder section of the machine works continuously. The performance of the machine is something that has to be tested. There are a couple of critical sections in the machine. In the first place it is not known how the valves operates under a pressure of 551 bars. The second critical section is the nozzle. After the mold opens the sprue has to come out of the stationary mold part and the plastic has to “break” at the smallest cross section. One of the problems could be that is does not break is a thread spins between the nozzle and the ejected part. This might cause problems when the mold closes again or when the next shot of polyethylene is injected. Further more a lot of tests have to done to determine the right temperatures for the different sections and the optimal cycle time. The duration of each stage of the cycle time is mainly determent by the velocity of the air cylinder rod. In the frame a mechanism has to be designed to lift the frame to the right altitude to fit with the extruder. It is also possible to design a machine within the budget of A$13,000. It might even be possible to lower the costs by using an I/O card instead of one of the most expensive ways of controlling, PLC.
9. References and bibliography.

Polymer Processing, James M. McKelvey, St Louis, Missouri 1962, John Wiley and Sons, Inc., New York.


Procedure for trouble shooting injection molds and injection molding problems, R.J. Groleau, ANTEC '89, pp. 327-329.
10. Appendix.

Appendix 1. Diagrams of the design.

Figure 5.1. The injection molding machine.
Figure 5.2.a.1  Topbarrel.
Figure 5.2.a.2  Strainer plate.
Figure 5.2.a.3  Cone shaped die
Figure 5.2.a.4  Barrel in mainblock
Figure 5.2.a.5  Mainblock
Figure 5.2.a.6  Valve, assembly
Design of an injection molding machine.

Figure 5.2.a.7  Valve 1
Design of an injection molding machine.

Figure 5.2.a.8  Valve 2
Figure 5.2.a.9  Sprocket
Figure 5.2.a.10  Sealing ring, bottom side of the valve
Figure 5.2.a.11  Sealing ring, top side of the sprocket
Figure 5.2.a.12  Assembly of components
Figure 5.2.b.1 Assembly of block that converts polymer flow from vertical to horizontal
Figure 5.2.b.2    Block 1
Figure 5.2.b.3  Block 2
Figure 5.2.b.4. Block 3
Figure 5.2.b.5 Block 4
Design of an injection molding machine.

Figure 5.2.b.6  Block 5
Figure 5.2.d.1  Injector mechanism, injection cylinder and flanges
Figure 5.2.d.2 Injection chamber
Figure 5.2.d.3 Injection plunger
Figure 5.2.d.4  Injection barrel, keeps plunger in right position
Design of an injection molding machine.

Figure 5.2.d.5  Cover for barrel
Figure 5.2.d.6  Flange 1, attached to the mainblock
Figure 5.2.d.7  Flange 2, front side of cylinder
Figure 5.2.d.8  Flange 3, rear side of cylinder
Figure 5.2.d.9 Flange 4, to adjust the stroke length
Figure 5.2.d.10  Nut to fix flange 4
Design of an injection molding machine.

Figure 5.2.e.1  Nozzle
Figure 5.2.e.2  Flange, attached to block and clamps nozzle
Figure 5.2.e.3  Stationary mold part (sprue)
Figure 5.2.e.4  Moving mold part (ejector pins)
Figure 5.2.f.3  Ejector pin (rear part)
Design of an injection molding machine.

Figure 5.2.f.4 Block with ejector plate
Design of an injection molding machine.

Figure 5.2.f.5  Ejector pin (middle, one underneath the sprue)
Figure 5.2.f.6 Assembly of ejector pins
Figure 5.2.f.7 Assembly of mold (opened)
Figure 5.2.f.8 Assembly of mold (closed)
Figure 5.2.f.9  Flange attached to moving mold part
Figure 5.2.f.10  Arm 1 of mold mechanism
Figure 5.2.f.11 Arm 2 of mold mechanism
Figure 5.2.f.12  
Trunnion that connect arm and mold.
Design of an injection molding machine.

Figure 5.2.1 Main frame
Beam that supports air cylinders of mold mechanism
Figure 5.2.h.3 Pillar that supports first injection cylinder and mold mechanism
Figure 5.2.h.4  Pillar that supports second injection cylinder
Figure 5.2.h.5  Pillar that supports mainblock
Appendix 2. Karnaugh diagrams.
Karnaugh diagram for signal A, first cylinder of mold mechanism

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The diagram shows the logic for the injection molding machine, with each cell representing a binary value for the variables a, b, c, d, and e.
Design of an injection molding machine

Karnaugh diagram for signal B, second cylinder of mold mechanism
Design of an injection molding machine.

Karnaugh diagram for signal C, first cylinder of injection mechanism

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The diagram represents the logic function for signal C, with the first cylinder of the injection mechanism.
Karnaugh diagram for signal D, second cylinder of injection mechanism
Design of an injection molding machine.

Karnaugh diagram for signal E, rotational cylinder of valve mechanism.